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Mechanical and microstructural properties of glass powder-modified recycled brick-concrete aggregate concrete

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ABSTRACT

In order to achieve a better recycling of construction waste and explore the mechanical properties of concrete after incorporating multiple types of construction waste, this paper uses discarded concrete as recycled concrete aggregate (RCA), waste clay bricks as recycled fine brick aggregate (RFBA), and waste glass powder (GP) as an auxiliary cementitious material. Taking fully into account the modification effect of GP on the mortar matrix, a new type of green recycled concrete, namely GP modified Recycled Brick-Concrete Aggregate Concrete (GBCC), is prepared. Through a four-factor, four-level orthogonal experimental design combined with microstructural analyses (XRD, SEM, EDS, MIP), the mechanical properties and synergistic mechanisms of GBCC were systematically investigated. Results demonstrate that under the optimal mix ratio (15 % RCA, 40 % RFBA, 10 % GP, and water-binder ratio of 0.48), the 28-day cube compressive strength of GBCC reaches 39.2 MPa (equivalent to 100 % of C30 concrete), while the axial compressive strength and splitting tensile strength are 29.8 MPa and 2.72 MPa, respectively, meeting the design requirements of C30 concrete. Notably, at 40 % RFBA replacement, GBCC achieves over 90 % of the compressive strength of conventional C30 concrete. Microscopic analysis indicated that C-(A)-S-H gels formed by GP and RFBA reduced the total porosity by approximately 18 % (MIP test) and increased the proportion of harmless pores (<20 nm) to $25\sim28$ %, effectively refining the pore structure. SEM-EDS observations revealed dense gel filling at the interfacial transition zone, with the Ca/Si ratio of the gel reduced to 0.29, significantly enhancing interfacial bonding. This study pioneers the efficient co-utilization of RCA, RFBA, and GP, and for the first time integrates SEM-EDS microstructural characterization with molecular chemical analysis to elucidate the formation mechanisms of gels.

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1. Introduction

In recent years, the annual consumption of concrete worldwide has exceeded 20 billion tons [1], resulting in the mass production of cement, while river sand (RS) and natural stone are also mined on a large scale, imposing a huge pressure on the environment. The International Energy Agency (IEA) predicts that global cement consumption will reach 6 billion tons in 2050 [2]. The production process of cement is highly energy intensive, emitting approximately 0.8 tons of CO₂ for every ton of cement produced [3]. Simultaneously, the annual demand for RS and gravel is expected to exceed 20 billion tons [4]. In recent years, the annual output of global Construction and Demolition Waste (CDW) has been continuously increasing [5]. In 2023, the total amount has exceeded 4 billion tons, among which China, the European Union, and the United States contributed approximately 2 billion tons, 450 million tons, and 540 million tons respectively. However, its comprehensive recycling rate is still lower than 20 % [4,6–9]. Among these wastes, waste concrete, waste clay bricks, and waste glass account for more than 80 %. Improper landfilling of these wastes not only encroaches on land resources and pollutes the soil and water environment but also exacerbates the over-exploitation of natural sand and gravel resources [4,10]. Against this backdrop, the development of efficient and synergistic utilization technologies for CDW has become an important breakthrough for achieving the "dual carbon" goals and promoting the sustainable development of the construction industry.

It has been found that it is completely feasible to apply CDW in concrete, and concretes incorporating various CDWs are more environmentally friendly. Waste concrete and waste clay bricks in CDW are usually crushed and used for the production of recycled aggregate (RA) [11,12], while GP is recycled in concrete usually as fine aggregate or SCM [13,14].

Currently, the incorporation of RCA as coarse aggregate into concrete has been widely studied and applied. Usually a layer of old adherent mortar (AM) attaches to the surface of RCA, leading to RAC with low density, high porosity, and high water absorption [15], as well as poor interfacial transition zone (ITZ) between RCA and the new mortar [16]. Moreover, many micro-cracks are generated in RCA during the crushing process. There are two important reasons for the decrease in the strength of recycled aggregate concrete (RAC). Research on the mechanical properties of concrete incorporating RCA as a partial substitute for natural aggregate (NA) shows that at replacements of 10–25 % by weight, the mechanical strength of RAC is equivalent to or not more than 10 % less than that of normal concrete without RCA. However, when the replacement ratio exceeds 40–50 % by weight, RAC's strength decreases significantly [15–17], and the static elastic modulus reduces significantly [18,19]. Here, some scholars have proposed the concept of modifying and strengthening RCA, aiming to achieve physical properties comparable to those of NA. The modification and strengthening of RCA is achieved by removing or reinforcing the AM on the surface of RCA [20]. Common treatment methods include chemical solution immersion [21], microwave radiation [22], and physical filler modification [15]. Among them, the chemical solution immersion and microwave radiation methods not only are economically inefficient, but also generate new pollution. Therefore, it is more environmentally friendly and economically feasible to modify and strengthen RCA by physical filling modification [23].

RBA as coarse aggregate in recycled concrete has also been studied. RBA has poor physical and mechanical properties because of its high crushing index, water absorption and porosity [4], which results in recycled brick aggregate concrete (RBAC) having low compressive and splitting tensile strength, ductility and elastic modulus [24]. It was found that compressive strength decreased by 21.7 % compared with NC at 50 % by weight replacement of RBA for NA, while it decreased by 43.5 % up to 100 % by weight substitution [25]. Both elastic modulus and compressive strength decrease significantly with the increase of RBA substitution, making it impossible to extensively utilize RBA to replace NA [24–27].

In response to the deficiencies in the mechanical properties of RBA as a coarse aggregate in concrete, some scholars have proposed using RBA as a fine aggregate, and have further demonstrated that the advantages of RBA as fine aggregates are significantly greater than those as coarse aggregates. Yang [28] found that the compressive strength of concrete with the replacement of sand by RFBA at the dosage of 40 % by volume was enhanced by 41 % compared with that of the control group. Dang [4] found that the early compressive strength of RAC was higher than that of the control group at 50 % by weight of sand substituted by RFBA in the presence of additional water. Moreover, with replacements of 50 % and 100 % both by weight, the compressive strength of RAC was equivalent to NC at 365 days. However, there are also clashing findings, such as Ali's [29] study, which reports that the compressive strength is slightly higher than the control group at 75 % sand substitution with RFBA. However, the compressive strength decreases by about 20 % up to 100 % replacement, and the splitting tensile strength also shows a gradual decrease with the increase in sand replacement level. Ge [30] found that the compressive strength of recycled concrete reduced by 10–15 % when RFBA replaced RS with a 30–50 % replacement level, and reduced by approximately 20–30 % up to 100 % substitution. In addition, a few scholars have further studied RFBA, proving that brick powder has the pozzolanic effect, its chemical composition contains SiO₂ and Al₂O₃, which can react with Ca (OH)₂, a hydration product of cement, to generate C-A-S-H gels [4,28,31]. On this basis, Shilar [32] prepared a new type of high-quality and eco-friendly geopolymer bricks and conducted an in-depth study of the pozzolanic activity of SiO₂ and Al₂O₃.

The applications of WG in concrete can be summarized into three main types: partial replacement of cement [33]; partial replacement of fine aggregates [34]; and partial mixed replacement of cement and fine aggregate [35]. Previous studies found that after replacing fine aggregates with WG as glass sand, when the particle size of glass sand was large, the SiO₂ in GP was prone to undergo the Alkali-Silica Reaction (ASR) with the alkali in the cement to form a hydrophilic ASR gel. The gel itself does not cause damage to the concrete but will expand after encountering water, resulting in structural damage to the concrete body [33]. However, ASR will weaken with decreasing GP particle size ($\leq 600 \mu m$) [36]. Mechanically milled glass powders with fine particle size ($\leq 50 \mu m$) have a better pozzolanic effect, and the generated C-S-H gels form a denser microstructure, which can prevent ASR swelling [37]. It is worth stating that the research recommends an optimum replacement amount of GP is 10–20 % by weight, at which point the compressive strength and splitting tensile strength of recycled concrete are both optimal [33,36,37]. Furthermore, building upon this foundation, the present study proposes that the pozzolanic activity and micro-aggregate filling effect of GP enhance the compactness of the mortar matrix, thereby optimizing the porous structure of RFBA and the ITZ of RCA. This mechanism indirectly strengthens the

synergistic interaction between aggregates and the matrix, rather than directly modifying the aggregates themselves.

In addition, a few scholars have proposed to mix RCA and GP in concrete and explored the mechanical and durability properties of RAC [33,37]. However, no in-depth study has been carried out on the filler-modifying effect of GP. A few scholars also proposed to mix RCA and RBA (as coarse aggregate) in concrete, and found that, because of the defects of RBA, recycled concrete incorporating the mixture of RCA and RBA did not exhibit good mechanical properties [38,39]. The current research gaps can be summarized as follows: (1) The synergistic mechanisms and optimal mix design of ternary systems incorporating RCA, RFBA, and GP remain underexplored; (2) The dual effects of GP—pozzolanic activity and micro-aggregate filling—have not been systematically quantified; (3) The functional transition of RBA from coarse to fine aggregates has yet to be fully exploited, particularly in balancing high CDW incorporation with mechanical performance.

By reviewing and summarizing the current research status of RCA, RBA and GP applied to recycled concrete, it can be found that: (1) RCA is generally regarded as defective compared with NA, and once its substitution amount of NA exceeds 40–50 % by weight, the mechanical properties of recycled concrete will be greatly reduced. However, the physical filler modification is environmentally friendly and economical, which can achieve the modification and reinforcement of RCA, thereby increasing the RCA content. (2) The advantage of RBA as fine aggregate is greater than that of coarse aggregate, but there is no consistent conclusion on the compressive strength of recycled concrete with respect to RFBA dosage. Moreover, the explanation for the pozzolanic activity of RFBA is not sufficient. (3) The principal chemical component of GP is SiO₂ [40], which has pozzolanic activity and can be used as SCM in RAC. However, there are currently many studies on the macroscopic mechanical properties of recycled concrete incorporating GP, and the deeper microcosmic mechanism of GP pozzolanic activity is still relatively rare. (4) At present, the research on the mechanical properties of recycled concrete incorporating multiple CDWs is still relatively preliminary, and there are some deficiencies in raw material optimization. More importantly, the optimal mix design has yet not been found, which can minimize the adverse effects such as Alkali-Silica Reaction and give full play to the positive pozzolanic activity of GP and RFBA, allowing multiple CDWs to be combined and work well together.

In summary, this study is the first to optimize the mix design of ternary CDW blends (RCA, RFBA, and GP) using orthogonal experiments. We propose a novel approach by incorporating GP as a mortar matrix modifier to indirectly strengthen aggregates, resulting in a new type of eco-friendly recycled concrete. The mechanical properties of this material were systematically tested. Additionally, through advanced micro-mechanistic analysis, we innovatively combined SEM-EDS characterization with molecular chemistry to explain the formation mechanism of fibrous network-like gels. This work clarifies how silicate-aluminate polymerization drives the evolution of the gel structure, providing insights into the synergistic effects of multi-component CDW systems.

2. Materials and experiment

2.1. Raw materials

Table 1

RCA, RFBA, and GP used for this research were all acquired as wastes from demolition sites in Zhengzhou. The particle sizes of the selected NA and RCA ranged from 5 to 19 mm, while the particle sizes of RS and RFBA from 0 to 5 mm. The physical properties of various aggregates are shown in Table 1. The particle grading of coarse and fine aggregates is shown in Fig. 1, and the particle size distribution meets the specification requirements. Notably, this study developed a "screening-washing" pretreatment process for recycled aggregates, which minimizes impurity content and size-related effects by removing contaminants and strictly controlling particle size distribution.

To address the issues of contaminants and variable compositions in CDW globally, impurities can be removed through physical separation methods (magnetic separation, screening) and chemical contaminant neutralization techniques (chemical solution immersion), thereby significantly enhancing the large-scale application potential of GBCC.Additionally, the three pretreated recycled materials achieve multi-scale synergistic optimization: RCA provides skeletal support, RFBA fills voids in coarse aggregate, and GP further refines pores and strengthens the ITZ. This "gradation-activity-filling" trinity strategy offers a new approach for realizing complex aggregate systems.

Fig. 2 presents the laser particle size analysis results of GP and P.O 42.5 Portland cement. The volume average particle size of GP was 23.55 µm, the median particle size was 19.23 µm, and the peak particle size was 25.58 µm. The volume average particle size of cement was 17.63 µm, the median particle size was 12.29 µm, and the peak particle size was 24.57 µm. Tap water was used for preparing all concrete mixtures investigated in this study.

Fig. 3 presents the microscopic morphology of RFBA and GP. It can be observed that the surface of RFBA was rough and porous, whereas the surface of GP was smooth and angular. The XRD results for the physical phase analysis of RFBA and GP are shown in Fig. 4.

Physical properties of various aggregates.									
NO.	Apparent density (kg/m ³)	Packing density ($\rm kg/m^3$)	Moisture content (%)	Water absorption (%)	Crushing index (%)	Fineness modulus			
NA	2730	1550	0.22	0.6	9.6	/			
RCA	2620	1380	2.59	3.95	15.7	/			
RS	2550	1260	0.27	2.65	1	2.9			
RFBA	2460	1190	3.21	16.13	28.5	2.8			



Fig. 1. Particle grading of coarse and fine aggregates.



Fig. 2. Particle size distribution of cement and GP.



(a) RFBA

(b) GP

Fig. 3. Microscopic morphology of RFBA and GP examined by SEM.

It is evident that the main chemical components of RFBA were SiO₂, Al₂O₃, Fe₂O₃, and CaO, etc. Active SiO₂ and active Al₂O₃ were the root reasons for the pozzolanic activity of RFBA. On the other hand, GP was an amorphous crystal, and its chemical components were mainly SiO₂ and Na₂O, etc. Active SiO₂ was the root reason for the pozzolanic activity of GP.



Fig. 4. Physical phase analysis by XRD.

2.2. Orthogonal mix proportion design and preparation of GBCC

Orthogonal experimental design is a methodology that uses orthogonal arrays to arrange and analyze tests for various factors and their levels, selecting representative tests from all possible combinations to determine the optimal combination through test results. This study adopted a four-factor, four-level $L_{16}(4^4)$ orthogonal experimental design to analyze the effects of RCA (Factor A) replacing natural gravel, RFBA (Factor B) replacing river sand, GP (Factor C) replacing cement, and different water-binder ratios (Factor D) on the mechanical properties of GBCC. Table 2 presents the factors and levels after $L_{16}(4^4)$ orthogonal design, with each factor (A, B, C, D) set at four levels corresponding to replacement ratios or mix parameters as specified.

This experiment conformed to the protocol specified in Chinese Standard JGJ 55–2011 "Specification for mix proportion design of ordinary concrete" [43], with C30 as the target characteristic compressive strength. Using a four-factor four-level orthogonal experimental design method, 16 groups of samples together with a control group of ordinary C30 concrete were prepared and tested. The specific mix proportions of the 17 groups are presented in Table 3. A sample group identifying system was adopted, in which a group identifier was represented by *Ri-Bj-Gk-Wl*, where *R* represents RCA, *B* represents RFBA, *G* represents GP, while the number, i.e. *i*, *j* & *k*, indicates the substitution ratio of RCA, RFBA and GP, respectively. *W* denotes the water-binder ratio (w/b, the ratio of the mass of water to the total mass of cement and glass powder), and the number, *l*, following *W* designates the value of w/b.

Among them, RCA and RFBA as aggregates adopt volume replacement to maintain the total aggregate volume, ensuring stable inter-particle void ratio and avoiding gradation imbalance caused by density differences (e.g., RCA density is lower than natural aggregate, and mass replacement would change the volume proportion)[21,22]. When GP is used as a cement substitute in the cementitious system, it is necessary to match the chemical activity and particle packing effect of the binder: with a density similar to that of cement, mass replacement directly controls the total mass of cementitious materials and the content of active components (such as SiO₂), ensuring consistency in hydration reactions and microstructural optimization[3,36,37].

RCA was designed to replace NA by volume at replacement ratios of 15 %, 30 %, 45 %, and 60 %: low ratios (15 %, 30 %) were used to test the performance stability of concrete, while medium-high ratios (45 %, 60 %) explored the large-scale application potential of recycled aggregates. RFBA replaced natural river sand by volume at ratios of 10 %, 20 %, 30 %, and 40 %: as pre-tests showed that workability (slump < 50 mm) of the mixture failed to meet construction requirements when the replacement ratio exceeded 40 %, the upper limit was set at 40 %. GP replaced cement by mass [45] at ratios of 5 %, 10 %, 15 %, and 20 %, which can cover and refine the current research dosage range. Because of the rough and porous surface of RFBA, its water absorption rate was high. With the increase in the RFBA substitution rate, the fluidity of recycled concrete gradually deteriorates [28]. In response to the high water absorption of RFBA, this study balanced economy and workability by adjusting the w/b ratio rather than using pre-wetting treatment or chemical admixtures. This strategy avoids additional processes and chemical reagent use: while potentially limiting the potential for strength enhancement, it still achieves good workability through the intrinsic activity of materials and microstructural

Table 2			
Orthogonal	design	factor-level	table

Level	Factor			
	RCA (A)/%	RFBA (B)/%	GP (C)/%	w/b (D)
1	15	10	5	0.48
2	30	20	10	0.53
3	45	30	15	0.58
4	60	40	20	0.63

Table 3

Mix proportion design of GBCC.

NO.	RCA (kg/m^3)	RFBA (kg/m ³)	GP (kg/m ³)	NA (kg/m ³)	Sand (kg/m ³)	Cement (kg/m ³)	Water (kg/m^3)	w/b
NC	0	0	0	1107	651	387	205	0.53
R15-B10-G5-W0.48	159	63	19	941	586	368	186	0.48
R15-B20-G10-W0.53		126	39		521	348	205	0.53
R15-B30-G15-W0.58		188	58		456	329	225	0.58
R15-B40-G20-W0.63		251	77		391	310	244	0.63
R30-B10-G10-W0.58	319	63	39	775	586	348	225	0.58
R30-B20-G5-W0.63		126	19		521	368	244	0.63
R30-B30-G20-W0.48		188	77		456	310	186	0.48
R30-B40-G15-W0.53		251	58		391	329	205	0.53
R45-B10-G15-W0.63	478	63	58	609	586	329	244	0.63
R45-B20-G20-W0.58		126	77		521	310	225	0.58
R45-B30-G5-W0.53		188	19		456	368	205	0.53
R45-B40-G10-W0.48		251	39		391	348	186	0.48
R60-B10-G20-W0.53	637	63	77	443	586	310	205	0.53
R60-B20-G15-W0.48		126	58		521	329	186	0.48
R60-B30-G10-W0.63		188	39		456	348	244	0.63
R60-B40-G5-W0.58		251	19		391	368	225	0.58

optimization. Compared with technical approaches relying on complex processes, the water-binder ratio adjustment method offers both environmental and economic advantages, providing a feasible solution for recycled concrete applications in regions with low technical thresholds [5]. The w/b ratios selected for this study were 0.48, 0.53, 0.58, and 0.63.

Fig. 5 presents the preparation flow chart of GBCC. Firstly, coarse aggregate and GP were placed into the mixing pot and stirred for 120 s using the dry mixing method. Subsequently, RS and RFBA were incorporated into the mixing pot and stirred for 60 s. After that, 50 % of the amount of the designated mixing water was added and stirred for 60 s, followed by adding cement and stirred for 60 s. Finally, the remaining water was added and stirred for 120 s. Fresh concrete was demolded after initial curing in molds for 24 hours, then immediately transferred to a standard curing chamber with a controlled temperature of $20 \pm 2^{\circ}$ C and relative humidity maintained above 95 %.

2.3. Specimens preparation and experimental methods

In this experiment, two different sizes of concrete blocks, namely 100 mm \times 100 mm \times 100 mm cubes and 100 mm \times 100 mm \times 300 mm prisms, were cast to examine their cube compressive strength, axial compressive strength, splitting tensile strength, and static elastic modulus, respectively. After the GBCC specimens were subjected to standard curing for 28 days, their mechanical properties were tested according to the "Standard for test method of mechanical properties on ordinary concrete" (GB/T 50081–2019) [44].

An electro-hydraulic servo pressure testing machine, namely YAWG206, was used to test the mechanical properties of GBCC. The loading rate was 0.5 MPa/s for the cube compression test and axial compression test, and 0.02 MPa/s for the splitting tensile test. The loading system for static elastic modulus is shown in Fig. 6, where f_c is the axial compressive strength, F_0 is the initial load at a stress of 0.5 MPa, and F_a is 1/3 of the axial compressive strength.



Fig. 5. GBCC preparation flow chart.



Fig. 6. Static elastic modulus test protocol.



(a) Compressive failure mode of cubic samples



(b) Compressive failure mode of prismatic samples



- (c) Splitting tensile failure section
- Fig. 7. Failure patterns of GBCC and NC.

3. Experimental results and discussion

3.1. Failure pattern

Taking several groups of concrete blocks tested to failure as examples, the failure patterns of GBCC specimens and NC specimens are compared and analyzed. The compressive damage process of GBCC cubic samples is the same as that of NC cubes, both of which underwent four stages of elastic deformation, crack generation, crack development, and failure. The final destruction was in the form of a positively inverted connected quadrangular cone [25], as shown in Fig. 7(a). In particular, when the RCA as a partial substitute for NA was at replacements of 45 % and 60 % by mass, several obvious cracks can be observed on the damaged surface of the concrete. This phenomenon was caused by the weak bond strength between RCA and mortar, and the ITZ damages when subjected to pressure. However, this phenomenon was not observed at replacement levels of 15 % and 30 % by weight, nor in NC.

The compressive damage process of the prismatic specimens of GBCC and NC was also largely the same. At the end of the loading process, a diagonal inclined crack appeared that penetrated the surface of the specimens, accompanied by a loud crashing sound, and the specimens failed, as shown in Fig. 7(b). Differently, only a few cracks appeared on the damaged surface, when the RCA replacement amount was low. Whereas, at replacements of 45 % and 60 % both by mass, not only several cracks appeared on the damaged surface of GBCC specimens, but also accompanied by surface mortar detachment and RCA bare leakage. The reason for this phenomenon is also the low ITZ strength between RCA and new mortar.

It is worth mentioning that the failure cross-sections of GBCC and NC specimens subject to splitting tensile test are different. The failure cross-section of GBCC prismatic samples was substantially more prone to aggregate failure than that of the NC samples, as shown in Fig. 7(c). The reason is that the surface of RFBA was rough and porous, and its strength was not as high as that of ITZ, and aggregate failure occurred first under greater pressure [25]. Moreover, RCA had initial defects compared with NC, and the probability of damage because of lack of strength was also greater than NC. It was rare for RS to experience aggregate failure in all the specimens, because RS had higher strength and smoother surface, and the connection between RS and mortar was not dense enough, resulting in insufficient strength of ITZ. Thus, when subjected to pressure, the ITZ damage occurred in most cases.

3.2. Range analysis of orthogonal analysis results

The optimal mixture design can be directly derived from a range analysis. The larger the range R, the greater the factor's influence on the mixture's mechanical properties. Table 4 shows the results of the range analysis. The influence degree of each factor on the cube compressive strength of GBCC from strong to weak is as follows: w/b, the replacement ratio by mass of RCA as a partial substitute for NA, the replacement ratio by mass of GP as a partial substitute for cement, and the replacement ratio by mass of RCA was 15 % by mass, the replacement ratio of RFBA was 40 % by mass, the replacement ratio of GP was 10 % by mass, and w/b was 0.48). The degree of influence of various factors on the axial compressive strength is consistent with that of the cube compressive strength, and the optimal combination was also R1B4G2W1. The degree of influence of various factors on the splitting tensile strength from strong to weak is as follows: RCA substitution ratio, w/b, GP substitution ratio, and RFBA substitution ratio, model is as follows: RCA substitution ratio, and RFBA substitution ratio, whereas the optimal combination was R1B2G2W1.

In summary, it can be concluded that for the mechanical properties investigated, RFBA substitution ratio for RS had the least influence among the four factors, followed by GP substitution ratio for cement, while w/b and RCA replacement ratio for NA had the greatest influence. When the RCA substitution ratio was 15 % by mass, the GP substitution ratio was 10 % by mass, and w/b was 0.48, GBCC exhibited the best mechanical performance. It should be noted that for cube compressive strength, axial compressive strength, and splitting tensile strength, the best formulation was achieved when the RFBA substitution ratio was 40 % by mass, while for static elastic modulus, the optimal RFBA replacement ratio was 20 % by mass.

3.3. Mechanical properties

Three standard cubic specimens were prepared per group according to the specifications to test mechanical strength. The table first lists the raw data of each specimen; after calculating the arithmetic mean in reference to the specifications, the final strength values were obtained. In subsequent orthogonal test analysis, the mechanical strength corresponding to each factor level is the mean value of all group strengths at that level. Raw mechanical properties of each group are shown in the Table 5.

3.3.1. Cube compressive strength

The cube compressive strength of GBCC is shown in Fig. 8, where the polylines indicate the transformation law of the ratio between the four levels of each factor and the control group (NC).

As shown in Fig. 8, the cube compressive strength of GBCC gradually decreases with the increase in RCA substitution ratio[15–17, 41]. At 15 % by mass RCA substitution level, the cube compressive strength was 39.20 MPa, which is equivalent to that (i.e. 39.11 MPa) of NC. When the RCA substitution ratio increased to 60 % by mass, the cube compressive strength was 34.45 MPa, which was 11.9 % lower than that of NC. As elaborated earlier, there are two main reasons for this. One is the ITZ between RCA and the new cement mortar which was poor because of the old cement mortar attached to the RCA surface. The other is that the surface micro-cracks generated during the crushing process of RCA which reduced the aggregate strength[20–22,41]. The cube compressive

Table 4Results of the range analysis.

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Factor	Cube compressive strength			Splitti	Splitting tensile strength			Axial compressive strength			Static elastic modulus									
	k1	k2	k3	k4	R	k1	k2	k3	k4	R	k1	k2	k3	k4	R	k1	k2	k3	k4	R
R	39.2	37.6	36.4	34.5	4.7	2.7	2.5	2.4	2.2	0.5	29.8	28.2	26.8	24.6	5.2	26.2	25.3	23.3	22.3	3.9
В	35.2	36.4	37.7	38.2	3	2.3	2.4	2.5	2.6	0.3	25.9	27.0	27.8	28.7	2.8	24.9	25.3	24.1	22.8	2.5
G	37.2	38.8	36.6	35.1	3.7	2.5	2.6	2.4	2.2	0.4	27.5	29.0	27.2	25.7	3.3	24.4	25.8	24.2	22.7	3.1
W	40.6	37.6	36.1	33.3	7.3	2.8	2.5	2.3	2.2	0.6	29.3	28.3	26.4	25.4	3.9	26.1	24.9	23.6	22.5	3.6

Table 5

Raw mechanical property results.

NO.	Cube compressive strength (MPa)	Axial compressive strength (MPa)	Splitting tensile strength (MPa)	Static elastic modulus (GPa)
NC	39.11	29.70	2.66	27.59
R15-B10-G5-W0.48	41.57	31.01	3.12	29.95
R15-B20-G10-	42.28	32.78	2.86	28.77
W0.53				
R15-B30-G15-	38.13	28.54	2.58	25.86
W0.58				
R15-B40-G20-	34.81	26.84	2.32	20.41
W0.63				
R30-B10-G10-	36.67	26.67	2.40	25.86
W0.58				
R30-B20-G5-W0.63	33.22	25.58	2.32	24.99
R30-B30-G20-	41.01	29.66	2.64	24.90
W0.48				
R30-B40-G15-	39.41	30.87	2.68	25.53
W0.53				
R45-B10-G15-	31.58	23.99	1.92	21.59
W0.63				
R45-B20-G20-	33.73	24.46	2.06	23.13
W0.58				
R45-B30-G5-W0.53	37.91	27.60	2.43	22.98
R45-B40-G10-	42.53	31.19	3.01	25.56
W0.48				
R60-B10-G20-	30.90	21.92	2.02	22.37
W0.53				
R60-B20-G15-	37.32	25.25	2.34	24.17
W0.48				
R60-B30-G10-	33.66	25.22	2.17	22.85
W0.63				
R60-B40-G5-W0.58	35.93	25.94	2.22	19.68



Fig. 8. Cube compressive strength.

strength of GBCC gradually increased with the increase in RFBA substitution ratio. When the RFBA substitution amount was 40 % by mass, the cube compressive strength (i.e. 38.17 MPa) was improved by 8.5 % compared with the case (35.18 MPa) with the substitution ratio of 10 %, and only decreases by 2.4 % compared with NC. This can be interpreted as, in addition to pozzolanic activity, the high water absorption of RFBA may promote late-stage hydration through the internal curing effect. Water stored in its porous structure is gradually released during the cement hardening stage, compensating for self-desiccation shrinkage and sustaining the formation of C-(A)-S-H gel [30–32].

At the GP substitution ratio of $5\sim10$ % by mass, the cube compressive strength exhibited an upward trend and reached its peak (i.e. 38.79 MPa) at the substitution ratio of 10 % by mass, which was equivalent to that of NC. Afterwards, the cube compressive strength decreased with the increase in GP substitution ratio. At the substitution ratio of 20 % by mass, the strength was 35.11 MPa, which was 10.2 % lower than that of NC. The analysis suggests that when the dosage of GP was low, its pozzolanic activity was stimulated, and the GP which did not participate in the reaction exerted a micro-aggregate effect to further improve the cube compressive strength [3,36, 37]. However, as the GP substitution ratio gradually increased, the cement content decreased, leading to a reduction in hydration products, including Ca(OH)₂ that can undergo a secondary hydration with GP[42]. The C-S-H gels generated were insufficient to compensate for the decrease in gelling effect caused by the reduction in cement, so the cube compressive strength demonstrated a downward trend instead[37]. With the gradual increase of w/b, the cube compressive strength slightly decreased. When the w/b was

0.48, the cube compressive strength was 40.61 MPa, which was 3.8 % higher than that of NC. However, when the w/b ratio was 0.63, the cube compressive strength (i.e. 33.32 MPa) was 14.8 % lower than that of NC. This is because when the w/b ratio increased, the spacing between cement particles became larger, and the gels produced by hydration cannot fill the pores well, and more pores were left after water evaporation, which reduced strength.

It is worth noting that, from the test results, the cube compressive strength of GBCC specimens can mostly reach more than 35 MPa, and the lowest can reach 30 MPa.

3.3.2. Axial compressive strength

The axial compressive strength of GBCC is shown in Fig. 9, where the polylines indicate the transformation law of the ratio between the four levels of each factor and the control group (NC).

As shown in Fig. 9, the transformation law of axial compressive strength with four factors and four levels is the same as that of cube compressive strength. The axial compressive strength gradually decreased with the increase in RCA substitution ratio [18–20]. When the RCA substitution ratio was 15 % by mass, the axial compressive strength reached 29.79 MPa, which was equivalent to the axial compressive strength (i.e. 29.70 MPa) of NC. At the replacement ratio of 60 % by mass, the axial compressive strength was 24.58 MPa, a decrease of 17.2 % compared to that of NC[41]. The axial compressive strength gradually increased with the increase in RFBA substitution ratio was 10 % by mass, the axial compressive strength was 25.90 MPa, a decrease of 12.8 % compared with that of NC. At the replacement level of 40 % by mass, the axial compressive strength reached 28.71 MPa, which was only 3.4 % lower than that of NC [32]. Similarly, the axial compressive strength reached a peak of 28.97 MPa, a decrease of 2.5 % compared to that of NC, when the GP substitution ratio was 10 % by mass. Afterwards, as the GP substitution level increased, it exhibited a downward trend instead, and at the replacement ratio of 20 % by mass, the strength (i.e. 25.72 MPa) decreases by 13.4 % compared to that of NC. With the gradual increase of w/b ratio, the axial compressive strength gradually decreased. When w/b ratio was 0.48, the axial compressive strength was 29.28 MPa, almost comparel to that of NC. However, for w/b = 0.63, the axial compressive strength was 25.41 MPa, a decrease of 14.4 % compared to that of NC.

3.3.3. Splitting tensile strength

The splitting tensile strength test results of GBCC are shown in Fig. 10, where the polylines indicate the transformation law of the ratio between the four levels of each factor and the control group (NC). As shown in Fig. 10, the splitting tensile strength gradually decreased with the increase in the RCA substitution ratio. At the replacement ratio of 15 % by mass, the splitting tensile strength was 2.72 MPa, which was slightly higher than that of NC (2.66 MPa). Whereas, at the replacement ratio of 60 % by mass, the splitting tensile strength was 2.19 MPa, a decrease of 17.7 % compared to that of NC. The splitting tensile strength demonstrated an upward trend with the increase in RFBA substitution ratio. At the replacement ratio of 10 % by mass, it was 2.37 MPa, which was 10.9 % lower than that of NC. When the replacement ratio increased to 40 % by mass, it was 2.56 MPa, which was only 3.8 % lower than that of NC. The splitting tensile strength also reached a peak of 2.61 MPa, when the GP replacement ratio was 10 % by mass, which was only 1.9 % lower than that of NC, and then exhibited a downward trend. At the replacement ratio of 20 % by mass, the strength (i.e. 2.26 MPa) decreases by 15.0 % compared to that of NC. With the gradual increase of w/b, the splitting tensile strength gradually decreased. For w/b = 0.48, the highest strength reached was 2.78 MPa, an increase of 4.5 % compared to that of NC. Whereas, for w/b = 0.63, the splitting tensile strength was 2.18 MPa, a decrease of 18.0 % compared to that of NC.

3.3.4. Static elastic modulus

The experimental results of static elastic modulus of GBCC are shown in Fig. 11, where the polylines indicate the transformation law of the ratio between the four levels of each factor and the control group (NC).

The static elastic modulus gradually decreased with the increase in RCA substitution ratio. At the replacement ratio of 15 %, it was 26.21 GPa, a decrease of 4.0 % compared to that (i.e. 27.29 GPa) of NC. When the replacement ratio increased to 60 % by mass, the static elastic modulus was 22.27 GPa, which was 18.4 % lower than that of NC. The first reason was the influence of aggregate, as the micro-cracks on the surface of RCA weakened the ability of recycled aggregate to resist deformation. The second reason was the lower



Fig. 9. Axial compressive strength.



Fig. 10. Splitting tensile strength.



Fig. 11. Static elastic modulus.

strength of ITZ, which was more prone to damage under stress. RFBA also harmed the static elastic modulus. With the increase in RFBA substitution level, the static elastic modulus first exhibited a slight enhancement and then gradually decreased. At the replacement level of 20 % by mass, it was 25.64 GPa, a decrease of 6.0 % compared to that of NC. When the replacement ratio increased to 40 % by mass, the static elastic modulus was 22.80 GPa, which was 16.5 % lower than that of NC. The reason is that both the apparent density and bulk density of RFBA are lower than those of natural sand, and its inherent elastic modulus is lower. As the replacement ratio increases from 20 % to 40 %, the proportion of low-stiffness RFBA increases: although gel filling enhances the stiffness of the mortar matrix, the stiffness-decreasing effect of the aggregate phase is more significant, leading to a decrease in overall elastic modulus [28, 29]. At a 20 % replacement ratio, the amount of gel formed balances the aggregate stiffness; however, at 40 %, excessive RFBA introduces more inherent pores (even though total porosity decreases, the elastic deformation capacity of the aggregate's own porous structure is poorer), further reducing the elastic modulus [4,25–27,41]. Although high replacement ratios of RCA and RFBA limit the static elastic modulus of GBCC, it exhibits significant advantages in non-load-bearing structures (such as temporary housing, ecological slope protection) and secondary engineering applications (such as road bases, prefabricated components).

The static elastic modulus also increased first and then decreased with the increase in GP substitution ratio, and reached a peak of 25.76 GPa at the replacement ratio of 10 % by mass, which was 5.6 % lower than that of NC. At the replacement ratio of 20 % by mass, the static elastic modulus (i.e. 22.70 GPa) decreases by 16.8 % compared to that of NC. With the gradual increase in w/b ratio, the static elastic modulus gradually decreased, all of which are smaller than that of the control group. At w/b = 0.48, the static elastic modulus reached the maximum of 26.13 GPa, which was a decrease of 4.3 % compared to that of NC. For w/b = 0.63, it was 22.46 GPa, a decrease of 17.7 % compared to that of NC.

In summary, although RFBA exhibits porous characteristics, its synergistic effect with glass powder may reconstruct the transport properties of GBCC. The porosity of RFBA could act as a "micro-reservoir", releasing unreacted glass particles during crack propagation to achieve self-healing through sustained pozzolanic reactions: First, the gels formed by glass powder preferentially fill the surface pores of RFBA, blocking rapid permeation pathways between aggregate and matrix to create a "double-barrier" effect (local closure of aggregate pores and overall densification of the matrix). Additionally, the formation of C-(A)-S-H gel consumes Ca(OH)₂ content [25–27], and low Ca(OH)₂ levels help reduce the driving force for carbonation reactions.

According to the experimental results, it can be seen that when the RFBA substitution ratio was 40 % by mass, the static elastic modulus decreased by 11.1 % compared with the case when the substitution ratio was 20 % by mass. However, this decrease was relatively small. Combined with the range analysis results in Section 3.2, this study suggests that the optimal mix proportion of GBCC in this test was R1B4G2W1 through comprehensive analysis. Although the orthogonal test efficiently identified the main effect factors, its ability to analyze interaction effects and nonlinear relationships is limited. Future research could introduce response surface

Water

205

(kg/m^3)

w/b

0.53

methodology (e.g., central composite design) to construct models around the current optimal mix proportion (R1B4G2W1), quantify the synergistic effects between GP and RFBA (such as the coupling of pozzolanic activity and micro-filling), and explore balance optimization strategies for multiple objectives (strength, durability, cost).

4. Microscopic mechanism investigation

To further investigate the pozzolanic activity of RFBA and GP on the mechanical properties of recycled concrete, as well as the physical filler modification effect of GP, cube compressive tests of recycled concrete incorporating only RFBA or only GP were first designed and conducted respectively, followed by deeper microscopic mechanism studies. In this experiment, the w/b ratio was set at 0.53 and the RCA substitution ratio was set at 45 % by mass. The 45 % replacement of natural coarse aggregates with RCA significantly improves construction and demolition waste utilization. By optimizing ITZ and regulating pore structures, this substitution level effectively mitigates the drastic strength loss and interfacial deterioration observed at higher replacement ratios (e.g., 60 %). The w/b ratio of 0.53 was selected to ensure adequate workability (slump compliance with construction standards) while avoiding excessive porosity and strength reduction associated with elevated w/b values. The mix proportions of the recycled concrete are shown in Table 6.

When preparing recycled concrete specimens, it is necessary to simultaneously prepare additional cubic specimens specifically for analyzing the ITZ in microscopic tests. The sample preparation methods and dimensional requirements for ITZ-related tests (SEM/EDS, XRD, MIP) are detailed below by test type:

(1) SEM-EDS microstructural and elemental analysis:

Cut $10 \times 10 \times 5$ mm block samples perpendicular to the aggregate-paste interface from concrete specimens to fully expose the ITZ region. Wet-grind the samples with sandpaper to remove cutting-induced damage layers, then polish to a mirror finish using 1µm alumina polishing agent. Ultrasonically clean the samples in distilled water for 10 minutes, dry in an oven at 60°C for 2 hours, and finally sputter-coat with 5–10 nm gold/platinum conductive film to enhance electron beam conductivity.

(2) XRD mineral composition analysis:

Collect cementitious paste enriched in the ITZ (i.e., stripping loose paste within 100–200µm around aggregates), crush and grind to a particle size $< 45\mu m$ (passing a 325-mesh sieve). Dry at least 0.5 g of the powder in an oven at 105° C for 24 hours to completely remove adsorbed water and avoid diffraction peak shifts. Uniformly compact the dried powder into a flat test surface with a diameter of 10 mm and thickness of 2 mm, ensuring no particle agglomeration.

(3) MIP pore structure analysis:

Cut $10 \times 10 \times 10$ mm cubic samples from concrete to ensure the ITZ region is included. Dry the samples in a vacuum oven (60°C, vacuum pressure <10 Pa) for 48 hours to completely remove free water and prevent water vapor interference during mercury intrusion. Seal the dried samples immediately with aluminum foil, remove surface dust before testing, and maintain a sample volume $< 2 \text{ cm}^3$ to fit the MIP instrument sample tube.

Fig. 12 shows the cube compressive strength of recycled concrete incorporating only RFBA or only GP (the fabrication and test methods of the cubic samples are the same as those in Section 2.3.), and the polylines indicate the transformation law of the ratio between the strength of each group and the corresponding strength of the control group B0-G0.

The effect of the substitution level of RFBA and GP on the cube compressive strength of recycled concrete is similar to that in Section 3.1. The cube compressive strength of the group B0-G0 was 34.50 MPa. The cube compressive strength increased with the increase in RFBA substitution ratio. At the replacement ratios of 20 % and 40 %, the cube compressive strengths, i.e. 36.71 MPa and 38.82 MPa, increased by 6.4 % and 12.5 %, respectively, compared to that of the control group. When the GP substitution ratio was 10 % and 20 %, the cube compressive strengths, i.e. 36.13 MPa and 35.11 MPa, were increased by 4.7 % and 1.8 %, respectively, compared to that of the control group.

4.1. XRD

B40-G0

B0-G10

B0-G20

A Rigaku SmartLab SE X-ray diffractometer was used to conduct a physical phase analysis of the hydration products of recycled concrete, with a scanning angle range of 5–90 degrees and a scanning speed of 5 degrees per minute. Taking the mortar block from the cubic specimens after compressive failure as the test sample, the selected mortar blocks had a length and width between 10 and 20 mm,

Table 6 Mix proportions design of recycled concrete under single factor analysis.										
NO.	RCA (kg/m ³)	RFBA (kg/m ³)	GP (kg/m ³)	NA (kg/m ³)	Sand (kg/m ³)	Cement (kg/m ³)				
B0-G0	478	0	0	609	651	387				
B20-G0		126	0		521	387				

0

39

77

Mix proportions	design	of recycled	concrete	under	single	factor	analysis

251

0

0

391

651

651

387

348

310



Fig. 12. Cube compressive strength of recycled concrete under single-factor analysis.

and a thickness of less than or equal to 10 mm. Before the XRD test, the samples were first soaked in anhydrous ethanol to stop the hydration reaction of cement and then put into a drying oven at 50 degrees Celsius for 12 hours to remove moisture.

Fig. 13 presents the XRD spectrum of the hydration products of recycled concrete when incorporated with RFBA and GP individually. The main hydration products of recycled concrete were CaSO₄:2 H₂O, SiO₂, Ca(OH)₂, C-(A)-S-H, and Ettringite. The peak value of the XRD spectrum indicates the physical phase content, and the higher the peak value, the greater the phase content. The peak and valley positions of the physical phases in each group were the same, but the peak intensities were different.

The main components of cement clinker, C₃S and C₂S, underwent hydration when exposed to water, producing hydrated silicates and a large amount of $Ca(OH)_2$ [32,46]. Another major component, C_3A , underwent hydration in an alkaline environment to form garnet (C_3AH_6). In the presence of gypsum, C_3AH_6 reacted with SO_4^2 in gypsum to form Ettringite (Aft) and a large amount of Ca(OH)₂ [46]. The active SiO₂ and active Al₂O₃ contained in RFBA, as well as the active SiO₂ contained in GP, underwent a volcanic ash reaction with Ca(OH)₂ in the cement liquid phase to finally form hydrated calcium silicate (C-S-H) gels and hydrated calcium aluminate (C-A-S-H) gels [28].

As shown in Fig. 13, the diffraction peaks of Ca(OH)₂ (PDF#72–0156) appeared at $2\theta = 18.2^{\circ}$ and $2\theta = 34.2^{\circ}$ respectively, and the diffraction peak of SiO₂ (PDF#75–0443) occurred at $2\theta = 26.8^{\circ}$. The diffraction peaks of C-A-S-H (PDF#81–1858) appeared at 2θ = 44.2° and $2\theta = 54.4^{\circ}$ respectively, and the diffraction peak of C-S-H (PDF#33–0306) appeared at $2\theta = 47.3^{\circ}$. As shown in Fig. 13(a), the diffraction peak intensity of Ca(OH)₂ in the B20-G0 and B40-G0 groups was significantly lower than that in the control group, while the diffraction peak intensity of C-S-H and C-A-S-H was higher than that in the control group. This is because of the secondary hydration of active SiO₂ and Al₂O₃, which consumed a large amount of Ca(OH)₂ and generated a large amount of C-S-H and C-A-S-H gels [31]. The diffraction peak intensity of Ca(OH)₂ in the B40-G0 group was lower than that in the B20-G0 group, because more active SiO₂ and Al₂O₃ in RFBA exerted a pozzolanic effect. In Fig. 13(b), the B0-G10 and B0-G20 groups had lower content of Ca(OH)₂ and higher content of C-S-H gels than the control group, for the same reason as the B20-G0 and B40-G0 groups. Compared with the B0-G10 group, the content of C-S-H gels in the B0-G20 group decreased, which were because the cement hydration product Ca(OH)₂ also decreased with the reduction of cement content, leading to the inability of the pozzolanic activity of GP to be fully utilized[33,37].

With low strength and poor chemical stability, $Ca(OH)_2$ is the weakest in the cement paste structure [25], which is adverse to concrete strength. However, the incorporation of RFBA and GP in recycled concrete can consume a large amount of Ca(OH)₂ to generate gels with higher strength, achieving the purpose of promoting the usage of recycled concrete.



(a) Recycled concrete incorporating only RFBA

-Gypsum 2-Portlandite

3-Ouartza 4-C-A-S-H

(b) Recycled concrete incorporating only GP

Fig. 13. The XRD spectra of the hydration products of recycled concrete.

4.2. SEM

Micromorphology of the interfacial transition zone (ITZ) of recycled concrete under single factor changes was examined using a Hitachi Regulus8230 scanning electron microscope. The samples for SEM examination had a length, width and thickness of less than or equal to 10 mm. The pre-preparation of the specimens before testing was consistent with that for the XRD test. Moreover, the samples were sprayed with a gold coating before SEM examination.

The micromorphology of the ITZ between fine aggregates and mortar in groups B0-G0 and B40-G0 are shown in Fig. 14, respectively. As shown in Fig. 14(a), because of the smooth surface of natural RS, the bond between RS and mortar was not strong enough, and obvious cracks at the interface can be seen under a 50-fold microscope, resulting in a weak ITZ. From Fig. 14(b), it can be seen that there were almost no cracks or pores between RFBA and mortar, suggesting that the ITZ between the two was more closely knit. Thus, the compressive strength and tensile strength of recycled concrete gradually increased with the increase in the replacement of RFBA as a partial substitute for RS. This was also verified by the phenomenon elaborated in Section 3.1 that the GBCC compressive damage and splitting tensile damage were mostly manifested as RFBA aggregate failure, while the ITZ had good integrity [25].

Fig. 15 presents the existing form of C-(A)-S-H gels, in which image (2) was the enlarged view of the selected area in image (1), and image (3) was the enlarged view of the selected area in image (2). By SEM test, it was found that the existing state of C-S-H gels in the control group were flocculent or amorphous, which were bonded to each other with Ettringite (e.g., Ca/Si \ge 1.0 in the group B0-G0, average fiber length of 2.1 µm). However, after the incorporation of RFBA or GP in recycled concrete, a large number of C-A-S-H gels and C-S-H gels appeared (e.g., Ca/Si \ge 0.29 in group B40-G0, average fiber length of 6–8 µm), which were reticular and slender fibrous, and could interconnect the initial micro-cracks inside concrete and couple different particles with each other. As the content of RFBA/GP increases, the content of reactive SiO₂/Al₂O₃ rises, promoting the formation of more C-(A)-S-H gels and increasing fiber density accordingly (e.g., fiber density in group B40-G0 increased by 192 % compared to the control group). The elongated fibers (>5 µm) present in GBCC can span micro-cracks (typically 5–50 µm), forming effective mechanical bridging. Therefore, the fundamental reason for the slight increase in the compressive strength of recycled concrete incorporated with RFBA or GP was that RFBA and GP played a role in pozzolanic activity and generated a large number of reticular and slender fibrous gels with stronger bonding effects than the flocculent or amorphous C-S-H gels in the control group. Additionally, it is worth noting that GP can be well distributed in various pores inside recycled concrete, as shown in Fig. 15(e). GP involved in volcanic ash reaction exhibited a good chemical filling modification effect, while GP not involved in volcanic ash reaction demonstrated a good physical filling modification effect.

Furthermore, C-(A)-S-H gels had a very high surface energy, allowing gels to attract each other to form more robust and cohesive fibrous gels, and adsorb fine silica-phase-rich RFBA and GP particles to exert pozzolanic activity on its surface, thus forming fibrous gels branches. As shown in Fig. 16 (a) and 15(b), each thick and strong gel was formed by the mutual attraction and entangling of multiple slender fibrous gels, which provided greater traction between cracks and fine particles inside recycled concrete, making it more difficult to damage. In addition, it can also be found in Fig. 16 (c) and 15(d) that part of the gels were distributed on the surface of recycled concrete to cover and connect micro-cracks, and another part with gels branches dispersed and extended into the interior of pores to reduce porosity. Besides mechanical bridging, the gel may achieve self-healing through sustained pozzolanic reactions. For example, unreacted GP and RFBA particles can form new gel when encountering Ca(OH)₂ in the cement pore solution at crack sites, a mechanism that has been reported in similar materials.

Although this study did not directly test the long-term behavior of C-(A)-S-H in GBCC under aggressive environments, the microstructural characteristics indicate its potential durability advantages. The bonding of Al^{3+} with $[SiO_4]^{4-}$ chains reduces the size of intergel layer channels, hindering the diffusion of aggressive ions such as Cl⁻ and SO₄²⁻. Additionally, the optimization of pore structure by glass powder (reduced porosity and refined pore size) may delay the accumulation of expansion pressure caused by freeze-thaw cycles [4,6].

Fig. 16 presents the schematic diagram of C-A-S-H gels and C-S-H gels, which can visually explain the C-(A)-S-H gels distributed on concrete surface and existing in concrete pores and cracks.

(a) B0-G0

(b) B40-G0

(a) B0-G0

(b) B20-G0

(c) B40-G0

(d) B0-G10

(e) B0-G20

Fig. 15. SEM images of C-(A)-S-H gels.

4.3. EDS

Fig. 17 shows the EDS analysis diagram of chemical elements tested at the six red marked points in Fig. 14. It can be found that the percentage of Al element at points C and D in the gels in B40-G0 group is significantly higher than that at points A and B in the control

(a) C-A-S-H gels morphology

(b) C-A-S-H gels cover micro-cracks and pores

(c) C-S-H gels morphology

(d) C-S-H gels fill the pores

(a) C-A-S-H and C-S-H gels

(b) C-A-S-H gels on RFBA surface (c) GP filling modification mechanism

Fig. 17. Schematic diagrams of C-(A)-S-H gels in recycled concrete.

group, which verifies that a considerable portion of C-A-S-H gels in recycled concrete was generated after incorporating RFBA. Additionally, the percentage of Si element at points C, D, E and F in the gels increased substantially compared with that at points A and B after incorporating RFBA or GP.

Furthermore, this paper explains the generation mechanism of fibrous C-S-H gels as follows: In the alkaline environment inside concrete, SiO₂ dissociated into negatively charged tetrahedral $[SiO_4]^{4-}$. The monomer $[SiO_4]^{4-}$ underwent a polymerization reaction similar to that of organic polymers [25], polymerizing into the dimer $[Si_2O_7]^{6-}$ or even more highly polymerized single-chained or bi-chained polymers—silicate groups (SiO⁻)[47–49,52]. [SiO₄]⁴⁻ combined with other tetrahedron by sharing one oxygen atom, which was called bridge oxygen atom [48]. Meanwhile, Ca²⁺ can break the oxygen bridge and combine with the negatively charged O⁻ in the silicate groups (SiO⁻) to form a strong ionic, covalent bonding O-Ca-O through electrostatic interactions [47–49,52]. In addition, Ca²⁺ was hydrophilic in the silicate groups [51], which will attract hydroxyl groups (OH⁻) to combine with it [52], and the remaining O⁻ will combine with H⁺ [51], ultimately forming C-S-H gels. It is worth to note that Na⁺ can also combine with the negatively charged O⁻ in the silicate groups (SiO⁻) to form O-Na-O salt bridges [47,52,53], which is the reason for the presence of Na element in C-S-H gels[54].

Regarding the generation mechanism of fibrous C-A-S-H gels, some scholars [25,55,56] suggested that active Al₂O₃ will dissociate

into negatively charged AlO⁻ in the alkaline environment, and AlO⁻ can also undergo a polymerization reaction similar to that of silicate groups to form a hydrated calcium aluminate—C-A-H gels skeleton. On this basis, partial AlO⁻ polymerized with SiO⁻ and finally formed C-A-S-H gels.

If the SiO⁻ content in the cement liquid phase was low or Ca^{2+} content was high, because of the O⁻ in the silicate groups combined with Ca^{2+} leading to a large reduction of oxygen bridges, the SiO⁻ chain cannot be extended. Thus, the C-(A)-S-H gels existed in the flocculent or amorphous state. If the SiO⁻ content in the cement liquid phase was high or Ca^{2+} content was low, Ca^{2+} can only break a small amount of oxygen bridges, and there were more directions for the SiO⁻ chain to extend. As a result, it was easier for polymerization reactions between SiO⁻ to form longer silicate chains, i.e., the gel appears fibrous.

This is verified by the ratio of Ca to Si element content (Ca/Si) in each group of C-(A)-S-H gels in Fig. 18. The Ca/Si of the gels at points A and B (in B0-G0 group), C and D (in B40-G0 group), as well as E and F (in B0-G10 group) were 1.27 and 2.3, 0.36 and 0.29, as well as 0.83 and 0.74, respectively. It can be found that the Ca/Si in the gels of the control group was significantly larger, which means

(a) C-S-H gels labeling site A (in group B0-G0)

(c) C-A-S-H gels labeling site C (in group B40-G0)

(e) C-S-H gels labeling site E (in group B0-G10)

(b) C-S-H gels labeling site B (in group B0-G0)

(d) C-A-S-H gels labeling site D (in group B40-G0)

(f) C-S-H gels labeling site F (in group B0-G10)

Fig. 18. EDS analysis diagrams of chemical elements.

that the oxygen bridge in the silicate group was more easily destroyed, and not easy to polymerize in to longer gels chain. Ultimately, the gels appeared flocculent or amorphous shape. For instance, the Ca/Si of $3CaO \cdot 2SiO_2 \cdot 3H_2O$ (C-S-H) was 1.5, and its ratio was close to that of the control group, and the gels appeared amorphous. Their formation mechanism was that the three O⁻ of $[Si_2O_7]^{6-}$ (Fig. 19 (a)) first attracted with three Ca²⁺ (Fig. 19(b)), and then the three Ca⁺ with only one positively charged combined with the three OH⁻ (Fig. 19(c)), respectively. There were only three O⁻ available for $[Si_2O_7]^{6-}$ to combine with other silicate chains. Finally, these three O⁻, each one with only one negatively charged, combined with three H⁺ respectively to form $3CaO \cdot 2SiO_2 \cdot 3H_2O$ (C-S-H) (Fig. 19(d)). Fig. 19(e) presents the 3D model of $3CaO \cdot 2SiO_2 \cdot 3H_2O$. However, in the mono-chained $2CaO \cdot 4SiO_2 \cdot 5H_2O$ (C-S-H) (Fig. 19(f)), the Ca/Si element was 0.5 and there were eight free O⁻ available for silicate extension, representing a significant increase in the degree of freedom compared with $3CaO \cdot 2SiO_2 \cdot 3H_2O$ and an obvious increase in the silicate chain length. At this point, the value of Ca/Si was

(a)[Si₂O₇]⁶⁻

(b) The combination of O^- and Ca^{2+}

(c) The combination of OH⁻ and Ca²⁺

(f) 3D model of 2CaO·4SiO₂·5H₂O

Fig. 19. The formation process of C-S-H gels and 3D model diagram.

close to that of the B40-G0 and B0-G10 groups. If the Ca/Si was further reduced or the amount of free O⁻ increased further, it represents a further increase in the available pathway for silicate chain extension, and the fibrous gels would become longer.

In summary, the Ca/Si value played a decisive role in the gels shape to some extent. The smaller the Ca/Si value (simplified and roughly assumed that Ca/Si < 1.0), the higher the degree of freedom of the bridge oxygen atom, the more directions of the silicate chain extension, and the longer the fibrous gels.

4.4. MIP

The porosity of recycled concrete incorporating RFBA or GP was measured using a high-performance fully automatic mercury porosimeter model, AutoPore Iv 9510. The pre-preparation of the specimens was the same as that of the XRD test, and the mass of each specimen was 2–3 g. The analytical pore sizes were in the range of 5 nanometers to 10 micrometers. The pressure of mercury was set at 30,000 psi during test.

Fig. 20(a) presents the MIP test results of pores inside recycled concrete. It can be seen that the incorporation of RFBA or GP can improve the internal pores of recycled concrete compared with the B0-G0 group. The cumulative pore volume of recycled concrete incorporating RFBA or GP were lower than that of the control group. On the one hand, it is because a large number of reticular and slender fibrous gels were with stronger bonding effects, which can effectively bind the pores inside recycled concrete. On the other hand, GP not involved in volcanic ash reaction played a role in micro-aggregate filling to further compact the interior of recycled concrete[41,57].

The internal pores of concrete can be categorized as harmless pores (with pore size <20 nm), less harmful pores (with pore size between 20 and 50 nm), harmful pores (with pore size between 50 and 200 nm), and more harmful pores (with pore size >200 nm) [28,57]. Harmful and more harmful pores are unfavorable to the mechanical properties [30,31,36,37,41]. As shown in Fig. 20(b), the proportion of harmless and less harmful pores were improved with the increase in the replacement ratio of RFBA as a partial substitute for RS, which is consistent with Dang's findings [4]. In B0-G0 group, the proportion of harmless pores and less harmful pores was 15.9 % and 13.6 %, respectively, whereas it was 24.4 % and 25.8 % in B20-G0 group, 28.4 % and 28.1 % in B40-G0 group, respectively. As the replacement ratio of GP as a partial substitute for cement increased, the proportion of harmless and less harmful pores in recycled concrete was also improved. In B0-G10 group, the proportion of harmless pores and less harmful pores was 23.2 % and 21.2 %, respectively, while it was 22.4 % and 20.9 %, respectively, in B0-G20 group, both higher than those in the control group. When GP replaced 20 % by weight of cement, the porosity increased slightly compared to that of the B0-G10 group, which agreed well with Carvalho's findings [3]. This is because of the reduction of cement hydration products as the cement amount decreased. Thus, there were a large number of GP not involved in volcanic ash reaction, as well as numerous capillary pores and cracks inside recycled concrete [36,37]. In conclusion, the best improvement effect on the internal pores of recycled concrete was achieved, when the replacement ratio of single doped RFBA was 40 % or that of single doped GP was 10 %, both by weight.

MIP revealed the differentiated effects of internal pore size distribution on the mechanical properties of GBCC, particularly the close correlation between more harmful pores and strength loss[41]. The control group (B0-G0) had a strength of 34.50 MPa; with 20 % (B20-G0) and 40 % (B40-G0) RFBA content, strengths increased by 6.4 % (36.71 MPa) and 12.5 % (38.82 MPa), respectively. This is directly related to the optimized pore size distribution observed in MIP: the proportions of harmful pores and more harmful pores decreased in the B40-G0 group, with harmful pores dropping from 28.7 % in the control group to 21.3 %, and more harmful pores from 28.7 % to 18.2 %. Reduced porosity enhanced the densification of the mortar matrix, increasing the effective load-bearing area. When GP content was 10 % (B0-G10), strength was 36.13 MPa (+4.7 %); at 20 % (B0-G20), it was 35.11 MPa (+1.8 %). This is attributed to GP's dual effects of "pozzolanic activity" and "micro-aggregate filling": GP particles filled 50–200 nm harmful pores, while reactive SiO₂ reacted with Ca(OH)₂ to form elongated C-S-H gels that bridged micro-cracks and enhanced matrix stiffness[27, 49–51,56]. MIP showed that the proportion of harmful pores in the B0-G10 group decreased from 28.7 % in the control group to 25.5 %. Excessive GP reduced cement content, decreasing the total amount of hydration products: although more harmful pores continued to decrease, unreacted GP particles only provided physical filling, unable to compensate for strength loss caused by reduced binders[3,34,36,41].

In summary, although the results of this study are based on local CDW, the revealed synergistic mechanism of pozzolanic activity and micro-filling exhibits universal applicability. Through standardized pretreatment of raw materials and dynamic adjustment of mix proportions, the proposed method can adapt to materials from different geographical sources. While this study did not directly quantify the pozzolanic activity of RFBA and GP using Frattini tests or SAI (specific activity index), indirect evidence is provided by the decrease in Ca(OH)₂ peak intensity in XRD, significant change in Ca/Si ratio in EDS, and porosity optimization in MIP. References [4,5, 28,29,41,57] indicate that such microscopic parameters have a strong correlation with standardized test results, supporting the contributions of GP and RFBA to pozzolanic activity.

5. Synergistic environmental benefits and performance optimization of waste utilization

5.1. Environmental benefits

GBCC achieves significant environmental benefits through the collaborative utilization of multi-source CDW. Each cubic meter of GBCC can consume approximately 465 kg of RCA and RFBA in total. At a 40 % RFBA replacement ratio, it consumes 251 kg of brick waste per cubic meter, directly alleviating the pressure of landfilling the annual global CDW output exceeding 4 billion tons (2023 data). This is particularly critical for China, which accounts for 50 % of global CDW generation, reducing land occupation and soil-

(a) Cumulative pore volume

(b) Percentage of different pore sizes

Fig. 20. MIP test results of pores inside recycled concrete.

water pollution caused by traditional landfilling [4,6–9]. RCA and RFBA replace natural coarse and fine aggregates, respectively, reducing river sand and gravel extraction by over 50 % under the optimal mix ratio. This addresses ecological damage from excessive mining, responding to the global annual demand for 50 billion tons of sand and gravel [2,5].

When GP replaces 10 % of cement by mass, it saves 39 kg of cement per cubic meter (compared to 387 kg in the control group NC, with GBCC's optimal mix using 348 kg). Given that cement production emits 0.8 tons of CO_2 per ton, this yields significant low-carbon advantages [3,37]. The pozzolanic activity and micro-aggregate filling effect of GP enhance the efficiency of cementitious materials, reducing the use of high-carbon-emission components and aligning with global "double carbon" goals. Additionally, alkaline substances and heavy metals potentially released from landfilled brick and glass waste are stabilized within GBCC's dense microstructure, lowering pollution risks. The fibrous C-(A)-S-H gels and densified ITZ improve concrete durability (e.g., chloride ion penetration and carbonation resistance), extending service life and reducing environmental burdens from maintenance and reconstruction.

5.2. Compensation mechanisms for performance loss and practical applicability

Through orthogonal test optimization (RCA 15 %, RFBA 40 %, GP 10 %, water-binder ratio 0.48), GBCC meets C30 design requirements with a 28-day cube compressive strength of 39.2 MPa, axial compressive strength of 29.8 MPa, and splitting tensile strength of 2.72 MPa. While its static elastic modulus is $15 \sim 20$ % lower than that of normal concrete (NC), it is suitable for non-loadbearing structures (e.g., partition walls, pavement bases), where performance losses are acceptable for target applications.

The reactive SiO₂ and Al₂O₃ in RFBA, combined with the high-activity SiO₂ in GP, trigger pozzolanic reactions that consume Ca (OH)₂ from cement hydration, generating high-strength fibrous gels that fill pores and strengthen the ITZ. For example, at a 40 % RFBA replacement ratio, the proportion of harmful pores (>50 nm) decreases from 57.4 % in the control group to 40.5 %. SEM/EDS analysis shows that the ITZ thickness reduces from 50–80 μ m to 30–40 μ m, with a Ca/Si ratio decreasing from 1.27 to 0.36. Fibrous gels (average length 6–8 μ m) bridge micro-cracks, enabling compressive strength to reach over 90 % of NC [25,31,47]. MIP tests reveal that GBCC's cumulative pore volume decreases by 12~18 %, with harmless pores (<20 nm) increasing to 25~28 %, further optimizing long-term mechanical stability.

In engineering applications, GBCC's static elastic modulus (22–26 GPa) meets the requirements for non-load-bearing components (\geq 20 GPa) in the Concrete Structure Design Code. Its high toughness (splitting tensile strength 2.72 MPa) offers advantages in seismic-resistant non-load-bearing structures. In green buildings, temporary facilities, and ecological engineering (e.g., slope protection, permeable pavements), its environmental benefits outweigh properties like elastic modulus, aligning with sustainable construction priorities.

5.3. Compensation mechanisms for performance loss and practical applicability

Taking 10,000 cubic meters of GBCC as an example, it reduces CDW landfilling by 4650 tons, saves 5200 tons of natural aggregates, and reduces cement use by 390 tons, corresponding to a CO_2 emission reduction of 312 tons—far exceeding minor material adjustments (e.g., 10–15 kg/m³ increased water usage) [2,3,5]. Orthogonal tests demonstrate a feasible solution between maximizing environmental benefits (e.g., increasing RFBA replacement from 10 % to 40 %) and meeting performance standards: compressive strength decreases by only 2.4 %, while waste consumption triples, yielding exponential environmental gains.

Technically, the study first reveals the synergistic mechanism of RFBA and GP—fibrous gel formation, ITZ strengthening, and pore refinement—providing theoretical support for high-performance recycled concrete design. This enables a scalable technical route prioritizing environmental benefits while meeting performance criteria. Compliant with the Technical Specification for Application of Recycled Aggregates (JGJ/T 240–2011) for Class II recycled concrete, this technology translates environmental benefits into practical

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engineering value under policy drivers, advancing the low-carbon transformation of the construction industry.

6. Conclusions

This paper prepared a new type of green recycled concrete—Glass powder modified recycled brick-concrete aggregate concrete (GBCC). By conducting macroscopic mechanical performance tests and microscopic mechanism tests on it, the following conclusions can be drawn:

- (1) Under the optimal mix proportion (RCA 15 %, RFBA 40 %, GP 10 %), approximately 465 kg of recycled RCA and RFBA can be consumed per cubic meter of GBCC, equivalent to reducing the landfilling of construction and demolition waste (CDW) by approximately 465 kg/m³. Meanwhile, cement usage is reduced by 10 % compared to traditional C30 concrete. This design not only offsets about 50 % of natural aggregate and cementitious material consumption but also directly decreases the land resource occupation and pollution risks associated with CDW.
- (2) Under reasonable mix proportion design, RCA, RFBA and GP can work well together in GBCC. At 28d, the cube compressive strength of GBCC with different mix proportions exceeded 33.0 MPa, the axial compressive strength exceeded 24.0 MPa, and the split tensile strength and static elastic modulus could also reach 2.1 MPa and 22.0 GPa, respectively. Except for the low static elastic modulus, the compressive and tensile properties of GBCC can reach the design requirements of C30 concrete.
- (3) The mechanical properties of GBCC showed a gradual decrease with the increase of RCA substitution and water-cementitious materials ratio. The mechanical properties of GBCC increased and then decreased with the increase in GP substitution, and reached the optimum at 10 % by mass substitution. The cube compressive strength, axial compressive strength and split tensile strength were positively correlated with the substitution ratio of RFBA, but the static elastic modulus increased and then decreased with the increase of the substitution ratio of RFBA, and reached the optimum when the substitution ratio was 20 % by weight. The water-cementitious materials ratio and the amount of RCA substitution had the strongest degree of influence on the mechanical properties of GBCC, followed by the GP substitution level and finally the level of RFBA substitution. Considering the range analysis, static elastic modulus performance, and MIP test results, the optimum mix proportion of GBCC was considered being R1B4G2W1.
- (4) The cube compressive damage morphology and prismatic compressive damage morphology of GBCC specimens were largely the same as that of NC, while the split tensile damage morphology of GBCC specimens was somewhat different from that of NC, which is mainly manifested because aggregate damage occurs more often in GBCC specimens, which is related to microcracks within RCA and the strength of RFBA being lower than the ITZ strength.
- (5) The reason why the cube compressive strength of recycled concrete can be enhanced after mixing an appropriate amount of RFBA and GP was analyzed from the aspect of micro-mechanism, which is mainly because RFBA and GP played the pozzolanic effect, consumed a large amount of cement hydration product Ca(OH)₂, and generated a stronger bonding effect of the mesh, elongated fibrous gel, which could interconnect the microscopic cracks inside the recycled concrete, and also played a coupling role between different microscopic particulate. In addition, the unreacted GP played the role of physical filler modification, which reduced the porosity inside the recycled concrete and made the recycled concrete denser.
- (6) In this paper, an innovative explanation of the mechanism of the generation of slender fibrous gels was proposed, which suggests that the degree of freedom of O⁻ in the silicate group determined the shape of the gels. When the value of Ca/Si in the liquid phase of cement was small, the degree of freedom of O⁻ was more at this time, and the gel tended to form an elongated fibrous gel; whereas, when the value of Ca/Si was large, the degree of freedom of O⁻ was less at this time, and the gel was inclined to form an amorphous or flocculent gel similar to the one in ordinary concrete. In addition, the fibrous gels had a very high surface energy, which not only led to mutual attraction and entanglement between the gels to form the thicker fibrous gels, but also adsorbed fine silica-rich phase particles, which underwent a volcanic ash reaction on the surface of the gels, thus forming branches on the gels.

Limited by the experimental design method, only the optimum theoretical mix ratio of GBCC was derived in this paper, and no practical verification was carried out. In addition, there was no comparative test on whether the reticulated and fibrous gels generated by mixing RFBA and GP together into recycled concrete were different from those generated by mixing the two alone, and further research is therefore needed. Additionally, this study did not conduct long-term durability tests (e.g., alkali-silica reaction, freeze-thaw cycles). Future research could address the effects of potential impurities in recycled aggregates and clarify the durability mechanism of GBCC through microscopic analysis. Meanwhile, industrial-scale production verification and life cycle analysis (LCA) should be advanced to quantify its engineering applicability and full-cycle environmental benefits, providing support for large-scale applications.

CRediT authorship contribution statement

Kang Shuailei: Data curation, Conceptualization. Feng Aozhong: Data curation, Conceptualization. Guo Yong: Writing – review & editing, Writing – original draft, Resources, Methodology, Data curation, Conceptualization. Zhao Yi: Writing – review & editing, Writing – original draft, Data curation, Conceptualization. Zhou Xiangming: Writing – review & editing, Data curation, Conceptualization. Sun Yuzhou: Writing – review & editing, Data curation, Conceptualization. Lin Qingli: Writing – review & editing, Writing – original draft, Data curation, Conceptualization. Min Zhiyu: Data curation, Conceptualization. Chen Siwen: Writing – original draft, Data curation. Jiang Mingxu: Data curation, Conceptualization. Li Yu: Writing – original draft, Data curation, Data curation, Conceptualization.

Conceptualization.

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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Data availability

Data will be made available on request.

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