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Effects of replacement ratio and curing age on the mechanical performance and microstructure of concrete with waste glass fine aggregate: A multiscale approach

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Abstract: Although waste glass aggregate has been widely investigated as a substitute for natural fine aggregate in concrete, the microstructural mechanisms governing its effects on pore evolution, interfacial transition zone (ITZ) characteristics, and mechanical response remain insufficiently clarified. This study investigated concrete containing 0%–100% waste glass fine aggregate (WGFA) at different curing ages using mechanical tests, mercury intrusion porosimetry (MIP), scanning electron microscopy (SEM), and energy-dispersive spectroscopy (EDS). The results show that WGFA incorporation changes the pore structure evolution from typical capillary pore refinement to a coupled process involving capillary pore reduction and partial filling of smaller pores. Under high WGFA replacement conditions, porosity decreases while the mean pore diameter increases, indicating a redistribution rather than simple refinement of pore structure. Meanwhile, the smooth and low-water-absorption surface of WGFA progressively weakens the ITZ and promotes interface microcracking. These microstructural changes lead to different mechanical responses: compressive strength is mainly governed by matrix densification, whereas flexural strength is more sensitive to ITZ deterioration. WGFA concrete exhibits a transition from matrix-densification-dominated behavior at low replacement levels to ITZ-cracking-controlled behavior at high replacement levels, and the recommended WGFA replacement ratio should be controlled within 20%.

Keywords: Waste glass; recycled aggregate; pore structure; microstructural evolution; concrete

1 Introduction

Cement concrete is one of the most widely used construction materials worldwide and consumes approximately 50–60 billion tons of natural aggregates every year [1]. However, the continuous extraction of sand and gravel has caused increasing resource shortages and environmental problems [2–3]. Meanwhile, approximately 200–300 million tons of waste glass are generated globally each year, while only 30%–40% is effectively recycled [4]. Due to its high SiO₂ content, stable chemical composition, and relatively uniform particle morphology after crushing and screening, recycled waste glass has attracted increasing attention as an alternative aggregate material for concrete applications [4–7]. However, waste glass also has some unfavorable characteristics, including a smooth surface texture [8], low water absorption [9], and potential alkali-silica reactivity (ASR), which may affect the mechanical properties and durability of concrete [10]. Therefore, understanding the role of waste glass in cementitious composites is important for the sustainable utilization of solid waste and the development of performance-oriented concrete materials.

Current studies show that the mechanical properties of concrete

containing WGFA are strongly affected by replacement ratio and particle size [10–13]. At relatively low replacement levels, WGFA can maintain or even improve concrete strength. When the replacement ratio is lower than 30%, the 7 d and 28 d compressive strengths increase by approximately 5%–9% and 4%–8%, while the flexural strength remains at about 90%–100% of the control concrete [11–13]. However, excessive replacement generally causes strength degradation. When the replacement ratio increases to 50%–100%, the 28 d compressive strength decreases by approximately 5%–20%, accompanied by an increased risk of ASR [14]. Particle size also has a significant influence on the mechanical response of waste-glass concrete. Fine glass particles smaller than 2 mm can improve cement paste uniformity and ITZ compactness, resulting in a 5%–10% increase in 28 d compressive strength, although the flexural strength may still decrease slightly by approximately 2%–4% [15–17]. As particle size increases, the negative influence of glass aggregates becomes more obvious. For glass particles in the range of 2.36–4.75 mm, the 28 d compressive and flexural strengths decrease by approximately 13%–20% and 7%–12% [18], respectively. When coarse glass aggregates with sizes of 4–16 mm are used, the compressive strength progressively

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decreases with increasing replacement ratio and can reach reductions of approximately 20%–30% at high replacement levels [19].

To explain the strength variation caused by WGFA incorporation, microscopic characterization has been widely used to reveal hydration products, ITZ morphology, elemental composition, and pore structure evolution. Commonly used techniques include SEM, EDS, and MIP [20–23]. Under the alkaline environment of cement hydration, the amorphous SiO_2 in waste glass can gradually dissolve and participate in pozzolanic reactions, forming secondary calcium silicate hydrate (C-S-H) gel that refines the pore structure and modifies the ITZ [20–23]. However, this process is highly sensitive to the alkaline concentration and the replacement level of glass [21]. EDS analysis has shown that the Ca/Si ratio in the ITZ can decrease to approximately 0.29 in glass powder modified concrete, indicating the formation of dense C-(A)-S-H gels [22–23]. SEM observations have further revealed that glass aggregate surfaces become partially etched and covered with hydration products at later ages [16,21]. MIP studies have demonstrated that glass powder dissolution leads to a denser microstructure and refined pore size distribution, which correlates with improved mechanical performance [24]. A finer pore structure with a higher proportion of harmless pores generally leads to higher strength and lower permeability [25–27]. These studies indicate that waste glass is not entirely inert and may participate in later-age hydration reactions. Similar pozzolanic behavior has been well documented in cementitious systems containing other silica-rich materials, such as silica fume. Due to its high amorphous SiO_2 content and large specific surface area, silica fume readily reacts with $\text{Ca}(\text{OH})_2$ to form additional C-S-H gel, thereby refining pore structure and enhancing the ITZ [28–29]. Compared with silica fume, waste glass aggregates have a considerably lower specific surface area, which significantly reduces their pozzolanic reactivity and makes their hydration behavior less predictable.

Despite these advances, several key aspects of WGFA concrete remain insufficiently understood. Existing microscopic investigations often examine hydration products, elemental composition, ITZ morphology, and pore refinement separately, while a unified explanation of mechanical performance that integrates these observations remains insufficiently established. In particular, the coupled effects of WGFA replacement level and curing age on pore structure evolution and ITZ characteristics, as well as their differentiated relationships with compressive versus flexural strength development, have not been systematically clarified. Most existing microscopic investigations on waste-glass concrete have focused on qualitative observations of hydration products or ITZ morphology [22–23], whereas systematic quantitative analysis of pore structure evolution using MIP, coupled with statistical correlations to mechanical properties, remains relatively limited. Moreover, a comparative understanding of how pore structure and interfacial morphology differently govern compressive strength and flexural strength is still lacking in WGFA concrete systems. A mechanism-oriented evaluation framework of glass aggregates based on microstructural parameters has not yet been established.

Therefore, this study focuses on the multiscale evolution mechanisms of WGFA concrete under different replacement ratios and curing ages. Particular attention is given to the influence of WGFA on pore structure evolution, ITZ characteristics, and their relationship with macroscopic mechanical properties. This study correlates pore refinement, ITZ evolution, interfacial cracking, and strength development to clarify the different mechanisms controlling compressive and flexural strengths in WGFA concrete. In addition, the role of waste glass during different stages of strength development is interpreted from the perspective of microstructural evolution, providing references for the mechanism-oriented utilization of waste glass in cement-based materials.

2 Experimental materials and methods

2.1 Raw materials

The raw materials used in this study include ordinary Portland cement, natural coarse aggregate, natural fine aggregate (NFA), WGFA, and a polycarboxylate-based high-range water reducer. The cement used is P-O 42.5 ordinary portland cement produced in Beijing. Table 1 summarizes the basic properties of cement.

The NFA consisted of river sand and manufactured sand mixes at a mass ratio of 1:3. The apparent density, water absorption, and fineness modulus of NFA are $2,695 \text{ kg/m}^3$, 1.4%, and 2.80, respectively. WGFA is produced from industrial waste flat glass through cleaning, crushing, and screening processes. To reduce the influence of gradation variation, WGFA is prepared with the same gradation distribution and fineness modulus as NFA. The water absorption of WGFA is 0.05%. The coarse aggregate is limestone with a continuous gradation of 5–30 mm. The apparent density, crushing value, water absorption, and clay content were $2,865 \text{ kg/m}^3$, 11%, 0.2%, and 0.1%, respectively. Fig. 1 shows the gradation of different aggregate components. The pore structural parameters of NFA and WGFA are summarized in Table 2. The porosity of NFA is 7.98%, while that of WGFA is 4.16%, which is approximately half of that of NFA.

The chemical composition of WGFA is analyzed using energy-dispersive X-ray fluorescence spectrometry. The main components include SiO_2 , CaO , MgO , Al_2O_3 and K_2O . The specific mass fractions of each constituent element are shown in Fig. 2. SiO_2 is the dominant component with a content of 80.3%. The water reducer used is the polycarboxylate-based high-range water reducer produced in Jiangsu. The water-reduction rate is 30%, and the retention time is 30–40 min.

2.2 Mix proportion of WGFA concrete

The concretes are designed with a target compressive strength grade of C40. A total of six proportions were prepared. The control mixture containing only natural fine aggregate is denoted as G0. In the remaining five groups, NFA is replaced by WGFA at

Table 1 Physical and mechanical properties of cement.

Property	Test value	Standard
Fineness	2.8	JTG E30—2005 (T 0502)
Density (g/cm^3)	3.08	JTG E30—2005 (T 0503)
Specific surface area (m^2/kg)	410	JTG E30—2005 (T 0504)
Initial setting time (min)	40	JTG E30—2005 (T 0505)
Final setting time (min)	450	JTG E30—2005 (T 0505)
Compressive strength of 3 d (MPa)	20	JTG E30—2005 (T 0506)
Flexural strength of 3 d (MPa)	4.1	JTG E30—2005 (T 0506)
Compressive strength of 28 d (MPa)	45	JTG E30—2005 (T 0506)
Flexural strength of 28 d (MPa)	6.7	JTG E30—2005 (T 0506)

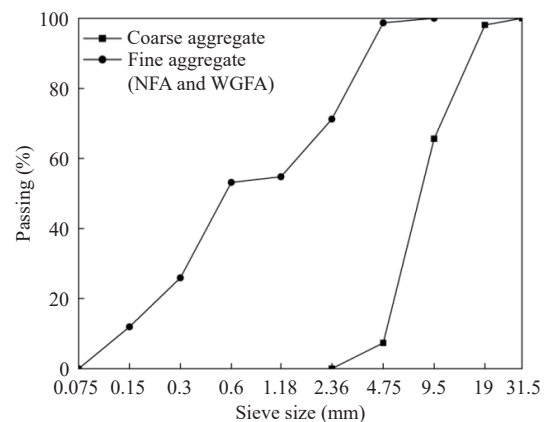


Fig. 1 Gradation curves of aggregates.

Table 2 Pore characteristics of NFA and WGFA.

Type	Pore volume (mL/g)	Specific pore surface area (m ² /g)	Porosity (%)
NFA	0.034	0.643	7.98
WGFA	0.017	0.001	4.16

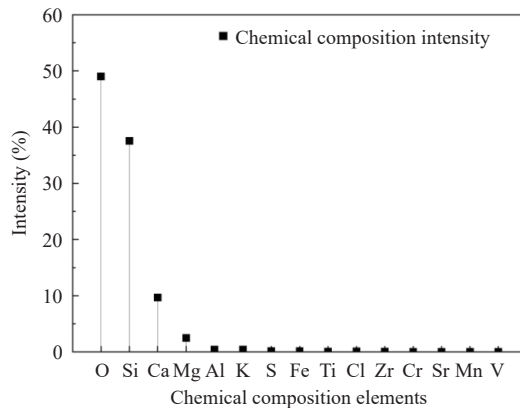


Fig. 2 Elemental composition of WGFA.

20%, 40%, 60%, 80%, and 100% by fine aggregate mass, denoted as G20, G40, G60, G80, and G100, respectively. The water-to-cement ratio of all mixtures is maintained at 0.35. Table 3 summarizes the detailed proportions. The slump of fresh concrete is measured according to the standard test method specified in GB/T 50080—2016. The concrete mixture is filled into the slump cone in three layers, with 25 rodding strokes applied to each layer. After surface leveling and vertical lifting of the cone, the slump value is determined as the vertical distance between the top of the cone and the highest point of the subsided concrete. Table 3 also contains the measured slump value.

2.3 Experimental program

A multiscale experimental approach was adopted to investigate the influence of WGFA replacement ratio on the mechanical properties, pore structure, and ITZ characteristics of concrete. Compressive strength and flexural strength tests were conducted to evaluate the macroscopic mechanical performance. MIP was used to characterize pore structure evolution, while SEM and EDS analyses were performed to investigate the microstructural characteristics of concrete. The overall experimental program is shown in Fig. 3.

2.3.1 Mechanical properties

Compressive and flexural strength tests are conducted according to GB/T 50081—2019, *Standard for Physical and Mechanical Property Tests of Concrete* [30]. The curing ages are 3 d, 7 d, and 28 d. Three parallel specimens are prepared for each group, and the average value is used for analysis. The compressive strength test is conducted using cubic specimens with dimensions of 100 mm × 100 mm × 100 mm. The loading rate is 0.5 MPa/s, and the testing machine capacity is 3,000 kN. The flexural strength test is conducted using the four-point loading method. The sample size is 400 mm × 100 mm × 100 mm. The loading rate is 0.06 MPa/s, and the test

machine capacity is 100 kN.

2.3.2 Pore structure

The pore structure of concrete is characterized using MIP. The test is conducted using a Micromeritics AutoPore 9605 mercury intrusion porosimeter. The samples are prepared from concrete cubes with dimensions of 100 mm × 100 mm × 100 mm after curing for 3 d, 7 d, and 28 d. The specimens are crushed into particles smaller than 15 mm × 15 mm × 15 mm before testing. To remove free moisture, the samples are dried in an oven at 100 °C until a constant mass is reached.

2.3.3 Microstructural characterization

The microstructure of concrete is characterized using SEM and EDS. SEM is used to observe the morphology and microstructural characteristics of the ITZ, while EDS is used to analyze elemental composition and distribution within the ITZ. The test specimens are prepared from concrete cubes with dimensions of 10 mm × 10 mm × 10 mm after curing for 3 d and 28 d. The specimens are crushed into particles smaller than 10 mm before testing. Prior to SEM and EDS analyses, the samples are gold-coated to improve electrical conductivity.

3 Results and discussion

3.1 Mechanical properties

Fig. 4 shows the compressive strength of WGFA concrete at different curing ages. The two-way ANOVA results in Table 4 indicate that both curing age and WGFA replacement ratio significantly affect compressive strength, with *F*-values of 312.612 and 15.465, respectively, and *P*-values lower than 0.001. The compressive strength generally exhibits a trend of first increasing and then decreasing with increasing WGFA replacement ratio. The G20 group achieves the highest compressive strength at all curing ages. Compared with the control group, the compressive strength increases by approximately 5%–8% at low WGFA replacement levels. However, when the WGFA replacement ratio exceeds 40%, the compressive strength gradually decreases. At WGFA replacement levels of 60%–100%, the compressive strength becomes lower than that of the control group. Similar trends are also reported in previous studies [13, 31, 32]. Taha et al. [13] reported that replacing 20%–30% of NFA with WGFA increases the compressive strength by approximately 5%–10%, while excessive WGFA replacement causes strength degradation. Park [32] also found that the compressive strength gradually decreases when the WGFA replacement ratio increases from 30% to 70%.

Fig. 4 also indicates that the influence of WGFA replacement ratio on compressive strength is more obvious at the early curing stage. At 3 d, the compressive strength of the G20 group increases by approximately 5.4% compared with the control group, while the G100 group shows a reduction of approximately 22.2%. As curing age increases, the strength difference between high-WGFA concrete and the control group gradually decreases. At 28 d, the compressive strength of the G20 group remains approximately 8.0% higher than that of the control group, whereas the reduction in the

Table 3 Mix ratio of WGFA concrete.

Types	Replace rate (%)	Mix proportion (kg/m ³)						Slump value (mm)
		Cement	Water	Water reducer	Fine aggregate		Coarse aggregate	
					NFA	WGFA		
G0	0	612.0	214.0	0.43	602.5	0.0	1 170.0	25.6
G20	20	612.0	214.0	0.43	482.0	120.5	1 170.0	42.4
G40	40	612.0	214.0	0.43	361.5	241.0	1 170.0	51.4
G60	60	612.0	214.0	0.43	241.0	361.5	1 170.0	60.5
G80	80	612.0	214.0	0.43	120.5	482.0	1 170.0	87.6
G100	100	612.0	214.0	0.43	0.0	602.5	1 170.0	102.3

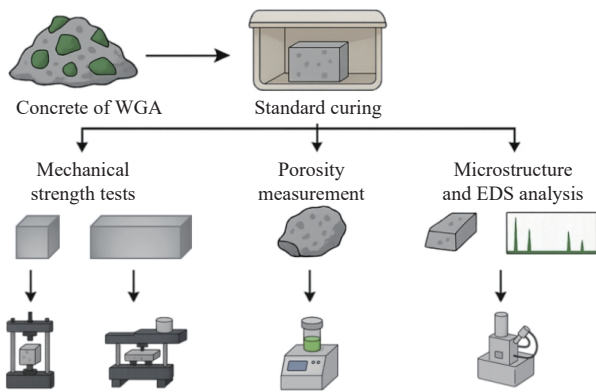


Fig. 3 Experimental program of WGFA concrete.

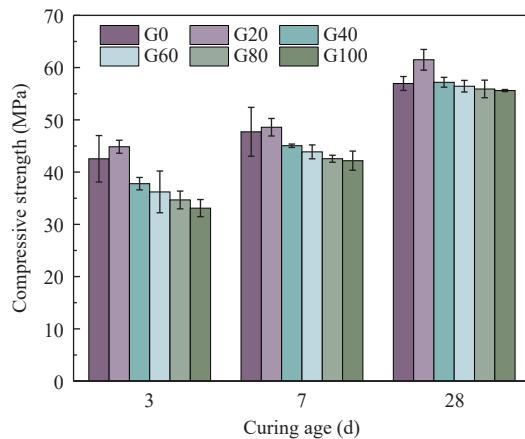


Fig. 4 Compressive strength at different replacement ratios and curing ages.

Table 4 Two-way ANOVA results for compressive and flexural strength.

Source of Variation	df	Compressive strength			Flexural strength		
		F-value	P-value	R ²	F-value	P-value	R ²
Curing age	2	312.612	< 0.001		349.873	< 0.001	
Replacement ratio	5	15.465	< 0.001	0.939	8.655	< 0.001	0.942

G100 group decreases to approximately 2.4%. To more intuitively compare the strength growth trends of each age period, the ratio of 28 d and 7 d compressive strengths of the concrete itself ($S_{c,28d}/S_{c,7d}$) under different WGFA contents, as well as the ratio of the 7 d and 3 d compressive strengths ($S_{c,7d}/S_{c,3d}$), is compared. Fig. 5 shows that both $S_{c,28d}/S_{c,7d}$ and $S_{c,7d}/S_{c,3d}$ increase with increasing WGFA replacement rate.

The values of $S_{c,28d}/S_{c,7d}$ are generally higher than those of $S_{c,7d}/S_{c,3d}$. However, the influence of WGFA replacement ratio is more obvious for $S_{c,7d}/S_{c,3d}$. When the WGFA replacement ratio reaches 40% or higher, the compressive strength ratio increases significantly. The $S_{c,7d}/S_{c,3d}$ and $S_{c,28d}/S_{c,7d}$ of the G100 group reached 1.27 and 1.32, respectively, which are higher than the corresponding values of 1.05 and 1.28 for the G0 group. These results indicate that increasing WGFA content promotes the later-age strength growth of concrete. Moreover, the early-stage compressive strength of high-WGFA concrete (G40-G100) remains relatively low. Although the strength growth rate during the middle and later curing stages becomes more pronounced, the 28 d compressive strength is still lower than that of the control group. Shao et al. [33] reported that the higher SiO₂ content in waste glass may slowly participate in the hydration reaction under alkaline conditions. Additional C-S-H gel is generated during this process, which improves the compactness of the concrete structure and promotes later-age strength development. However, the smooth surface char-

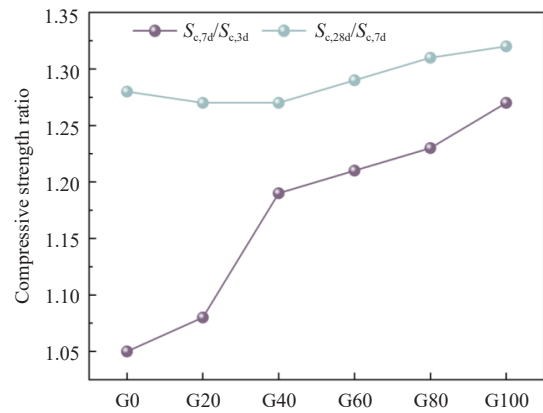


Fig. 5 Compressive strength ratios between curing stages of WGFA concrete.

acteristics and weak interfacial bonding of glass particles limit this compensating effect [34–35].

Fig. 6 shows the flexural strength development of WGFA concrete at different curing ages. The two-way ANOVA results in Table 4 indicate that both curing age and WGFA replacement ratio significantly affect flexural strength, with *F*-values of 349.873 and 8.655, respectively, and *P*-values lower than 0.001. Unlike compressive strength, flexural strength decreases continuously with increasing WGFA replacement ratio. At 3 d, the differences between groups remain relatively small. Compared with the G0 group, the flexural strength of the G20-G100 groups decreases by approximately 0.9%–1.6%. However, the reduction becomes more obvious at 7 d and 28 d. At 7 d, the flexural strength decreases by approximately 4.9%–21.3%, while the reduction at 28 d reaches approximately 4.8%–14.0% as the WGFA replacement ratio increases from 20% to 100%. Similar trends are also reported in previous studies [32, 34]. Ling et al. [34] found that the flexural strength of cement mortar decreases by approximately 13% when the WGFA replacement ratio increases from 0% to 40%. Park et al. [32] also reported that the flexural strength decreases by approximately 10%–15% at WGFA replacement levels of 30%–40%.

Fig. 7 compares the flexural strength ratios between different curing stages. The $S_{f,7d}/S_{f,3d}$ ratio decreases significantly with increasing WGFA replacement ratio. The value of the G100 group decreases to 1.24, which is significantly lower than the value of 1.55 for the G0 group. In contrast, $S_{f,28d}/S_{f,7d}$ shows a slight increasing trend with increasing WGFA replacement ratio. The G100 group reaches a value of 1.26, slightly higher than the value of 1.16 for the G0 group. These results indicate that increasing WGFA content weakens the flexural strength development during the middle curing stage, while the later-age flexural strength growth

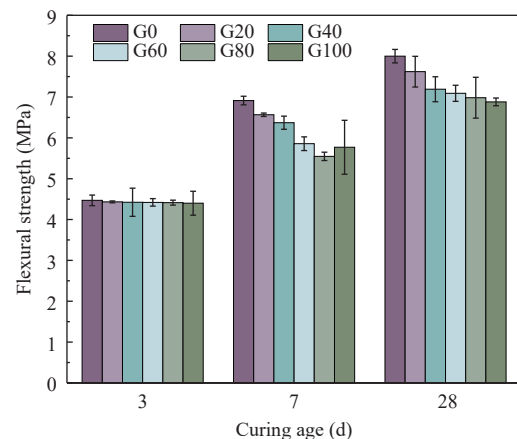


Fig. 6 Flexural strength at different replacement ratios and curing ages.

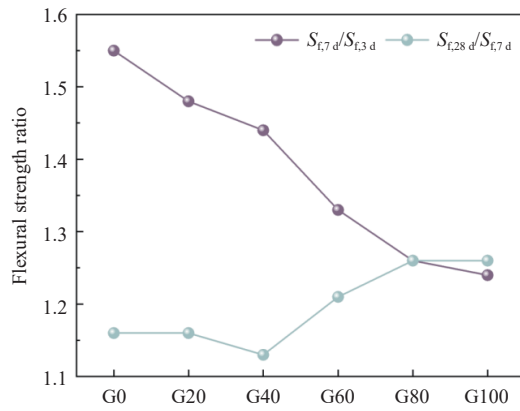


Fig. 7 Flexural strength ratios between curing stages of WGFA concrete.

gradually becomes more pronounced at high WGFA replacement levels. However, the overall flexural strength of high-WGFA concrete remains lower than that of the control group throughout the curing process.

3.2 Pore structure evolution

MIP is used to characterize the pore structure of WGFA concrete at curing ages of 3 d, 7 d, and 28 d. Fig. 8 shows the pore size distribution curves of each concrete group. All groups exhibit a distinct single-peak pore distribution characteristic, and the modal pore diameters are mainly concentrated within the range of 10–100 nm. To further evaluate the influence of WGFA replacement ratio and curing age on pore structure evolution, the pore distribution curves are analyzed to obtain the total pore volume, porosity,

specific pore surface area, mean pore diameter, and modal pore diameter, as summarized in Table 5.

Table 5 shows that the porosity and total pore volume of all groups decrease continuously with increasing curing age. As further confirmed by the ANOVA results in Table 6, pore volume and porosity are the two parameters most consistently affected by curing age and WGFA replacement ratio. The F -values of curing age and replacement ratio are 14.554 and 5.106 for pore volume, and 26.657 and 4.930 for porosity, respectively, with all corresponding P -values lower than 0.05. Therefore, pore volume and porosity are selected as the primary quantitative indicators for analyzing the overall pore structure evolution of WGFA concrete. Mean pore diameter and modal pore diameter are further used as supplementary descriptors to interpret the mechanism.

Fig. 9 further illustrates the evolution of porosity and total pore volume under different WGFA replacement ratios. At the same WGFA replacement level, the reduction in porosity becomes more pronounced with increasing curing age. At 3 d, WGFA replacement has little influence on porosity. The porosity of the G20 group is slightly higher than that of the G0 group, while the porosity of the G40–G100 groups remains close to that of the control group. This result indicates that WGFA mainly plays an inert-filling role during the early curing stage and does not significantly promote hydration. At 7 d and 28 d, the porosity decreases significantly with increasing WGFA replacement ratio. At 7 d, the porosity reductions of the G80 and G100 groups reach approximately 5.2% and 21.6%, respectively, compared with the G0 group. At 28 d, the porosity difference further increases, and the porosity of the G100 group becomes approximately 30.9% lower than that of the G0 group. Previous studies reported that amorphous SiO_2 in waste glass can gradually participate in secondary pozzolanic reactions

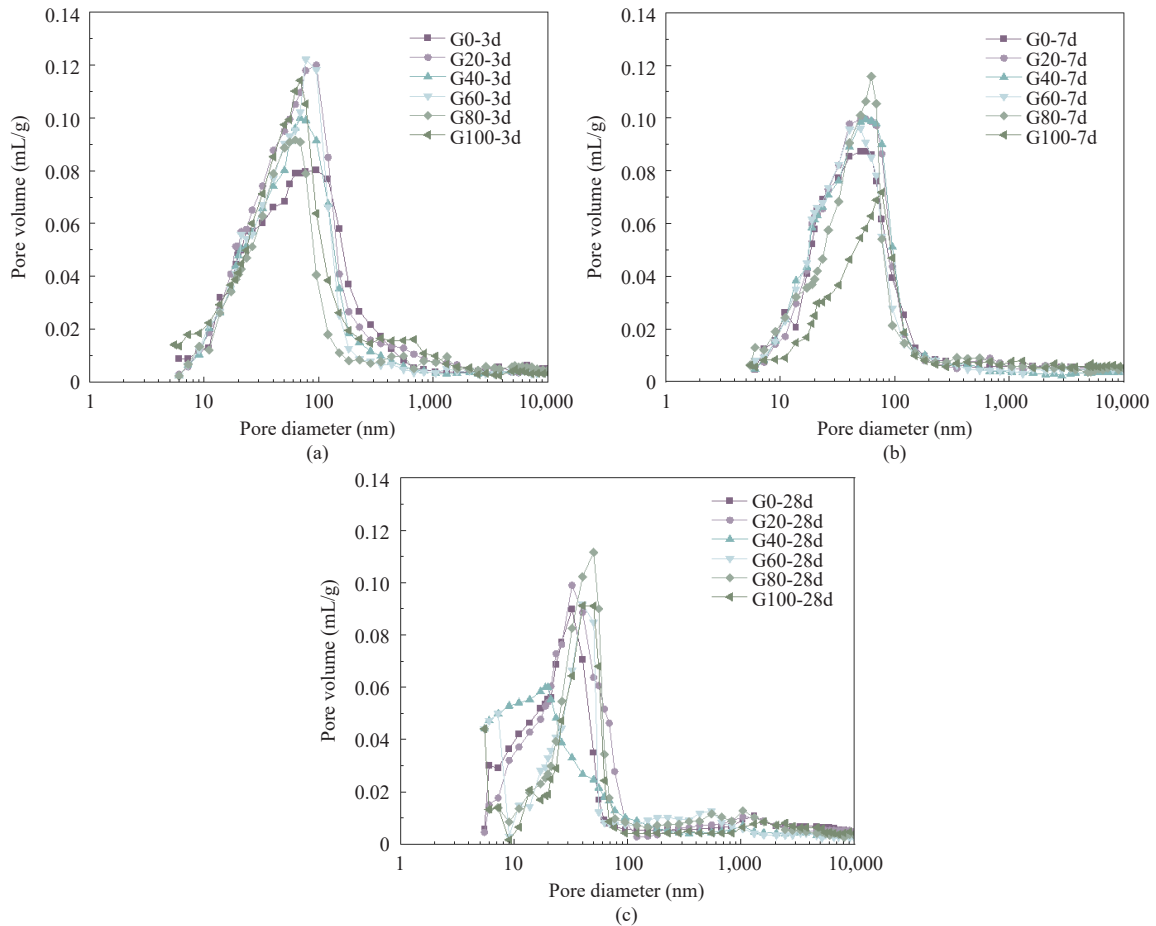


Fig. 8 Pore size distribution curves of WGFA concrete at different curing ages. (a) 3 d; (b) 7 d; (c) 28 d.

Table 5 Pore structure parameters of WGFA concrete at different replacement ratios and curing ages.

Mix	Age	Pore volume (mL/g)	Specific pore surface area (m ² /g)	Modal pore diameter (nm)	Mean pore diameter (nm)	Porosity (%)
G0	3 d	0.103	8.717	95.43	47.26	20.04
	7 d	0.090	9.832	50.34	36.74	17.66
	28 d	0.091	11.498	32.41	31.80	16.22
G20	3 d	0.124	10.376	79.11	47.74	22.55
	7 d	0.112	10.317	55.77	43.35	20.43
	28 d	0.107	10.880	32.40	39.31	18.82
G40	3 d	0.106	8.820	77.18	47.98	19.40
	7 d	0.100	10.851	55.74	37.02	18.19
	28 d	0.067	10.916	26.29	42.20	12.96
G60	3 d	0.107	9.208	77.13	46.55	19.48
	7 d	0.097	10.792	55.77	35.85	18.99
	28 d	0.062	4.697	40.26	52.48	12.06
G80	3 d	0.099	8.494	69.99	46.44	19.62
	7 d	0.086	9.066	62.49	38.03	16.74
	28 d	0.071	6.869	50.3	41.61	13.20
G100	3 d	0.104	9.907	69.06	42.10	20.08
	7 d	0.063	5.799	40.27	43.49	13.84
	28 d	0.057	4.154	40.26	54.55	11.21

Table 6 Summary of two-way ANOVA results for pore structure parameters.

Pore structure parameter	Source of Variation	df	F-value	P-value	R ²
Pore volume	Curing age	2	14.554	0.001	0.845
	Replacement ratio	5	5.106	0.014	
Porosity	Curing age	2	26.657	<0.001	0.886
	Replacement ratio	5	4.930	0.016	
Specific pore surface area	Curing age	2	0.684	0.527	0.497
	Replacement ratio	5	1.703	0.221	
Modal pore diameter	Curing age	2	30.709	<0.001	0.866
	Replacement ratio	5	0.613	0.693	
Mean pore diameter	Curing age	2	2.459	0.135	0.457
	Replacement ratio	5	0.702	0.635	

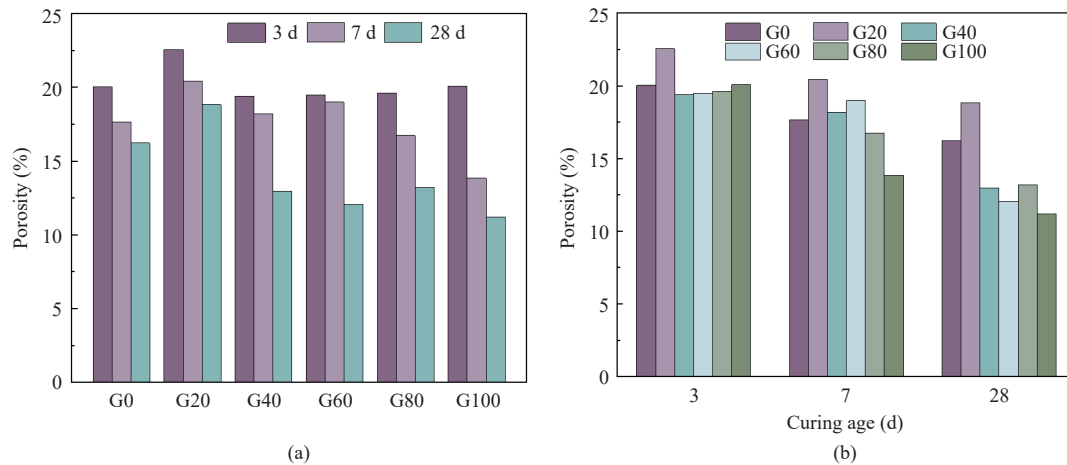


Fig. 9 Porosity evolution of WGFA concrete under different replacement ratios and curing ages. (a) Comparison by replacement ratio; (b) Comparison by curing age.

under alkaline conditions and generate additional C-S-H gel, thereby promoting pore filling and structural densification [33, 36, 37].

Fig. 10 illustrates the evolution of mean pore diameter with WGFA replacement ratio and curing age. The mean pore diameters of the G0 and G20 groups decrease continuously with increasing curing age, showing a typical pore refinement process. In contrast, the G40–G80 groups exhibit a trend of first decreasing and then increasing, while the G100 group shows a continuous increase in mean pore diameter with curing age. Notably, under some WGFA replacement conditions, porosity decreases continuously while the mean pore diameter increases. For example, Table 5 shows that the porosity of the G100 group decreases significantly with curing age, whereas the mean pore diameter continuously increases. This result indicates that the pore evolution of WGFA concrete is not simply a transformation from large pores to small

pores, but rather a coupled evolution process involving different pore-size ranges.

To further investigate the pore evolution mechanism, the pores are classified into gel pores, transitional pores, and capillary pores according to pore size. Fig. 11 compares the pore number distributions within different pore-size ranges. For the G0 and G20 groups, the pore volume within the range of 100–1,000 nm decreases continuously with curing age, while the proportion of pores smaller than 100 nm gradually increases. This result indicates that capillary pores are continuously refined during hydration, causing the pore size distribution to shift toward the small-pore range. As a result, the mean pore diameter decreases continuously with curing age.

For the G0 and G20 groups, the pore evolution behavior shows a typical pore-refinement process during curing. The modal pore diameter continuously shifts toward the smaller pore range with in-

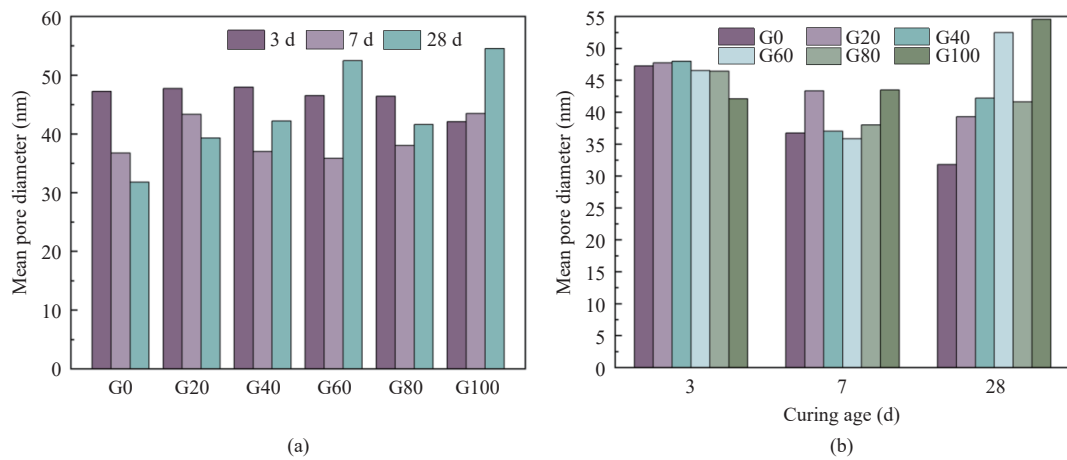


Fig. 10 The mean pore diameter of concrete with different WGFA replacement ratios at different curing ages. (a) Grouped by replacement ratio; (b) Grouped by curing age.

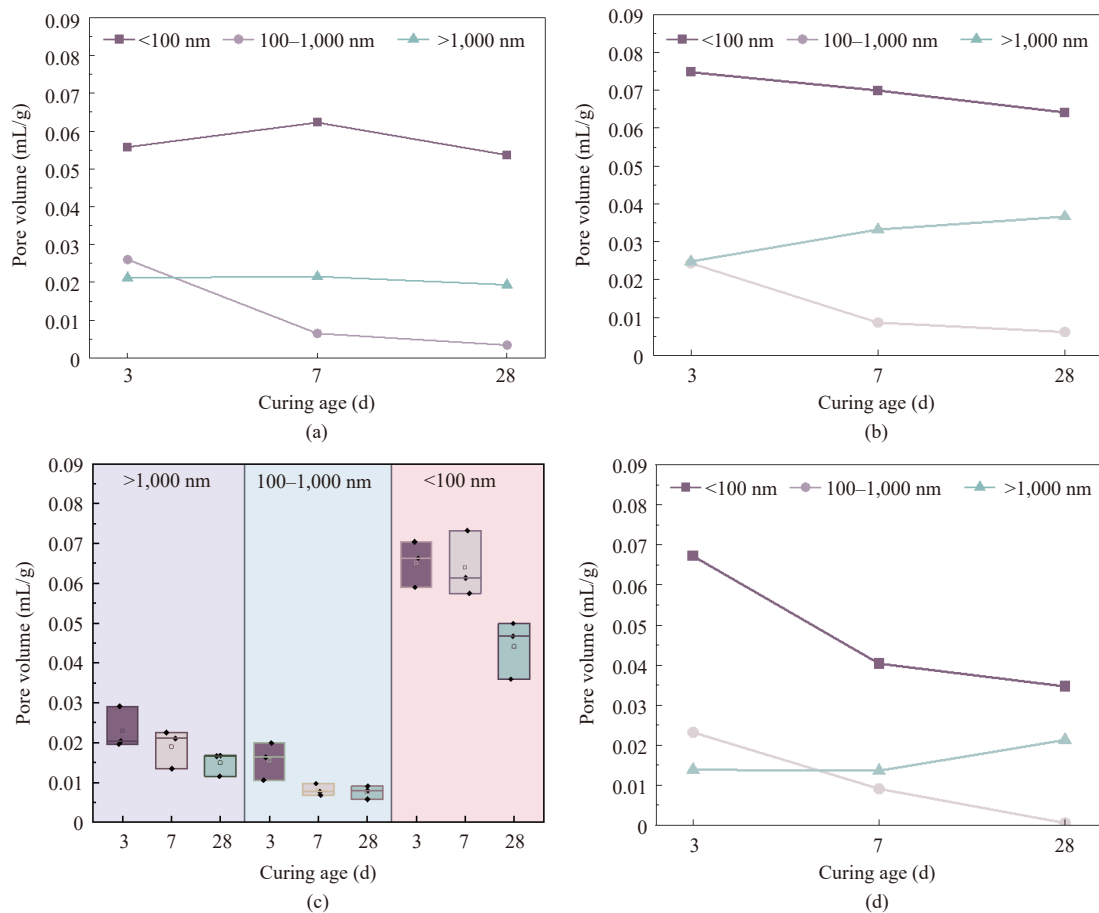


Fig. 11 Evolution of pore volume distribution within different pore-size ranges at different curing ages: (a) G0; (b) G20; (c) G40, G60, and G80; (d) G100.

creasing curing age. For the G0 group, the modal pore diameter decreases from 95.43 nm at 3 d to 32.41 nm at 28 d, while the corresponding value of the G20 group decreases from 79.11 nm to 32.40 nm. Fig. 11(a) and (b) show that the pore volume within the range of 100–1,000 nm decreases continuously, whereas the proportion of pores smaller than 100 nm gradually increases. This result indicates that capillary pores are continuously refined during hydration, causing the pore-size distribution to shift toward the small-pore range. As a result, the mean pore diameter of both groups decreases continuously with curing age.

The pore evolution behavior of the G40–G80 groups differs from that of the low-WGFA groups. The modal pore diameters of these groups are initially concentrated within the range of 69–78 nm at

3 d and decrease to approximately 55–63 nm at 7 d. Fig. 11(c) shows that the pore volume within the range of 100–1,000 nm decreases significantly during this stage, indicating that the filling effect of hydration products on capillary pores is dominant. As a result, the mean pore diameter further decreases at 7 d. However, the modal pore diameters of the G40–G80 groups further converge to the range of 20–50 nm at 28 d, while the numbers of gel pores and transitional pores smaller than 100 nm decrease significantly. Meanwhile, the peak intensity of the modal pore distribution decreases by approximately 20%–26% compared with that at 3 d. These results indicate that small pores are continuously filled and sealed during later-age hydration. Because the reduction in gel pores and transitional pores becomes more pronounced, the statist-

ical center of the pore distribution gradually shifts toward the relatively larger pore range, causing the mean pore diameter to increase again.

Under the high WGFA replacement condition in the G100 group, the modal pore diameter decreases from 3 d to 7 d and then remains relatively stable from 7 d to 28 d, consistently concentrating within the range of approximately 40–50 nm. Fig. 11(d) shows that although the capillary pores exhibit significant attenuation, the numbers of gel pores and transitional pores also decrease continuously throughout the curing process. Therefore, the continuous reduction in gel pores and transitional pores becomes the main reason for the significant decrease in porosity in the G100 group. Fig. 12 illustrates the corresponding pore evolution mechanism.

Fig. 13 further compares the pore number distributions of

WGFA concrete within different pore-size ranges at various curing ages. Fig. 13(a)–(c) correspond to pores smaller than 100 nm, pores within the range of 100–1,000 nm, and pores larger than 1,000 nm, respectively. During the curing period from 3 d to 28 d, the numbers of gel pores, transitional pores, and capillary pores in all groups show an overall decreasing trend, indicating that the pore structure is continuously filled with increasing curing age. Among them, the reduction in capillary pores is the most significant, indicating that larger pores are continuously filled and segmented during hydration. Meanwhile, the numbers of gel pores and transitional pores also decrease significantly. These results suggest that the pore evolution of WGFA concrete is not simply a transformation from large pores to small pores. Instead, secondary hydration products continuously generate during later curing stages

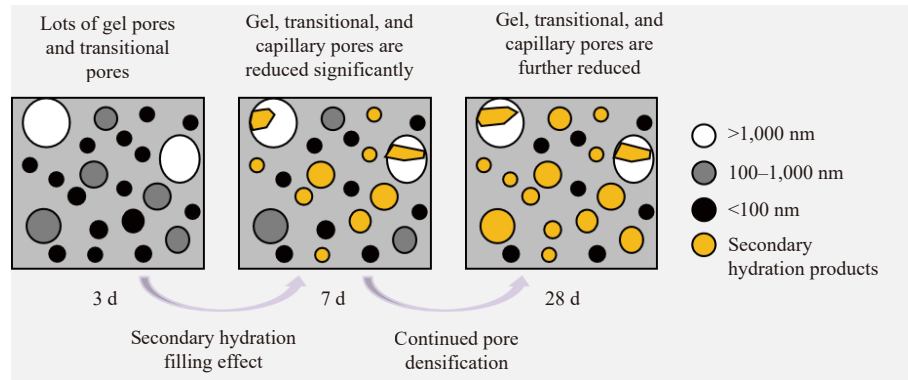


Fig. 12 Schematic illustration of pore structure evolution in G100 concrete during curing.

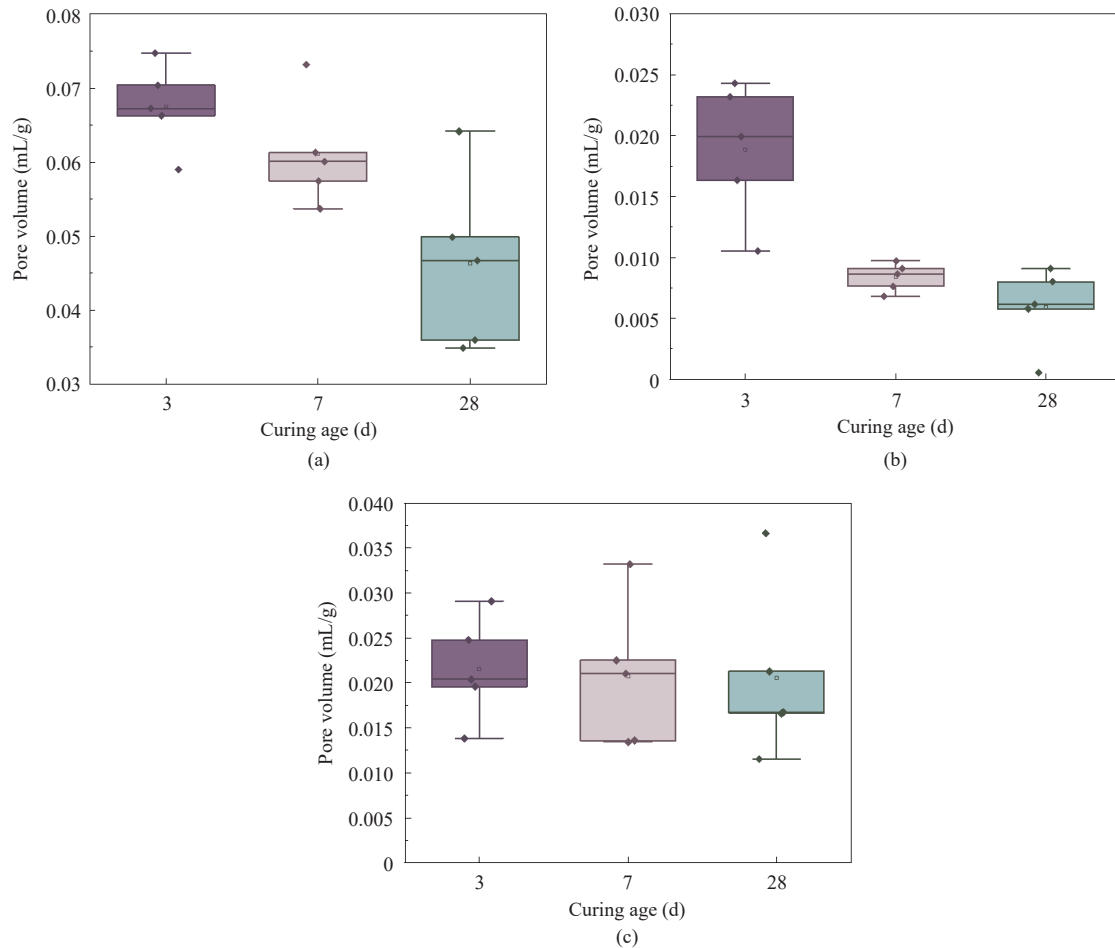


Fig. 13 Statistical distributions of pore volume within different pore-size ranges at different curing ages. (a) <100 nm; (b) 100–1,000 nm; (c) >1,000 nm.

and further fill and seal the gel pores and transitional pores.

Overall, the reduction in porosity of WGFA concrete is not solely caused by capillary pore filling. The numbers of gel pores and transitional pores also decrease significantly during the middle and later curing stages. At high WGFA replacement levels, fine WGFA particles gradually participate in secondary hydration reactions. Additional hydration products are continuously generated during curing. These products not only refine the capillary pores but also further fill and seal the gel pores and transitional pores. Therefore, the pore evolution of WGFA concrete is not simply a transformation from large pores to small pores. Under some WGFA replacement and curing conditions, the overall porosity continuously decreases, while the mean pore diameter increases simultaneously. To further clarify the microstructural origin of this pore-evolution behavior, SEM and EDS analyses were conducted to investigate the ITZ characteristics of WGFA concrete.

3.3 Microstructural characterization

Fig. 14 and Fig. 15 show that the main elements at the WGFA concrete interface include Ca, Si, Al, S, and O. According to the EDS results, the Ca/Si ratio of the G0 group is approximately 2.87. This relatively high Ca/Si ratio indicates that the ITZ in the control group mainly consists of calcium-rich hydration products. After incorporating WGFA, the Si concentration at the interface increases significantly, while the Ca/Si ratio decreases by approximately 50%–60% compared with that of the G0 group. Previous studies reported that a lower Ca/Si ratio indicates the formation of denser C-S-H gels [38]. This phenomenon is mainly related to the dissolution behavior of WGFA under alkaline conditions. Soluble silica

gradually dissolves from the glass surface and participates in secondary hydration reactions, generating additional C-S-H gels and promoting ITZ densification [39–43]. At the same time, the Al signal intensity near the WGFA interface increases by approximately 10%–15% compared with that of the G0 group. This result indicates that part of the Al element participates in the formation of C-(A)-S-H gel. Previous studies reported that C-(A)-S-H gel possesses a lower Ca/Si ratio, a longer silicate-chain structure, and stronger interlayer bonding than ordinary C-S-H gel [41, 44, 45]. Relevant studies further reported that the formation of C-(A)-S-H gel can reduce the porosity of the ITZ by approximately 15%–30%, thereby inhibiting the connectivity of large pores and reducing stress concentration near the interface [17, 46]. The dense hydration products observed in the present study further confirm the pore refinement and interface densification behavior discussed in the previous section.

Fig. 15 further illustrates the interface morphology between fine aggregates and cement paste under different WGFA replacement levels. Based on the distributions of Si and Ca elements, the aggregate phase and cement paste phase can be clearly identified. The widths of interface microcracks are quantitatively measured, and the results are summarized in Fig. 16. The interface between NFA and cement paste exhibits an irregular and dense morphology without obvious cracks. The interface region is mainly filled with continuously distributed C-S-H gels. In contrast, the interface between WGFA and cement paste becomes relatively straight and smooth.

At a low WGFA replacement level, the interface structure remains relatively dense. In the G20 group, although the ITZ does

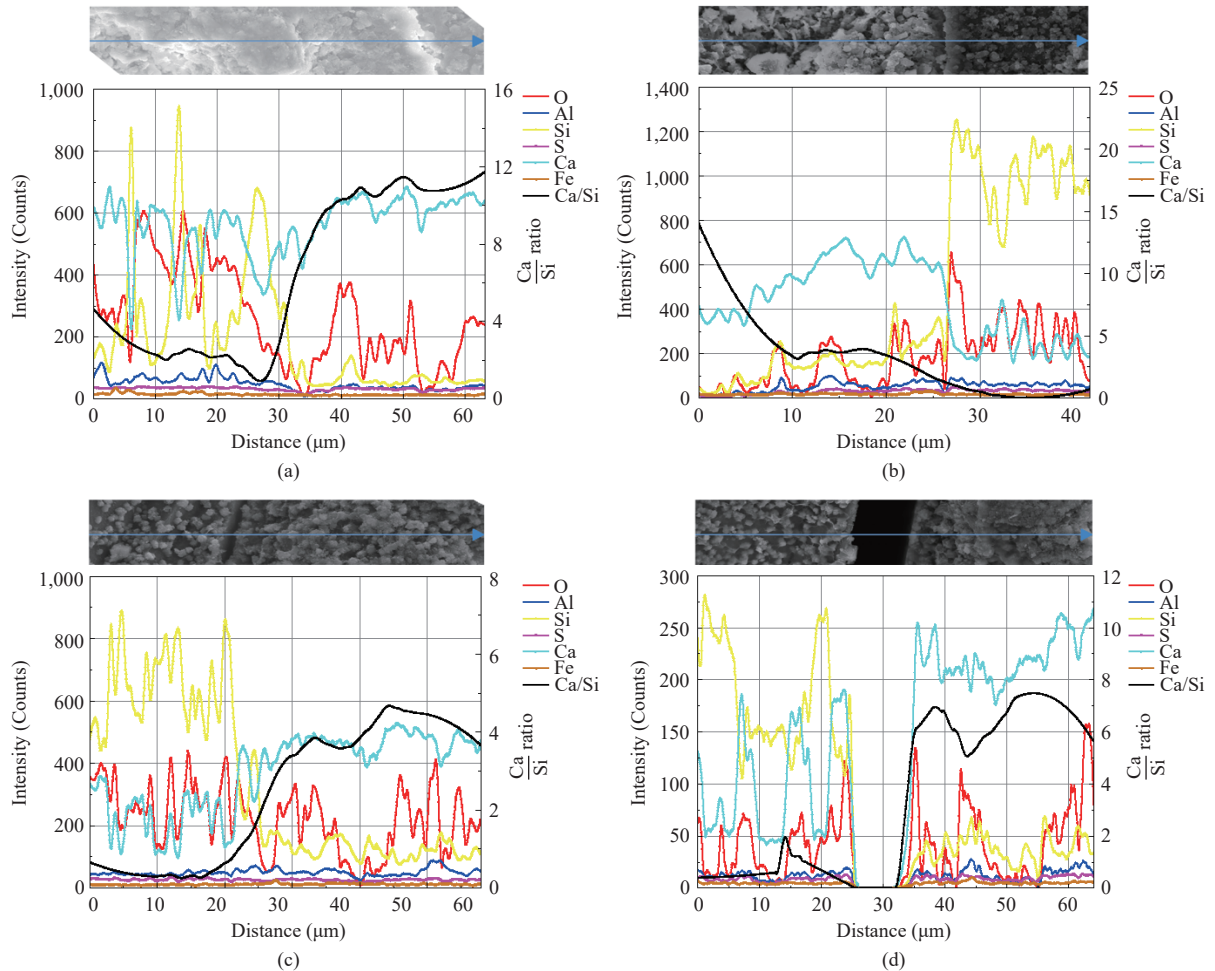


Fig. 14 EDS line-scan profiles of elemental distribution along the selected path. (a) G0; (b) G20; (c) G60; (d) G100.

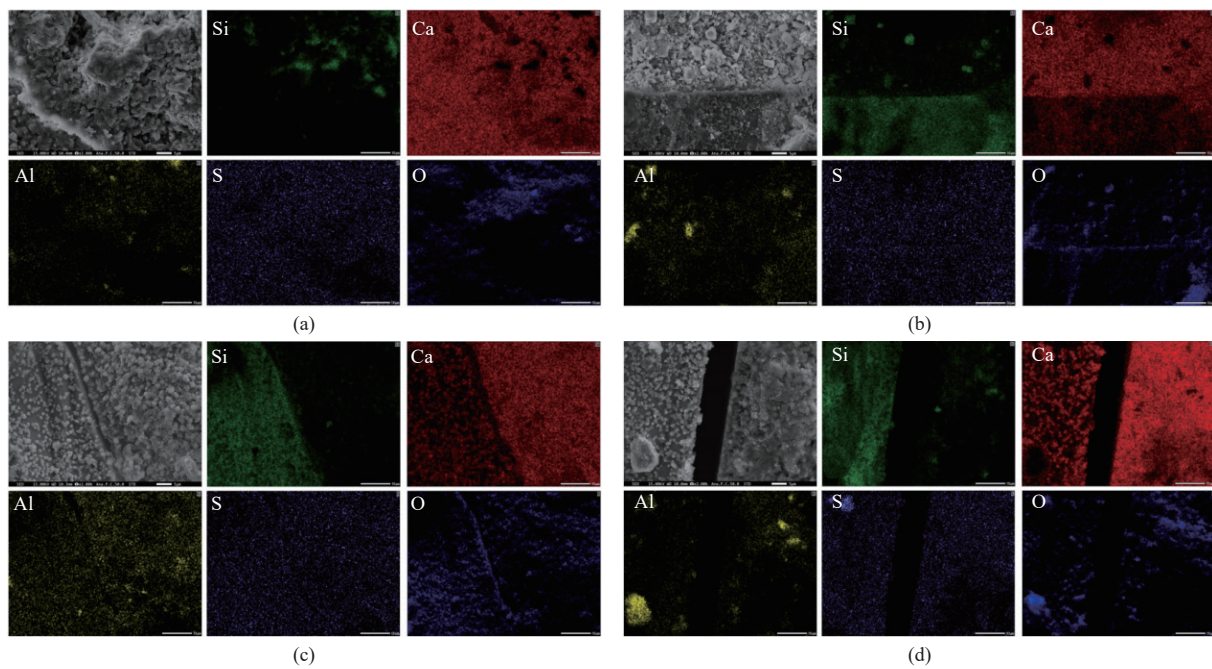


Fig. 15 EDS elemental mapping results for concrete. (a) G0; (b) G20; (c) G60; (d) G100.

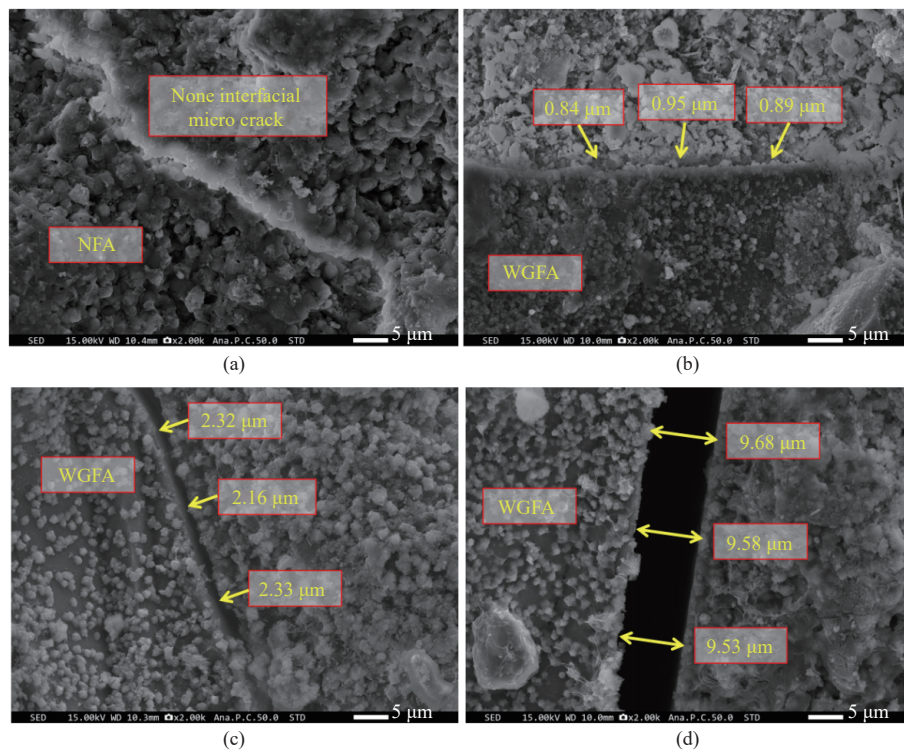


Fig. 16 Microcrack width at the fine aggregate–cement paste interface for concrete. (a) G0; (b) G20; (c) G60; (d) G100.

not exhibit a tightly interwoven structure, the crack width remains smaller than 1 μm . Meanwhile, a large number of white hydration-product particles are uniformly distributed on the WGFA surface, indicating that the secondary hydration reaction still promotes local densification near the interface. At this stage, WGFA not only plays a filling role but also contributes to the densification of the cement paste through secondary hydration reactions. As the WGFA replacement level further increases, the interface deterioration gradually becomes more pronounced. In the G60 group, the crack width increases to approximately 2–3 μm . Although the surface dissolution reaction of WGFA continues, the hydration products

gradually become discontinuously distributed near the interface, and local peeling phenomena begin to appear between WGFA and cement paste.

Under the full WGFA replacement condition, the interface deterioration becomes much more severe. In the G100 group, the crack width further increases to approximately 9–10 μm , and obvious separation between the cement matrix and WGFA can be observed. At the same time, more white hydration-product particles accumulate on the WGFA surface in the G60 and G100 groups, indicating that the secondary hydration reaction becomes more pronounced with increasing WGFA replacement ratio. During this

stage, the WGFA surface dissolution reaction continues. However, the products are mainly distributed in the outer layer of the aggregate and do not form a continuous body with the cement paste; instead, a shell-like deposition structure forms on the WGFA surface. During mechanical loading, stress is concentrated in the ITZ, causing cracks to preferentially extend along the interface, enhancing their connectivity and increasing the material's overall brittleness [47]. Previous studies have confirmed, through SEM observations, the presence of debonding zones and pore-rich areas around the glass aggregates [47–48]. Such structures will become the main pathways for crack initiation and propagation under external loads, thereby making the ITZ an important factor in controlling the failure mode. In summary, as the WGFA replacement rate increases, the width of interface cracks significantly widens, indicating that the ITZ's bonding ability gradually weakens, reducing its interface strength and significantly increasing the risk of interface cracking.

The progressive deterioration of interface bonding is closely related to the surface characteristics of WGFA itself. Fig. 17 shows that NFA exhibits a rough and irregular surface, whereas WGFA presents a smooth and dense morphology. The rough surface of NFA promotes stronger mechanical interlocking and forms a denser ITZ [8, 47–49]. In addition, WGFA exhibits an extremely low water absorption rate. Unlike natural aggregates, WGFA hardly absorbs water during hydration [50]. As a result, free water easily accumulates near the WGFA-cement paste interface, leading to a locally high water-cement ratio and insufficient interface filling. After water evaporation, interface microcracks gradually form and further weaken the interface strength [9], as shown in Fig. 18. Overall, as the WGFA replacement ratio increases, the ITZ gradually evolves from local weakening to crack connectivity and finally to large-scale interface separation. This process becomes one of the main reasons for the reduction in flexural performance and the increase in brittleness of WGFA concrete.

3.4 Mechanical evolution mechanism

The results indicate that the mechanical performance of WGFA concrete is governed by the coupled effects of pore structure evolution and ITZ deterioration. Under alkaline conditions, the gradual

dissolution of the WGFA surface releases dissolved silica and Al species, which participate in secondary hydration reactions and generate additional C-S-H and C-(A)-S-H gels. These hydration products continuously fill capillary pores and transitional pores, reduce porosity, and promote matrix densification. The refinement of the pore structure increases the effective load-bearing area and alleviates internal stress concentration, thereby contributing to compressive strength development [27, 51]. Moreover, the smooth surface and low water absorption rate of WGFA weaken the interfacial bonding between aggregate and cement paste. As the WGFA replacement ratio increases, interface defects gradually evolve from local discontinuities to interconnected microcracks, resulting in reduced resistance to tensile stress transfer and crack propagation [11, 47]. Therefore, compressive strength is mainly governed by matrix densification associated with pore refinement, whereas flexural strength is more strongly controlled by the integrity and continuity of the ITZ.

Fig. 19 summarizes the multiscale coupling relationship between mechanical properties and microstructural evolution. To further examine the rationality of the proposed stage division, a two-factor ANOVA was performed by comparing the interaction effects between curing age and replacement rate with those between curing age and the proposed evolution stage. The replacement-rate factor represents the original WGFA replacement levels, while the stage factor represents the three evolution stages defined according to the coupled changes in strength, porosity, and ITZ characteristics. As shown in Table 7, the curing age and the proposed stage interaction exhibits higher statistical significance than the curing age and the replacement rate interaction for both compressive and flexural strength, as reflected by larger *F*-values and smaller *P*-values. This result indicates that the proposed stage-based classification provides a more effective representation of the coupled influence of curing age and WGFA incorporation on the mechanical evolution of concrete.

In the first stage, corresponding to low WGFA replacement levels, the secondary hydration effect remains dominant. Although local interface discontinuities begin to appear, the ITZ still maintains a relatively dense structure with only limited microcrack formation. At this stage, the pore-refinement effect induced by secondary hydration compensates for the weak interfacial deterioration caused by WGFA incorporation. As a result, compressive strength continues to increase, while flexural strength shows only a slight reduction. Meanwhile, the higher mid-term compressive strength growth rate further indicates that WGFA promotes later-stage hydration and matrix densification under low replacement conditions.

As the WGFA replacement ratio further increases, the beneficial effect of pore densification and the detrimental effect of ITZ deterioration gradually approach a dynamic equilibrium state. Although secondary hydration reactions continue to generate additional C-S-H and C-(A)-S-H gels and further reduce the Ca/Si ratio within the

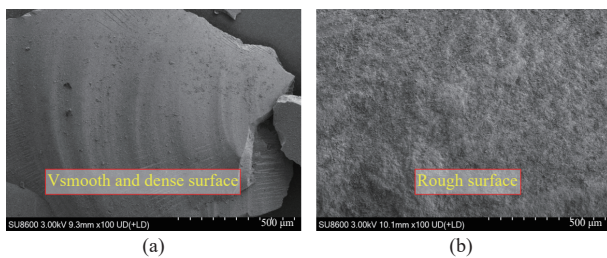


Fig. 17 SEM images of WGFA and NFA surfaces under 100× magnification. (a) WGFA; (b) NFA.

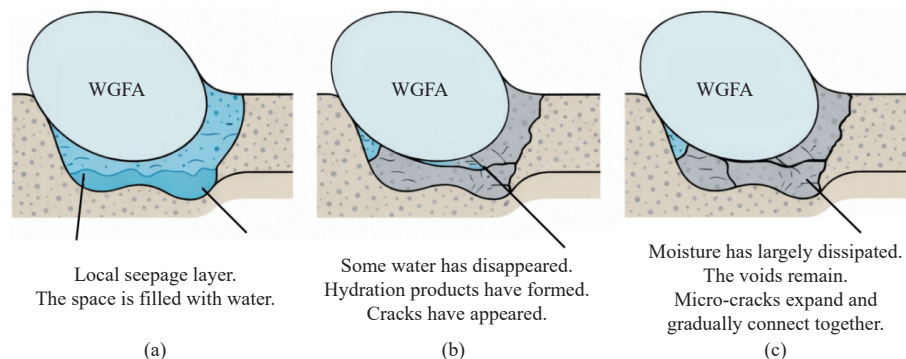


Fig. 18 Schematic illustration of ITZ evolution around WGFA during curing. (a) Early stage; (b) Middle stage; (c) Later stage.

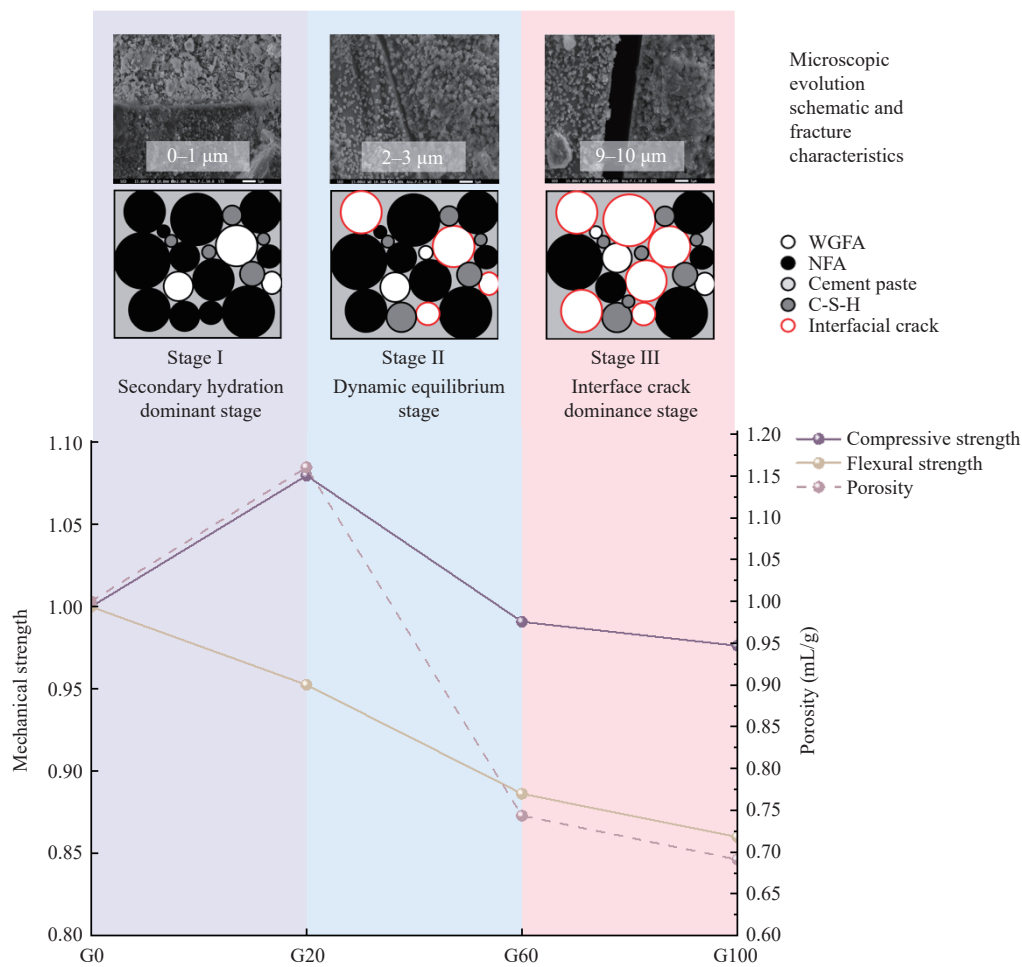


Fig. 19 Schematic illustration of the multiscale coupling mechanism between mechanical strength and microstructure evolution in WGFA concrete.

Table 7 The results of the two-factor analysis of ANOVA for mechanical properties.

Source of Variation	df	Compressive strength			Flexural strength		
		F-value	P-value	R ²	F-value	P-value	R ²
Age × replacement ratio	10	1.631	0.137	0.955	2.904	0.018	0.963
Age × stage	6	3.204	0.005		4.541	0.001	

ITZ, interface defects become increasingly pronounced. Microcracks and local peeling phenomena gradually appear around the WGFA surface, and the number of weak interface regions continuously increases. Under this condition, pore refinement still contributes to compressive strength development, while the deterioration of interface continuity significantly weakens flexural resistance. Therefore, compressive strength gradually stabilizes, whereas flexural strength becomes much more sensitive to WGFA incorporation.

At high WGFA replacement levels, the mechanical behavior becomes dominated by interface cracking. Although secondary hydration products continue to fill gel pores and transitional pores during later curing stages, the densification effect is no longer sufficient to compensate for severe ITZ deterioration. The interface microcracks gradually evolve from isolated defects into interconnected crack networks along the WGFA surface. As a result, crack propagation becomes increasingly controlled by the weakened ITZ, leading to a pronounced reduction in flexural performance and a significant increase in material brittleness. Under this condition, compressive strength remains relatively close to that of the control group because of the continued pore-refinement effect, whereas flexural strength decreases continuously due to the progressive loss

of interface integrity.

Overall, the mechanical evolution of WGFA concrete is governed by the coupled effects between matrix densification induced by secondary hydration and interface weakening caused by WGFA surface characteristics. The secondary hydration reaction mainly controls the evolution of pore structure and compressive strength, while the integrity and continuity of the ITZ dominate flexural behavior and crack resistance [31, 34]. Therefore, the divergence between compressive and flexural strength evolution in WGFA concrete fundamentally originates from the different controlling mechanisms of the cement matrix and the ITZ.

4 Conclusions

This study systematically investigated the influence of WGFA replacement on the pore structure evolution, ITZ characteristics, and mechanical performance of concrete. The main conclusions are summarized as follows:

(1) WGFA contributes to pore refinement and matrix densification during curing, leading to an initial increase and subsequent decrease in compressive strength, with the optimum performance observed at 20% replacement.

(2) Increasing WGFA replacement progressively weakens the ITZ because of the smooth and low-water-absorption surface of glass particles, resulting in continuous deterioration of flexural strength.

(3) The pore evolution of WGFA concrete involves the coupled reduction of capillary, gel, and transitional pores. Under high WGFA replacement conditions, porosity may decrease simultaneously with an increase in mean pore diameter.

(4) WGFA concrete exhibits a transition in the governing microstructural mechanism with increasing replacement ratio, shifting from matrix densification and pore refinement at low WGFA contents to ITZ-dominated cracking behavior at high replacement levels.

(5) The mechanical evolution of WGFA concrete is governed by the coupled effects between matrix densification and ITZ deterioration. Considering both mechanical performance and microstructural stability, the recommended WGFA replacement ratio should be controlled within 20%.

5 Future research

Future studies should further investigate the fractal characteristics of pore-structure evolution in WGFA concrete under different curing ages and replacement ratios. The current results indicate that, under high WGFA replacement conditions, the pore evolution behavior exhibits the coexistence of decreasing porosity and increasing mean pore diameter, which may limit the applicability of conventional fractal-dimension models. Therefore, future work should focus on establishing a modified fractal characterization approach considering the coupled effects of pore parameters, curing age, and WGFA replacement level to better describe the multiscale pore evolution behavior of WGFA concrete.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

Author contribution statement

Shanshan Jin: Conceptualization, Investigation, Writing, Supervision. Liuhuan Li: Data curation, Experiments, Writing, Investigation. Zhihao Feng: Methodology, Experiments, Writing, Supervision. Yang Zhang: Data curation, Experiments, Investigation. Zhihua Wang: Data curation, Experiments. Zhi Suo: Conceptualization, Investigation, Writing, Supervision.

Data availability statement

The datasets generated during and analyzed during the current study are not publicly available due to privacy or ethical restrictions but are available from the corresponding author on reasonable request.

able request.

Use of AI statement

During the preparation of this work, the authors did not use any AI tools. The authors take full responsibility for the final content.

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