

Performance and microstructure of concrete containing green and LCD glass sand as fine aggregates

Research Article

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Abstract: Rapid urbanization and environmental regulations have led to a shortage of natural river sand, prompting the use of alternative aggregates. This study evaluates green waste glass and liquid crystal display (LCD) glass sand as partial substitutes for manufactured sand (MS) in concrete. Comprehensive tests assessed mechanical properties (compressive and flexural strength), durability (drying shrinkage, impermeability, sulfate resistance), and alkali-silica reaction (ASR) potential. Microstructural evolution was analyzed using mercury intrusion porosimetry (MIP), scanning electron microscopy (SEM), and electrical resistivity. Results demonstrate that a 20% green glass substitution (GG20) achieved optimal performance, with 28-day compressive and flexural strengths of 51.8 MPa and 6.1 MPa, respectively. Both glass types significantly reduced drying shrinkage and enhanced sulfate resistance by refining pores. Despite increased ASR activity in the LCD group, pozzolanic reactions and the micro-filling effect densified the paste matrix. This research validates specialized waste glass as a sustainable performance enhancer for manufactured sand concrete, offering a robust theoretical foundation for eco-friendly construction.

Keywords: Green waste glass • LCD glass sand • Manufactured sand concrete • Mechanical properties • Durability • Microstructure

Nomenclature and abbreviations

Symbol/ Abbreviation	Definition	Unit
ASR	Alkali-silica reaction	—
C-S-H	Calcium silicate hydrate	—
GG	Green Glass	—
ITZ	Interfacial transition zone	—
K_f	Sulfate resistance coefficient	%
LCD	Liquid crystal display	—
MIP	Mercury intrusion porosimetry	—
MS	Manufactured sand	—

RS	River sand	—
SEM	Scanning electron microscopy	—
SSD	Saturated surface dry	—
TG	LCD Glass	—
ρ	Electrical resistivity	k Ω cm
ϕ	Porosity	%

1. Introduction

1.1 The global aggregate crisis and ecological implications

Concrete is the primary material for global infrastructure, but its massive consumption has triggered a shortage of natural river sand. Yang [1] investigated the quality improvement methods for sand used in the construction

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industry to ensure structural safety. A UNEP report [2] highlighted the need for new solutions to global sand resource governance to prevent ecological collapse. Huang [3] analyzed the application status of building aggregates and emphasized the importance of utilizing mineral sand. Furthermore, Gavrillets [4] detailed the biodiversity loss and riverbed degradation caused by the global sand crisis. Ren [5] proposed countermeasures to develop alternative minerals to address construction shortages. These factors have forced the industry toward manufactured sand (MS). However, MS often has a high stone powder content and angular shapes, which hinder workability, as noted by Son et al. [6] and Min [7] in their respective studies on aggregate morphology.

1.2 Evolution of waste glass in cementitious systems

Disposal of waste glass presents significant environmental challenges as it is non-biodegradable. Meyer [8] proposed greening the concrete industry by reusing industrial waste to reduce carbon footprints. Tamanna et al. [9] examined the performance of recycled waste glass sand as a partial replacement for natural aggregates, demonstrating its potential for resource conservation. Rana et al. [10] explored the effect of waste glass on the properties of recycled brick aggregate concrete, while Kou and Poon [11] investigated the filling capacity of self-compacting concrete using recycled glass. Additionally, Bohn et al. [12] developed novel methods for producing ceramic pavers from waste glass, demonstrating the method's versatility.

Finely ground glass serves as a pozzolanic material. Song et al. [13] emphasized the synergistic effect of glass

powder and recycled aggregates in optimizing concrete microstructure. Bhat and Rao [14] found that using glass powder as a partial replacement for cement effectively improves concrete compressive strength. The pozzolanic activity in glass was further studied by Li et al. [15], who examined its role in blended cement mortar, and Shayan and Xu [16], who observed that amorphous silica reacts with Ca(OH)_2 to form secondary C–S–H gels. Shi et al. [17] detailed the characteristics of this reactivity across different glass types, while Soldado et al. [18] highlighted the importance of mixture compactness in low-carbon concrete. Specialty glass types, such as CRT glass explored by Ling and Poon [19], and various recycled types reviewed by Ahmed and Rana [20], exhibit varied hydration kinetics. However, alkali–silica reaction (ASR) remains a concern. Chen et al. [21] noted the mitigation of ASR for tunnel waste rock, and Du and Tan [22] provided methods for ASR inhibition in mortar. Zhao et al. [23] discussed the impact of contaminated glass in UHPC, while Sacconi and Bignozzi [24] analyzed the expansion behavior of recycled fine aggregates in high-alkali environments.

1.3 Innovation and objectives of this study

While many studies focus on common bottle glass, the interaction between specialized LCD glass and manufactured sand remains underexplored. This study aims to evaluate glass sand as a “micro-structure modifier” specifically for basalt-based MS systems. By employing mercury intrusion porosimetry (MIP), scanning electron microscopy (SEM), and electrical resistivity, we reveal how the chemical differences between green soda-lime glass (GG) and LCD aluminosilicate glass (TG) dictate the concrete's mechanical threshold and ion transport properties.

2. Materials and methods

2.1 Raw materials

The cementitious material used was P.O. 42.5 ordinary Portland cement. Its physical properties and chemical compositions are detailed in Tables 1 and 2. The surface morphology of typical cement particles is shown in Figure 1.

Property	Value
Specific surface area (m^2/kg)	358
Initial setting time (min)	151
Final setting time (min)	220
28 day compressive strength (MPa)	48.6
28 day flexural strength (MPa)	8.5

Table 1. The physical properties of cement.
Source: Author's contribution.

CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	TiO ₂	SO ₃	Other	Loss
56.5	23.1	7.6	3.4	1.9	0.7	2.2	2.8	1.8

Table 2. Chemical composition of cementitious materials (wt%).

Source: Author's contribution.

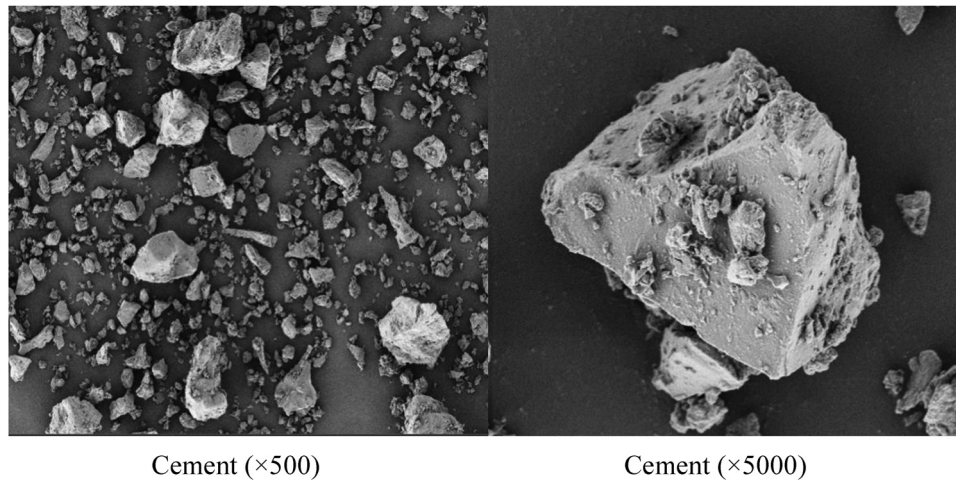


Figure 1. SEM Image of a cement particle.

Source: Author's contribution.

Project	Apparent density (kg/m^3)	Bulk density (kg/m^3)	Crush index (%)	Needle content (%)	Water absorption (%)
Gravel	2,710	1,840	5.0	3.6	1.5

Table 3. The properties of coarse aggregate.

Source: Author's contribution.

Coarse aggregate (gravel) properties and gradation are listed in Tables 3 and 4. Fine aggregates included river sand (RS), manufactured sand (MS), green glass (GG), and LCD glass (TG). Their natural accumulation appearance is shown in Figure 2. The crystal structure analysis is shown in Figure 3. XRD Atlas of two types of glass sand and river sand. SEM images in Figure 4. The SEM image of fine aggregate confirms the morphology. Physical properties and chemical compositions are detailed in Table 5. The performance index of waste glass is given in Table 5. Particle size distributions of fine aggregates are given in Table 6, and Table 7 lists chemical compositions of fine aggregates (wt%).

2.2 Mixing procedure

To ensure uniform dispersion of glass flakes and avoid clumps of manufactured sand powder, a standardized mixing procedure was adopted:

- (1) Dry Mixing (60 s): Mix coarse and fine aggregates (MS combined with GG or TG) to homogenize the granular skeleton.
- (2) Adding Cement (60 s): Add cement and stir until the aggregate surfaces are uniformly coated.

- (3) Wet Mixing Phase I (120 s): Slowly add 80% of the design water to initiate initial hydration and pozzolanic activity.
- (4) Final Stabilization (60 s): Add the remaining 20% water and continue stirring until a uniform, cohesive consistency is achieved.

2.3 Test methods and procedures

Four mixtures followed Table 8. Mixture proportions of concretes are given in kg/m^3 . A 20% replacement was selected based on optimal thresholds reported by Arivalagan and Sethuraman [25], who investigated mechanical-strength improvements, and by He [26], who focused on particle packing. Tests followed standard procedures for fresh properties [27], mechanical strength [28], durability

Sieve size (mm)	Sieve size (mm)					
	2.5	5.0	10	16	20	25
Gravel (%)	99.8	78.2	53.4	21.5	2.3	0

Table 4. Accumulated sieve allowance of gravel.

Source: Author's contribution.

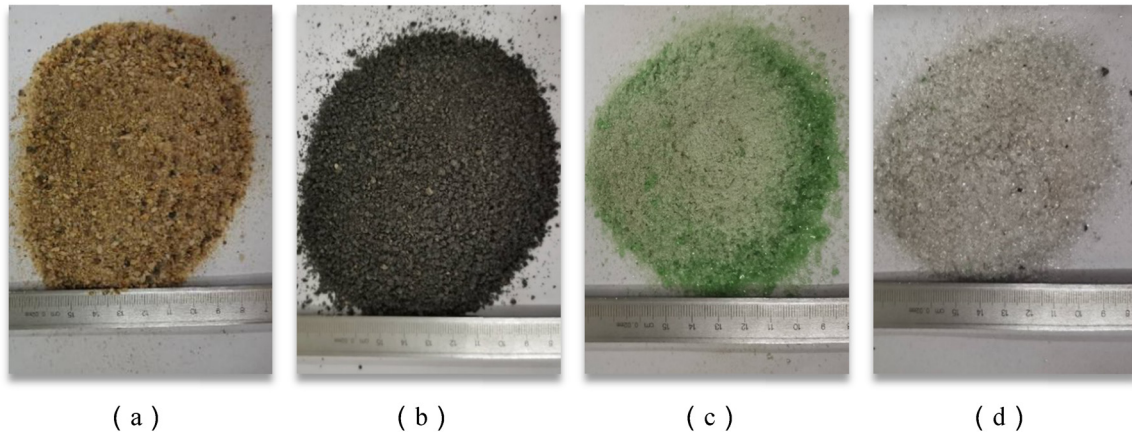


Figure 2. The natural accumulation of fine aggregates. (a) RS, (b) MS, (c) GG, and (d) TG.

Source: Author's contribution.

[29], and resistivity [30]. Alkali aggregate reactions were evaluated in accordance with JGJ 52 [31]. Microstructural analyses used MIP [32] and SEM [33]. Tests that followed the standards are listed in Table 9.

surface of glass increases “effective water” available for lubrication, as shown in Table 11. Slump of concrete. Yoo et al. [35] noted that the non-absorbent nature of glass improves filling capacity and workability in manufactured systems.

3. Results and discussion

3.1 Workability and stone powder content

Substitution with clean glass sand reduces the total stone powder content (Table 10. Stone powder content of mixed sand). Topçu and Canbaz [34] reported that the smooth

3.1.1 Mechanical performance: Intrinsic micro-cracks vs filling effect

Results are in Table 12, Figures 5 and 6. GG20 reached 51.8 MPa at 28 days via pozzolanic refinement. However, TG20 strength (50.1 MPa) was lower. Zhang [36] discussed the impact of sand content on the development of concrete strength. Park et al. [37] found that angular particles and

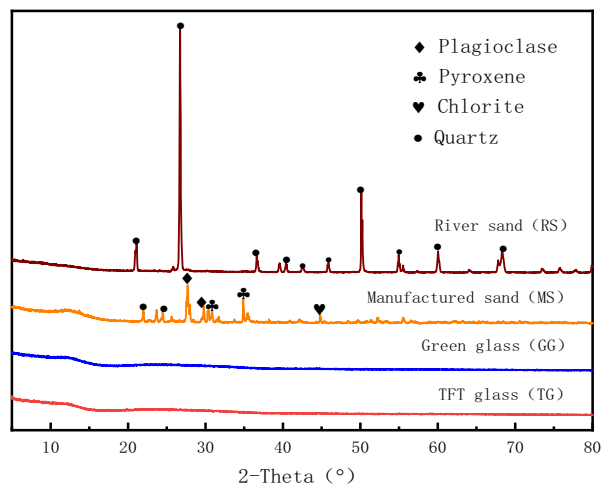


Figure 3. XRD Atlas of two types of glass sand and river sand.

Source: Author's contribution.

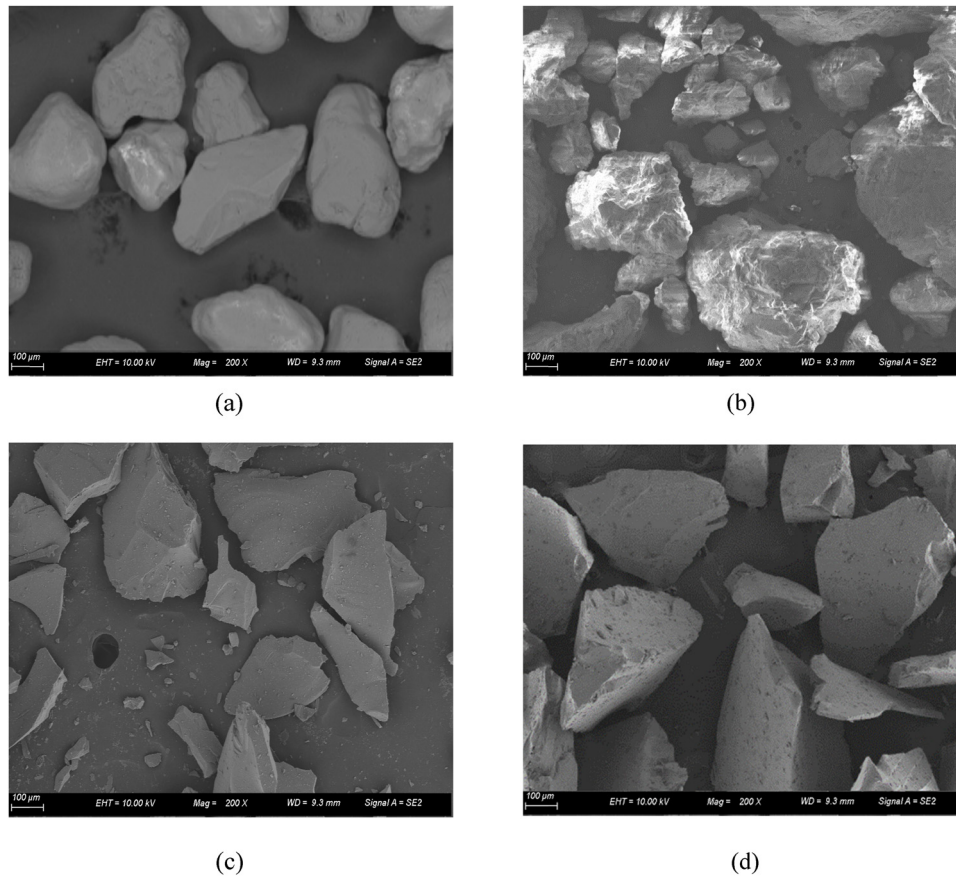


Figure 4. SEM Image of fine aggregate. (a) RS, (b) MS, (c) GG, and (d) TG.

Source: Author's contribution.

internal flaws from glass crushing increase stress concentrations, which is further discussed in the microstructural Section 3.4. Pore distribution results are summarized in Table 13.

Aggregates	The specific gravity (SSD)	The water absorption (%)	Fineness modulus (F.M.)	Crush index (%)
River sand (RS)	1.7	1.5	2.5	11.8
Manufactured sand (MS)	1.5	1.8	2.6	5.4
Green glass (GG)	1.2	0.2	2.3	17.6
TFT glass (TG)	1.3	0.1	2.4	18.3

Table 5. The performance index of waste glass.
Source: Author's contribution.

3.1.2 Durability and transport properties

Impermeability: Detailed in Table 14. Glass particles act as micro-aggregates, reducing penetration height.

Sulfate Resistance: Detailed in Table 15. Figure 7 shows the appearance after the attack. TG20 demonstrates superior resistance ($K_f = 88.6\%$) because its lower porosity (Table 13) increases pore tortuosity, hindering the capillary transport of sulfate ions (SO_4^{2-}).

Sieve size (mm)	2.36	1.18	0.60	0.30	0.15	0.075
RS (%)	0.0	33.0	54.7	80.2	95.4	99.0
MS (%)	0.0	35.0	46.6	87.6	98.3	99.6
GG (%)	0.0	25.1	49.1	80.5	81.8	98.4
TG (%)	0.0	31.5	50.3	75.0	91.6	98.2

Table 6. Particle size distributions of fine aggregates.
Source: Author's contribution.

Component	Al ₂ O ₃	SiO ₂	Fe ₂ O ₃	MgO	K ₂ O	CaO	Na ₂ O	BaO	SrO	Cr ₂ O ₃	Other	Loss
RS	6.4	84.3	1.8	0.4	0.3	3.1	—	—	—	—	3.5	0.2
MS	14.3	46.7	17.9	4.0	1.6	8.7	3.1	—	—	—	3.3	0.3
GG	3.0	66.6	2.3	1.8	0.9	10.6	12.6	—	—	0.5	1.2	0.5
TG	2.5	56.2	1.4	0.2	7.3	0.8	7.7	10.6	11.1	—	2.0	0.2

Table 7. Chemical compositions of fine aggregates (wt%)

Source: Author's contribution.

Mix no.	Cement	River sand	Manufactured sand	Green glass	TFT glass	Gravel	Water
RS	413	658	—	—	—	1,209	178
MS	413	—	658	—	—	1,209	178
GG20	413	—	526	132	—	1,209	178
TG20	413	—	526	—	132	1,209	178

Table 8. Mixture proportions of concretes (kg/m³)

Source: Author's contribution.

Test method	Specimen dimensions (mm) and types	Referenced standards
Methylene blue test	Fine aggregates	ASTM C 144-03 [33]
Slump test	Concrete mixture	GB/T 50080-2016 [34]
Flexural strength test	150 × 150 × 550 (concrete)	GB/T 50081-2019 [28]
Compressive strength test	150 × 150 × 150 (concrete)	GB/T 50081-2019 [28]
Dry shrinkage test	100 × 100 × 515 (concrete)	GB/T 50082-2009 [29]
Impermeability test	The upper diameter is 175 mm, the lower diameter is 185 mm, and the height is 150 mm (concrete)	GB/T 50082-2009 [29]
Sulfate resistance test	100 × 100 × 100 (concrete)	GB/T 50082-2009 [29]
Alkali aggregate reaction	25 × 25 × 280 (mortar)	JGJ 52-2006 [31]
Absorption test	100 × 100 × 100 (concrete)	GB/T 50081-2019 [28]
Surface resistivity test	150 × 150 × 150 (concrete)	ASTM D257-14 [30]
MIP	10 × 10 × 10 (paste)	ASTM D4404-10 [35]
SEM	<10 mm fragments (paste)	ASTM C1723-10 [36]

Table 9. Test items and referenced standards

Source: Author's contribution.

Mix no.	MB	Stone powder (%)	Mix no.	Slump (mm)	Cohesion	Water retention
RS	0.2	1.02	RS	83	Good	None
MS	1.3	2.20	MS	58	Good	None
GG20	1.0	1.61	GG20	64	Good	None
TG20	0.9	1.53	TG20	71	Good	None

Table 10. Stone powder content of mixed sand

Source: Author's contribution.

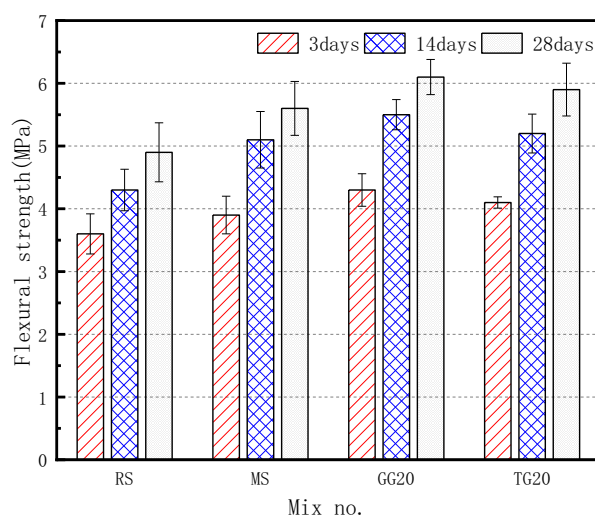
Table 11. Slump of concrete

Source: Author's contribution.

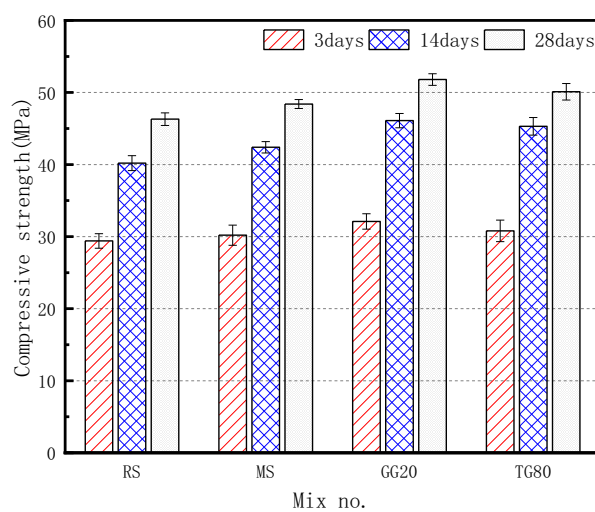
Mix no.	Compressive strength (MPa)			Flexural strength (MPa)		
	3 days	14 days	28 days	3 days	14 days	28 days
RS	29.4 ± 1.0	40.2 ± 1.1	46.3 ± 0.9	3.6 ± 0.3	4.3 ± 0.3	4.9 ± 0.4
MS	30.2 ± 1.4	42.4 ± 0.8	48.4 ± 0.6	3.9 ± 0.3	5.1 ± 0.5	5.6 ± 0.4
GG20	32.1 ± 1.1	46.1 ± 1.0	51.8 ± 0.8	4.3 ± 0.4	5.5 ± 0.2	6.1 ± 0.3
TG20	30.8 ± 1.5	45.3 ± 1.2	50.1 ± 1.1	4.1 ± 0.2	5.2 ± 0.3	5.9 ± 0.4

Table 12. Mechanical properties of concrete (average value ± standard deviation)

Source: Author's contribution.

**Figure 5.** Flexural strength of concrete.

Source: Author's contribution.

**Figure 6.** Compressive strength of concrete.

Source: Author's contribution.

Mix no.	Porosity (%)	Average pore diameter (nm) (%)	Probable pore diameter (nm)	Pore size distribution (%)			
				<20 nm	20–50 nm	50–200 nm	>200 nm
RS	11.02	37.02	40.26	20.01	21.23	27.12	31.64
MS	15.51	40.12	40.27	22.72	22.58	26.21	28.49
GG20	12.43	27.84	32.40	28.22	23.32	25.86	22.60
TG20	12.09	30.21	38.26	24.24	22.86	25.91	26.99

Table 13. Concrete pore size distribution at 28 days

Source: Author's contribution.

Mix no.	Impermeability grade	Penetration height (mm)
RS	P12	67
MS	P12	96
GG20	P12	83
TG20	P12	74

Table 14. Impermeability of concrete

Source: Author's contribution.

Mix no.	Compressive strength (MPa)		Sulfate resistance coefficient (%)
	Control specimen	Sulfate wetting-drying cycle	
RS	42.6	47.0	90.5
MS	45.1	52.4	86.0
GG20	50.3	57.2	87.9
TG20	47.1	53.1	88.6

Table 15. Sulfate resistance of concrete (after 15 wet-dry cycles)

Source: Author's contribution.



(a)



(b)



(c)



(d)

Figure 7. Appearance of the specimen after sulfate attack. (a) RS, (b) MS, (c) GG20, and (d) TG20.

Source: Author's contribution.

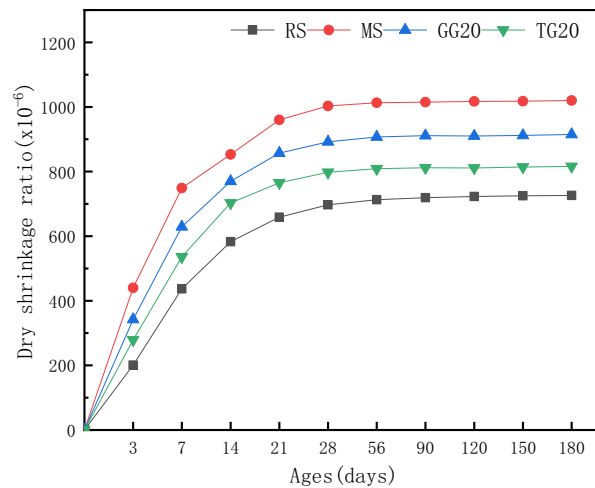


Figure 8. Drying shrinkage of concrete up to 180 days.

Source: Author's contribution.

Drying Shrinkage: Non-absorbent glass sand reduces capillary tension and shrinkage, as shown in Figure 8. Drying shrinkage of concrete up to 180 days, which was also discussed by You [38] regarding CRT glass.

Electrical Resistivity & Water Absorption: Details are shown in Figure 9. Different kinds of concrete water absorption are shown in Figure 10. Different kinds of concrete resistivity. Wei et al. [39] used resistivity to study cement hydration kinetics, while Kim et al. [40] found that replacing LCD glass alters ion transport paths.

ASR Expansion: Slurry rod expansion rate vs age curve shows that TG20 reached 0.11% expansion at 14 days (Figure 11), exceeding the 0.1% safe threshold.

Pore Refinement: Table 13 Concrete pore size distribution at 28 days and Figures 12–14 confirm refinement. Zeng et al. [41] used MIP to analyze pore-structure evolution, while Han and Liang [42] optimized mix designs for manufactured sand concrete.

3.2 Microstructural interpretation via SEM

SEM images of RS, MS, GG20, and TG20 at 3 and 28 days show the evolution of the ITZ and aggregate matrix across different aggregate systems and curing ages (Figures 15–18).

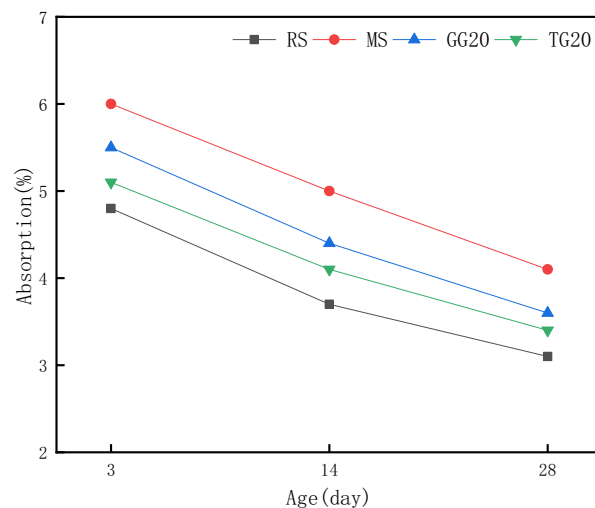


Figure 9. Different kinds of concrete water absorption.

Source: Author's contribution.

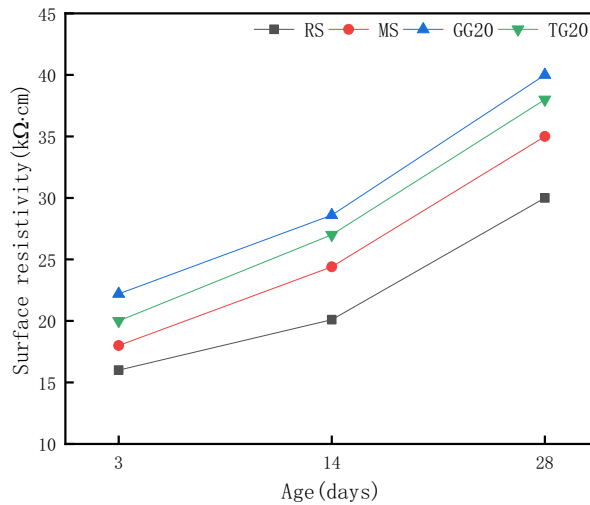


Figure 10. Different kinds of concrete resistivity.

Source: Author's contribution.

RS (Figure 15): Figure 15(a and b) show the hydration products inside the river sand concrete. At 3 days of age, small microcracks and unreacted calcium hydroxide (C-H) crystals are visible between the hydration products. Noticeable interfacial cracks within the ITZ are observed between river sand and the cement paste at 5,000× magnification, which acts as the leading cause of strength reduction. By 28 days, at 10,000× and 5,000× magnification, the hydration products are tightly packed, resulting in a denser pore structure than at 3 days. A fibrous network of C-S-H gel appears near the ITZ, with layered C-H crystals covering the surface and significantly fewer pores.

MS Group: SEM Images of manufactured sand concrete at 3 and 28 days are shown in Figure 16(a and b), respectively. At 3 days, a large number of sheet-like C-H crystals and a small amount of flocculent C-S-H gel are generated. Many pores and visible cracks are evident near the ITZ at 5,000× magnification. By 28 days, the sheet-like C-H crystals continue to hydrate into a layered C-S-H gel, yielding a more consistent pore structure without noticeable internal pores. At 1,000× magnification, the 28-day sample shows more complete hydration than the 3-day age, with no apparent holes on the specimen surface.

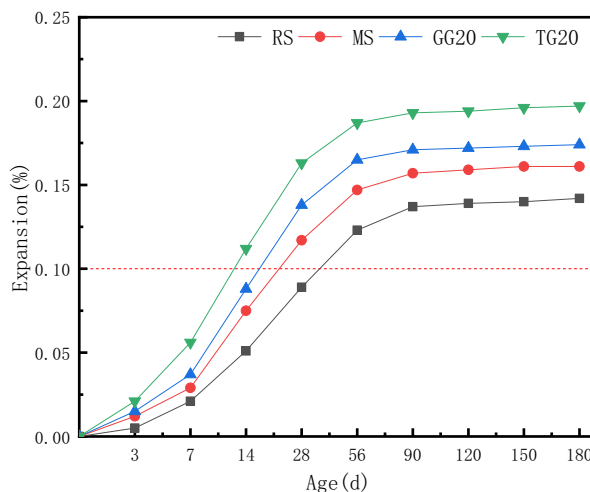


Figure 11. Slurry rod expansion rate vs age curve.

Source: Author's contribution.

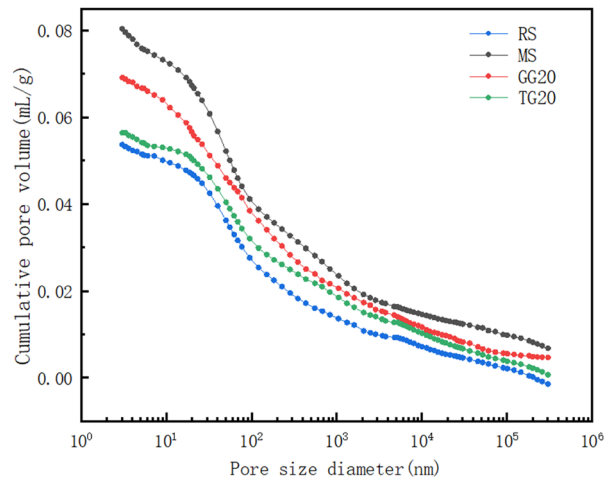


Figure 12. Integral curves for the distribution of pore sizes in different concrete.

Source: Author's contribution.

GG20 (Figure 17): Figure 17(a and b) are SEM images of GG20 concrete at 3 and 28 days, showing the hydration reaction process. At 3 days of age, under 10,000 $\times$ magnification, a needle-like C–S–H gel formed between the green glass sand and the manufactured sand. Layered C–H crystals were embedded in the C–S–H gel, accompanied by a small number of micro-cracks. At 28 days of age, cement hydration becomes more complete, and the needle-like C–S–H gel and sheet-like C–H crystals gradually transform into a layered C–S–H gel. No apparent cracks formed in the interfacial transition zone of the aggregate, resulting in a dense structure. At 1,000 $\times$ magnification, many small

pores are visible on the surface of the 3-days sample, whereas the 28D sample surface is free of small pores. Compared with MS and RS, the pore structure is denser, confirming the mechanical performance results and indicating strong pozzolanic bonding through the reaction of amorphous silica.

TG20 (Figure 18): The micro development process of TG20 concrete can be observed in Figure 18(a and b). At 3 days of age, cracks appeared between the glass aggregate and hydration products, and the flocculent C–S–H gel formed by cement slurry hydration was sparsely distributed. The sheet-like C–H crystals were stacked loosely.

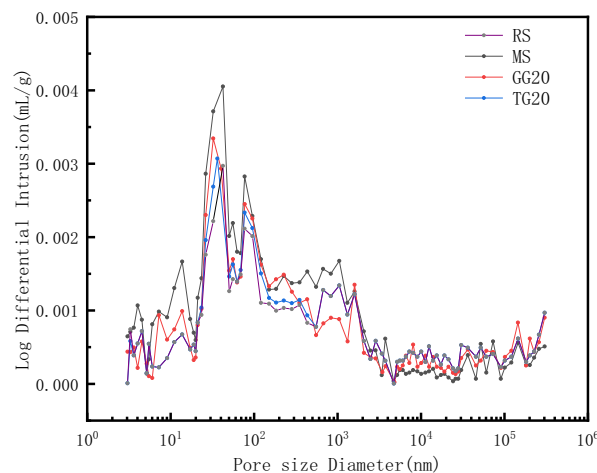


Figure 13. Differential curve of pore size distribution of different concrete.

Source: Author's contribution.

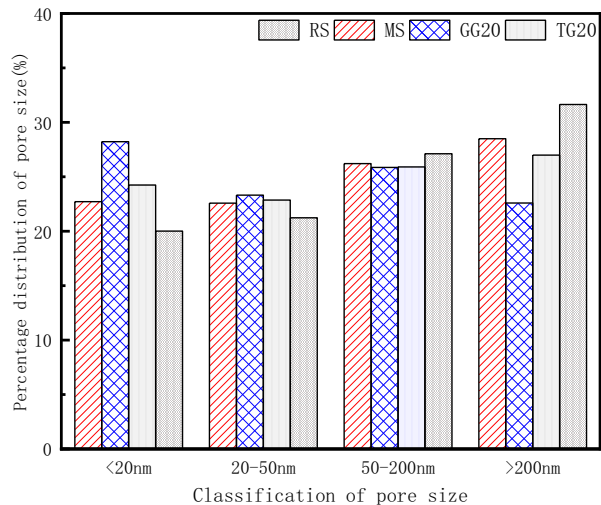


Figure 14. Pore size distribution of different concrete specimens.

Source: Author's contribution.

Compared with Figure 17(a and b), the concrete system had more pores. At 28 days of age, the hydration products in the concrete are tightly packed at 10,000× and 5,000×

magnification, and the pore structure is relatively dense compared to that at 3 days of age. At 28 days, SEM reveals intrinsic micro-cracks on the LCD glass surface from

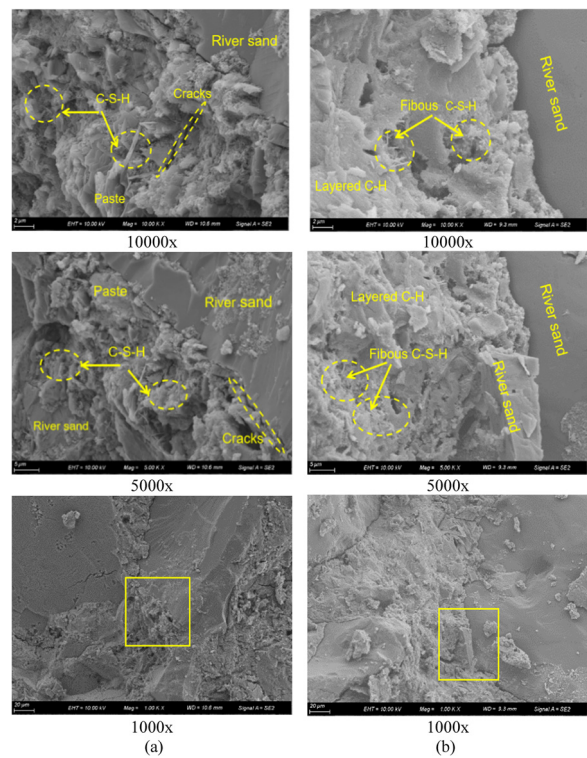


Figure 15. SEM images of RS at (a) 3 days and (b) 28 days.

Source: Author's contribution.

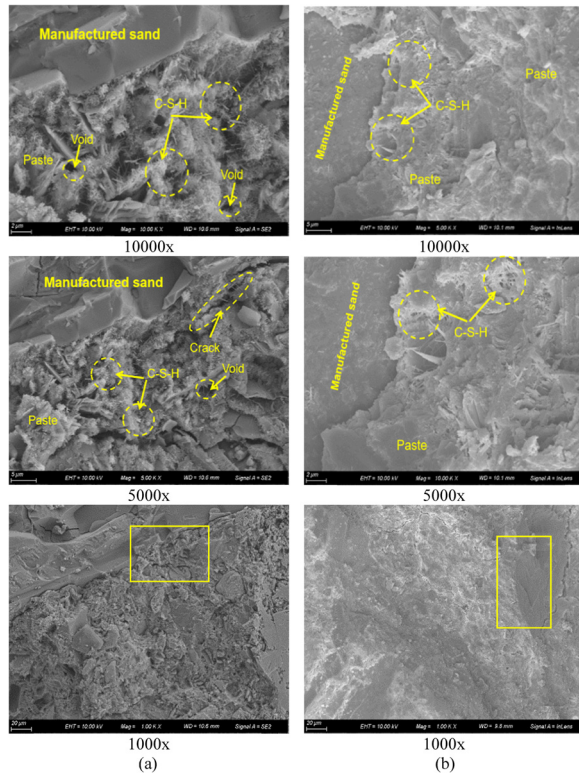


Figure 16. SEM images of MS at (a) 3 days and (b) 28 days.

Source: Author's contribution.

crushing, as observed by Gilabert et al. [43] in interface energy studies and Keerio et al. [44] in silica fume systems. These trans-granular cracks explain the mechanical bottleneck despite a densified surrounding matrix, as the structural integrity of the aggregate itself limits the load-bearing capacity. This is also why TG20's resilience is lower than GG20's.

4. Conclusions

Through comprehensive experiments and multi-scale analysis, this study systematically compared the effects of replacing 20% of manufactured sand (MS) with green recycled glass sand (GG) and LCD waste glass sand (TG) on the performance of C30 concrete. The following main conclusions and engineering application recommendations are drawn based on the experimental results and in-depth discussion.

- (1) Optimal Substitution: Replacing 20% manufactured sand with green glass sand (GG20) achieves the best mechanical performance, reaching a 28-day compressive strength of 51.8 MPa.

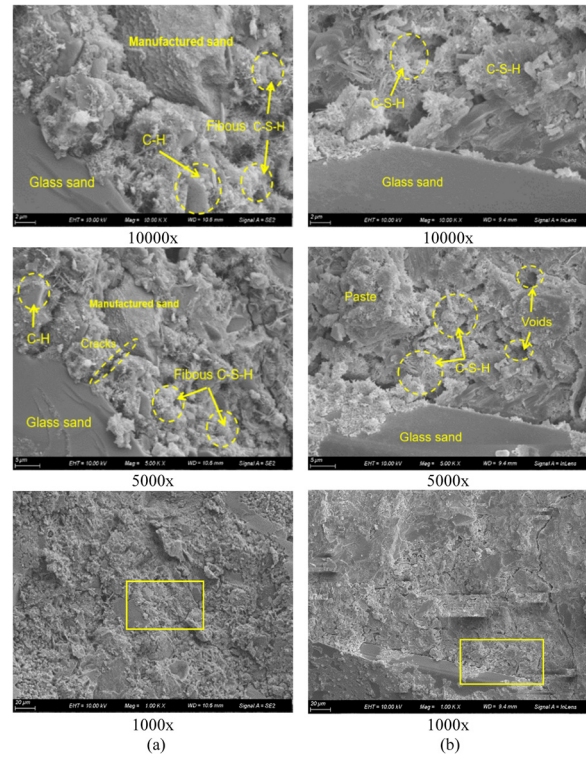


Figure 17. SEM images of GG20 at (a) 3 days and (b) 28 days.

Source: Author's contribution.

- (2) Workability Improvement: Incorporating clean waste glass sand reduces stone powder content and interparticle friction, effectively improving flowability.
- (3) Durability Mechanism: Glass aggregates refine pore structure, enhancing sulfate resistance and resistivity, which aligns with findings by Meng et al. [45] on green concrete.
- (4) Mechanical Bottleneck: The strength of LCD concrete is limited by intrinsic micro-cracks in particles, as noted by Singh and Mohanty [46] on waste glass powder.
- (5) Safety Risk: LCD glass exhibits high ASR risk (0.11% at 14 days, Figure 11), requiring chemical mitigation as suggested by Freitas et al. [47].

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Author contributions

Conceptualization, Methodology, Resources, Supervision, Writing—original draft, Writing-review & editing.

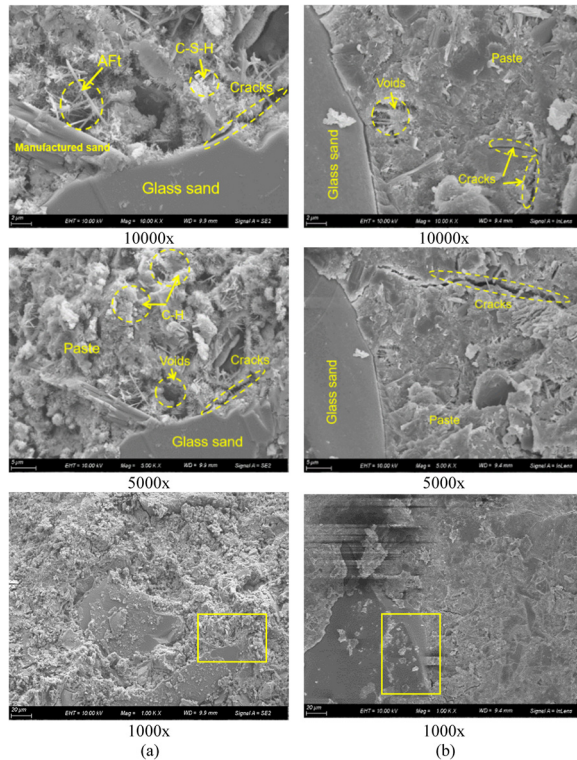


Figure 18. SEM images of TG20 at (a) 3 days and (b) 28 days.

Source: Author's contribution.

Investigation, Data curation, Formal analysis, Visualization.
Validation, Project administration.

Conflict of interest statement

Author states no conflict of interest.

Data availability statement

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

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