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Durability-related transport properties and microstructural evolution of pavement concrete incorporating recycled sugarcane bagasse

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Abstract: The growing demand for sustainable construction materials has stimulated interest in the utilization of agricultural by-products in concrete. Recycled sugarcane bagasse (RSB) represents a potentially valuable bio-based resource; however, its influence on durability-related performance and microstructural development in concrete remains insufficiently understood. This study investigates the effects of incorporating RSB at dosages of 0–2.5% (by volume of concrete) on porosity, water absorption, chloride-ion penetrability, and microstructural characteristics of concrete. A comprehensive experimental program was conducted, including porosity and water absorption measurements, rapid chloride penetration test (RCPT), and microstructural analyses using Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), scanning electron microscopy (SEM), and thermogravimetric analysis (TG/DTG). The results show that increasing RSB content progressively increased porosity from 9.24% to 21.74%, water absorption from 3.93% to 10.59%, and the charge passed from 1332 to 4119 C, indicating reduced resistance to chloride ingress. Microstructural observations revealed that increasing RSB content progressively disrupted matrix continuity and increased internal heterogeneity, leading to a more open pore structure and reduced resistance to fluid and ionic transport. In contrast, mixtures containing low RSB contents (0.5–1.0 vol.%) showed less pronounced deterioration in durability-related indicators than mixtures with higher RSB contents. Overall, the findings indicate that while excessive RSB incorporation can adversely affect matrix compactness and transport resistance, limited dosages may be less detrimental and remain technically feasible within the investigated mixture range.

Keywords: Recycled sugarcane bagasse; sustainable concrete; porosity; water absorption; chloride penetrability; microstructure.

1. Introduction

The construction industry is under increasing pressure to reduce its environmental footprint while maintaining the long-term performance of infrastructure materials. Ordinary Portland cement concrete remains the most widely used construction material worldwide, but its extensive production and consumption are associated with high energy demand, depletion of natural resources, and significant greenhouse gas emissions [1]. In response, increasing attention has been directed toward the development of more sustainable concrete through the incorporation of recycled, waste-derived, and bio-based materials [2]. Among these, agricultural residues are particularly attractive because they are abundant, renewable, and often underutilized, especially in countries with strong agro-industrial activity [3, 4]. Their valorization in concrete not only helps reduce waste disposal but also supports circular economy strategies by converting low-value residues into useful construction resources.

Sugarcane bagasse is one of the most abundant agricultural by-products generated by the sugar industry [5]. After juice extraction, large quantities of fibrous bagasse remain and are commonly burned for energy recovery or discarded at low added value. However, the increasing volume of this residue has raised environmental and resource-efficiency concerns, creating a need for more beneficial reuse pathways [6]. Due to its fibrous nature, low density, and lignocellulosic composition, sugarcane bagasse and its derived ash have attracted growing interest in cement-based materials, including mortar, concrete, lightweight composites, insulation products, and geopolymer systems [5]. In principle, their use may reduce raw material demand, lower unit weight, and improve sustainability performance. At the same time, the incorporation of bio-based particles or fibers may alter water demand, pore distribution, interfacial bonding, and matrix compactness, which can

strongly influence durability-related properties [7].

Previous studies have shown that recycled sugarcane bagasse (RSB), especially in the well-studied ash-derived form of sugarcane bagasse ash (SCBA), can enhance cementitious performance when used at suitable dosages. Subhani et al. [8] reported in a review that SCBA-based binary concretes often achieved about 10–20% higher compressive strength at an optimum replacement level near 20%, while ternary and quaternary blends could reach up to 40% total cement replacement without loss of strength and with improved resistance to chloride penetration, air permeability, and water permeability. Sobuz et al. [9] found that incorporating 0–20% SCBA improved the workability of lightweight concrete by about 40–50%, and mixtures containing up to 10% SCBA showed approximately 10–30% better hardened performance than the control. Sankeeth et al. [10] similarly observed that 5–10% SCBA improved strength and durability at 28 days, whereas 15% SCBA gave the best longer-term performance. Tabish et al. [7] further showed that 20% ultra-fine SCBA increased the 365-day compressive strength to 49.2 MPa, corresponding to about 18.6% above the control, while also reducing embodied energy and CO₂-equivalent emissions by about 18%. In geopolymer systems, Rihan et al. [11, 12] reported that partial replacement of fly ash with 5–20% SCBA under ambient curing could produce compressive strengths in the range of 40–56 MPa, while Fakhruddin [13] and Hamcumpai et al. [14] showed that low SCBA contents can improve strength, matrix density, and, in some cases, chloride resistance and toughness.

Similar trends have also been reported for pore structure and transport-related behavior. Ramírez-Arellanes et al. [15] found that concretes containing SCBA showed a 4–6% reduction in porosity after long-term curing, together with strong correlations between ultrasonic parameters and durability indicators. Yuan et al. [16] reported that

15% SCBA in 3D-printed concrete increased tensile strength by 10.0%, improved interlayer bond strength by 31.4%, and reduced interfacial porosity by 69% after 90 days. Vieira et al. [17] showed that blended systems incorporating residual SCBA could maintain performance without detrimental effects, with reduced absorption and void-related indices. Navaneetha et al. [18] and Nirmal et al. [19] likewise reported that SCBA-based ternary systems improved strength and durability at moderate replacement levels, especially through pore refinement and reduced chloride permeability. However, the beneficial range is not unlimited. Anandaraj et al. [20] identified 1% sugarcane bagasse fiber as the optimum dosage in bottom-ash concrete, while Meghana and Madhukumar [21] found better performance at moderate SCBA contents than at higher replacement levels. Zúniga et al. [22] also indicated that although sugarcane bagasse can be incorporated in bio-based composites, excessive contents may increase degradation susceptibility. Collectively, these findings suggest that sugarcane-derived materials are generally most effective at low-to-moderate dosages, whereas excessive contents may reduce matrix compactness and increase durability-related risk. However, most of these findings were obtained for ash-derived systems rather than for directly incorporated RSB, and therefore they are used here only as indirect guidance rather than as directly transferable evidence.

Although the existing literature provides useful evidence, most previous studies have focused on SCBA as a supplementary cementitious material rather than RSB used directly as a fibrous bio-based constituent in concrete. In addition, many studies have mainly emphasized compressive strength, workability, lightweight behavior, or sustainability performance, while the effects of RSB on durability-related properties remain insufficiently clarified. This limitation is important because porosity, water

absorption, and chloride penetrability directly reflect the accessibility of the internal pore network to water and aggressive ions, which strongly influence service life, maintenance demand, and resistance to deterioration, especially in humid or chloride-rich environments.

Therefore, when RSB is incorporated into concrete, it is necessary to evaluate not only its feasibility but also its effects on matrix structure and transport-related behavior. Techniques such as FTIR, XRD, SEM, and TG/DTG are needed to relate changes in porosity, water absorption, and chloride transport to matrix compactness and phase stability. However, important gaps remain for RSB. Limited quantitative information is available on how increasing RSB content affects these properties over curing time, and the relationships among them remain unclear. In addition, microstructural evidence is often presented only descriptively rather than being directly linked to durability results. As a result, the combined effects of RSB on matrix structure, transport behavior, and thermal or mineralogical characteristics are still insufficiently understood.

To address these gaps, the present study investigates the effect of RSB on the durability-related and microstructural performance of concrete. Concrete mixtures containing 0.0, 0.5, 1.0, 1.5, 2.0, and 2.5 vol.% RSB were prepared and evaluated. The experimental program included porosity, water absorption, and rapid chloride penetrability tests at 28 and 56 days, together with FTIR, XRD, SEM, and TG/DTG analyses to interpret the associated matrix changes. In addition, correlation analysis was used to examine the relationships between porosity, water absorption, and chloride penetrability. The novelty of this study lies in linking transport-related durability indicators with multi-scale microstructural characterization, including FTIR, XRD, SEM, and TG/DTG. In particular, the study focuses on directly incorporated RSB particles with fibrous morphology, which are fundamentally different

from SCBA used as a supplementary cementitious material in most previous studies. This approach helps clarify the mechanisms governing pore-structure evolution in concrete incorporating RSB. Unlike most previous studies that focused primarily on SCBA as a supplementary cementitious material, the present work investigates directly incorporated RSB particles and evaluates how

increasing RSB dosage influences matrix compactness, pore connectivity, and chloride transport behavior. The findings provide useful guidance for the sustainable use of RSB in concrete and help identify dosage ranges that remain technically feasible from a durability perspective.

2. Preparation of recycled sugarcane bagasse

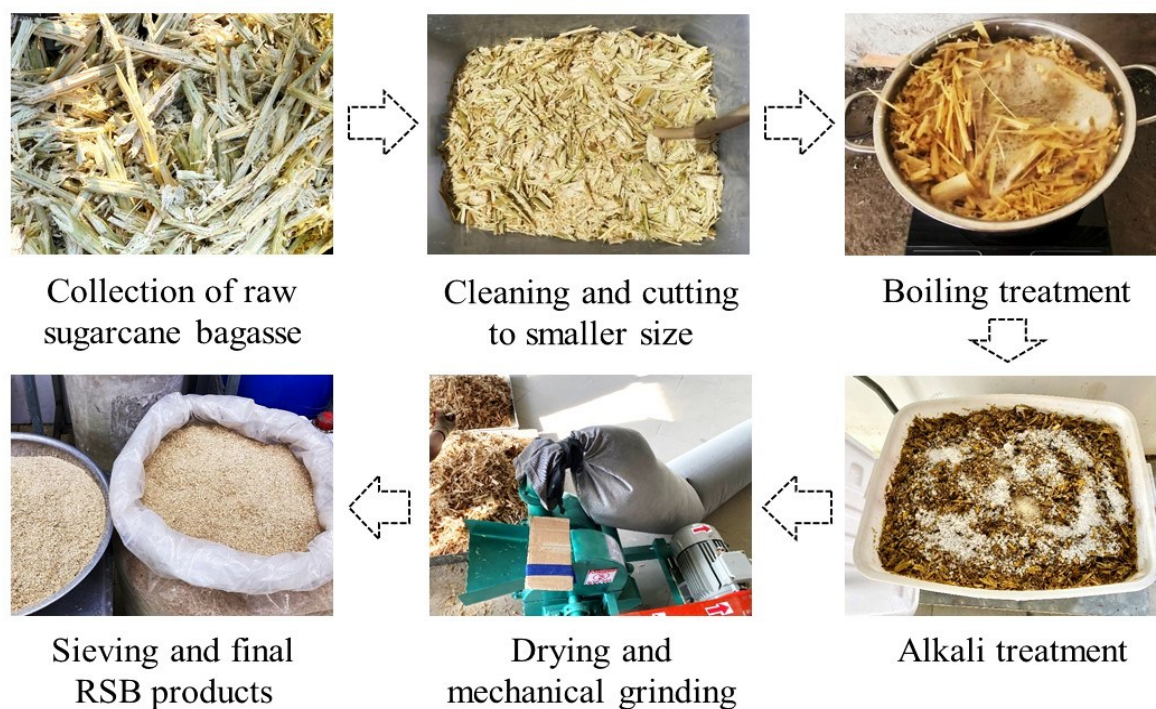


Fig. 1. Experimental recycling procedures for RSB

Raw sugarcane bagasse was collected from a local sugar-processing source and transported to the laboratory in sealed plastic bags. First, the raw bagasse was manually sorted to remove visible impurities such as soil, dust, damaged outer rind, and residual foreign matter [20]. It was then washed with tap water and cut into smaller pieces with an approximate length of 20–30 mm using scissors and a laboratory knife (Fig. 1). The cleaned and cut bagasse was subsequently subjected to boiling treatment in water at $98 \pm 2^\circ\text{C}$ for 60 min to remove residual sugar, soluble organic compounds, and surface contaminants [22]. After boiling, the material was drained and allowed to cool naturally to room temperature for approximately 30–45 min. The boiled bagasse was then immersed in a 3 wt.% NaOH aqueous solution

at room temperature ($27 \pm 2^\circ\text{C}$) for 3 h, using a solid-to-solution ratio of about 1:10 by mass. During alkali treatment, the mixture was stirred manually every 30 min to ensure uniform exposure of the raw sugarcane bagasse to the solution. At the end of the treatment period, the bagasse was removed and repeatedly washed with clean water until the rinse water reached a nearly neutral condition ($\text{pH } 7 \pm 0.5$). The washed material was then spread in a thin layer and pre-drained for 2 h, followed by oven drying at $70 \pm 5^\circ\text{C}$ for 24 h. After drying, the material was mechanically ground using a laboratory grinder for 3–5 min until a more uniform particle form was obtained. The ground product was then sieved, and the fraction passing the 2.5 mm sieve and retained on the 0.15 mm sieve was collected as RSB for concrete

production. The final RSB product was stored in sealed moisture-proof plastic bags at room temperature until use.

3. Materials and experimental methods

3.1. Materials

The primary binder used in this study was Portland cement with a specific gravity of 3.07, classified as grade 40 and conforming to TCVN 2682:2020 [23]. This cement was used as the main hydraulic binder because of its stable quality in terms of fineness, chemical composition, and strength development. In addition, two supplementary cementitious materials, namely ground granulated blast-furnace slag (GGBFS) and fly ash (FA), were incorporated to form a blended binder system. The fly ash was classified as Class F according to TCVN 10302:2014 [24] and was obtained from a thermal power plant in southern Vietnam. GGBFS was used as a latent hydraulic material to improve the mineral

composition of the binder system. RSB, prepared according to the procedure described in Section 2, was used as the bio-based modifying material in the concrete mixtures.

The major oxide compositions of cement, GGBFS, and FA are presented in Table 1. Cement was dominated by CaO (56.6 wt.%), together with SiO₂ (21.0 wt.%) and Al₂O₃ (6.8 wt.%), confirming its role as the primary calcium-rich hydraulic binder in the blended system. GGBFS exhibited a more balanced composition, containing 38.1 wt.% CaO, 30.8 wt.% SiO₂, and 13.9 wt.% Al₂O₃, indicating its potential contribution to secondary binder reactions and matrix development. In contrast, FA contained the highest proportions of SiO₂ (53.3 wt.%) and Al₂O₃ (25.2 wt.%), but only 0.9 wt.% CaO, which is consistent with the characteristics of low-calcium Class F FA. Among the three binder materials, FA also showed the highest loss on ignition (6.0 wt.%), compared with 3.7 wt.% for cement and 1.3 wt.% for GGBFS.

Table 1. Primary chemical compositions of binder materials

Primary elements (wt.%)	Cement	GGBFS	FA
SiO ₂	21.0	30.8	53.3
Al ₂ O ₃	6.8	13.9	25.2
Fe ₂ O ₃	3.2	1.0	5.5
CaO	56.6	38.1	0.9
MgO	3.3	6.6	0.6
SO ₃	2.6	1.2	0.2
K ₂ O	0.7	0.3	2.4
Na ₂ O	0.2	0.1	0.2
Loss-on-ignition	3.7	1.3	6.0
Others	1.9	6.7	5.7

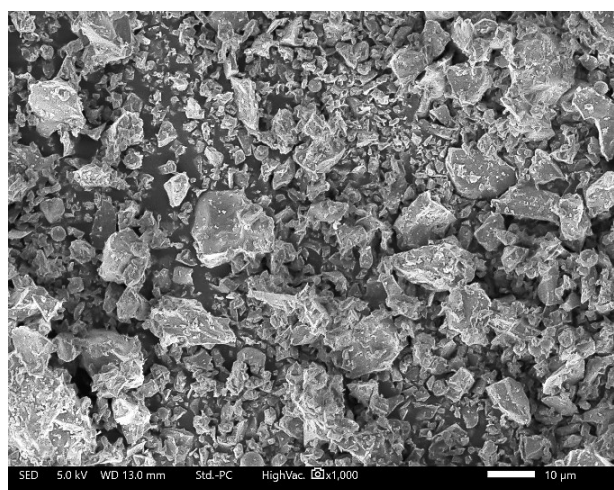
The morphological characteristics of the raw materials are shown in Fig. 2. The cement particles (Fig. 2a) exhibited irregular angular shapes with a relatively rough surface texture, while GGBFS particles (Fig. 2b) also appeared predominantly angular and fragmented, with particle sizes and morphology generally comparable to those of cement. In contrast, FA particles (Fig. 2c) were mainly spherical and smoother in appearance, which is a typical morphological feature of fly ash

and may contribute to particle packing and dispersion within the blended binder system. The RSB particles (Fig. 2d) showed a distinctly different morphology from the mineral binder materials, characterized by elongated, layered, and fibrous features with a rough surface texture. This clear morphological contrast suggests that RSB was not only compositionally different from the binder materials but also structurally more irregular and anisotropic. Such differences are important because they may

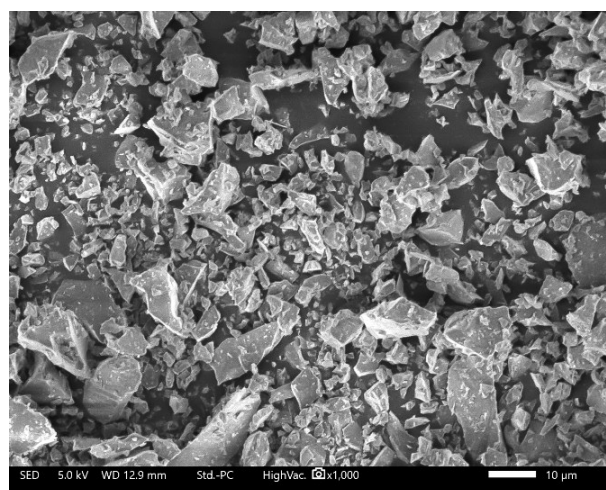
influence particle packing, matrix compactness, and the internal pore structure of the concrete.

From both the chemical composition in Table 1 and the morphology shown in Fig. 2, the four materials played clearly different roles in the mixture system. Cement served as the principal calcium-rich binder, GGBFS and FA acted as mineral supplementary materials with distinct chemical and

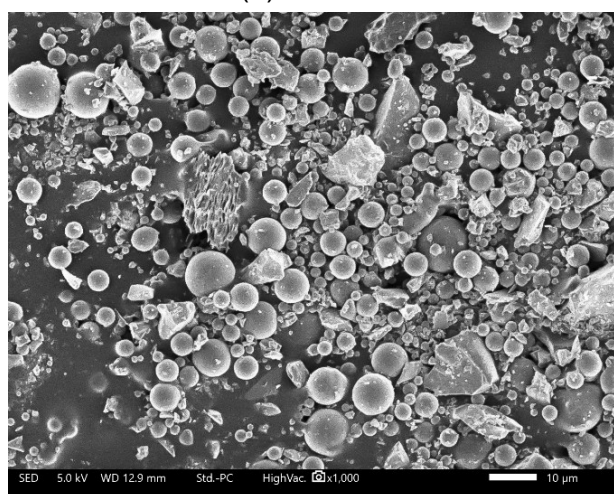
particle characteristics, and RSB functioned as a bio-based modifier with a fibrous morphology that was expected to affect the internal structure of the concrete more strongly than the mineral powders [25, 26]. This combination provided an appropriate material basis for evaluating how RSB influences the durability-related and microstructural performance of the developed concrete mixtures.



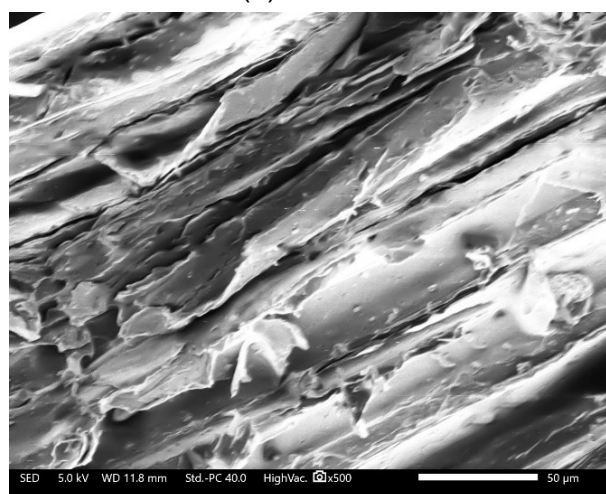
(a) Cement



(b) GGBFS



(c) FA



(d) RSB

Fig. 2. SEM images of binder materials and RSB particles

Figs. 3 and 4 briefly present the FTIR spectra and XRD patterns of the binder materials used in this study. As shown in Fig. 3, PC, GGBFS, and FA exhibited distinct FTIR features, indicating clear differences in their chemical characteristics. Cement showed representative bands near 1126, 879, and 520 cm^{-1} , while GGBFS exhibited notable bands around 927, 669, and 501 cm^{-1} [27]. FA was

characterized by prominent bands near 1072, 788, and 555 cm^{-1} , which are consistent with its more siliceous and aluminous nature. Similarly, the XRD patterns in Fig. 4 confirmed clear mineralogical differences among the three binder materials. PC showed distinct crystalline peaks mainly associated with alite, belite, calcite, and portlandite [18], whereas GGBFS exhibited a broad

amorphous hump, indicating its predominantly glassy structure. In contrast, FA showed characteristic quartz and mullite peaks. These FTIR and XRD observations are in good

agreement with the chemical composition data presented in Table 1 and confirm that the blended binder system consisted of chemically and mineralogically different materials.

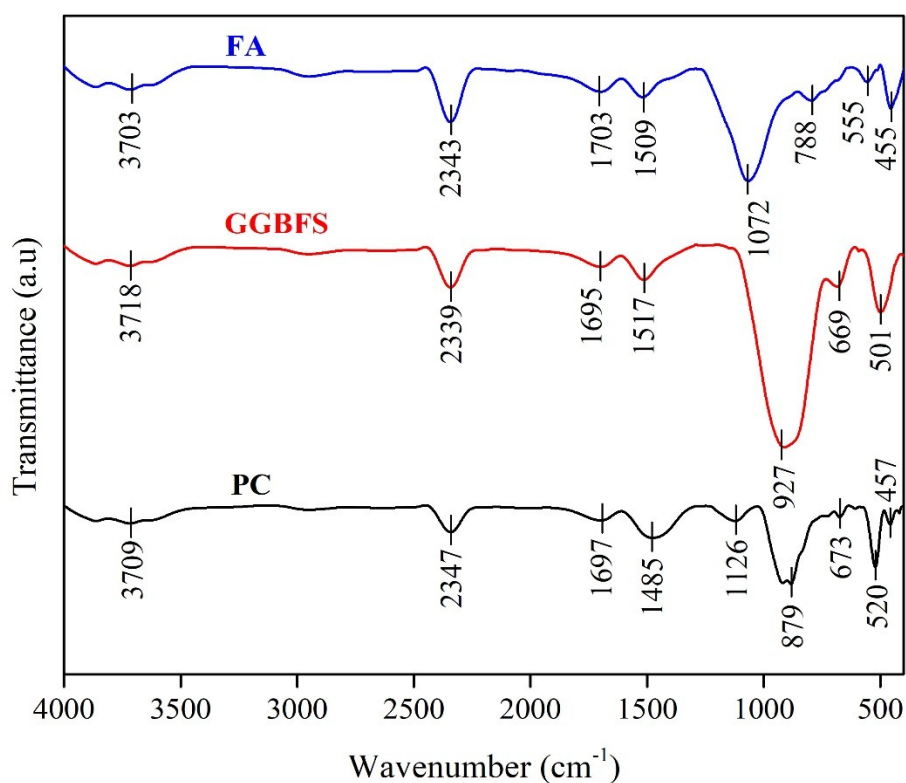


Fig. 3. FTIR spectra of binder materials

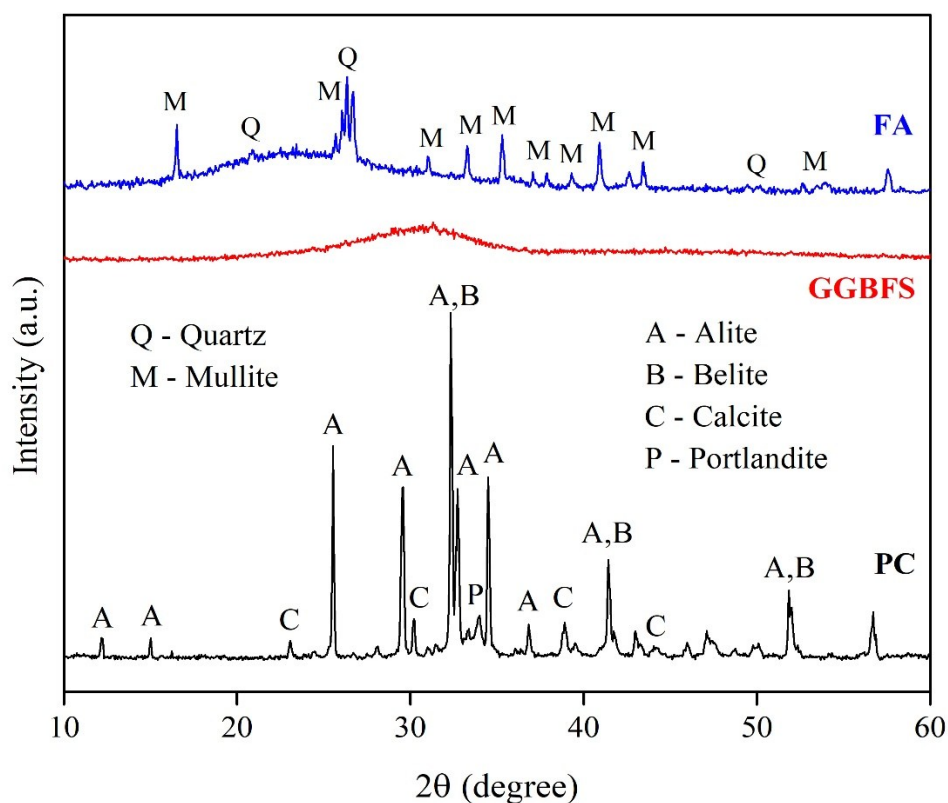


Fig. 4. XRD patterns of binder materials

Table 2. Physical properties of sand and stone

Materials	Density (kg/m ³)	Water absorption (%)	Particle size range (mm)	Fineness modulus
Sand	2770	1.31	0.14 – 5.0	3.26
Stone	2750	1.12	5 – 19	-

The physical properties of the fine and coarse aggregates used in this study are summarized in Table 2. The fine aggregate was natural sand with a density of 2770 kg/m³, water absorption of 1.31%, particle size range of 0.14 – 5.0 mm, and fineness modulus of 3.26, indicating a relatively coarse grading within the fine aggregate range. The coarse aggregate was crushed stone with a density of 2750 kg/m³, water absorption of 1.12%, and particle size range of 5 – 19 mm. The relatively close density values of sand and stone suggest good compatibility in aggregate blending, while their low water absorption values indicate limited moisture uptake during concrete production. Together, these aggregate properties provided a stable granular skeleton for evaluating the influence of RSB on the concrete mixtures.

3.2. Mixture proportions and sample preparation

The mixture proportions of the concrete specimens are presented in Table 3. A type-G high-range water-reducing admixture (superplasticizer, SP) conforming to TCVN 8826:2011 [28] was used at a constant dosage of 5.5 kg/m³ for all mixtures. The slump was measured according to TCVN 3106:2022 [29] and remained approximately 4 cm across all mixtures. The RSB was used in a saturated surface-dry (SSD) condition. This preconditioning helped minimize variations in effective water content and maintain comparable fresh-state consistency among mixtures. A total of six mixtures were prepared, including one control mixture (RSB-0.0) and five RSB-modified mixtures containing 0.5, 1.0, 1.5, 2.0, and 2.5 vol.% RSB. The binder composition was kept constant for all mixtures at 223.4 kg/m³ of cement, 173.9 kg/m³ of GGBFS, and 99.4 kg/m³ of FA. Likewise, the aggregate contents were fixed at 657.4 kg/m³ of

sand and 1112.4 kg/m³ of stone, with 173.8 kg/m³ of water and 5.5 kg/m³ of SP. The RSB was introduced as an additional bio-based modifying component rather than as a direct replacement for any specific mixture constituent. Because the binder, water, and aggregate contents were kept unchanged, increasing RSB content may influence particle packing and compaction efficiency, in addition to the intrinsic characteristics of the RSB particles. This approach was adopted to isolate the influence of RSB content on the internal structure and durability-related behavior of the concrete mixtures.

As shown in Table 3, increasing the RSB content was accompanied by a clear reduction in compressive strength. The control mixture achieved the highest compressive strength of 44.8 MPa, while the strength decreased to 29.6, 24.1, 17.2, 7.1, and 4.7 MPa for RSB contents of 0.5, 1.0, 1.5, 2.0, and 2.5 vol.%, respectively. Compared with the control mixture, these values correspond to strength reductions of approximately 33.9, 46.2, 61.6, 84.2, and 89.5%, indicating that the incorporation of RSB had a pronounced influence on the mechanical performance of the concrete. This trend also suggests that higher RSB contents substantially weakened the matrix structure, which is consistent with the durability-related results discussed later. For specimen preparation, the dry binder materials, sand, and stone were first mixed to obtain a uniform dry blend. The pre-prepared RSB was then introduced according to the target dosage, followed by the addition of water and SP. Mixing was continued until a homogeneous mixture was obtained. The fresh concrete was then cast into molds, compacted, and demolded after 24 h. After demolding, the specimens were cured under standard laboratory curing conditions until the

designated testing ages of 28 and 56 days. The prepared specimens were subsequently used for

porosity, water absorption, RCPT, FTIR, XRD, SEM, and TG/DTG analyses.

Table 3. Material proportions of concrete specimens

Mix ID.	Materials (kg/m ³)								Compressive strength (MPa)
	Cement	GGBFS	FA	Sand	Stone	Water	SP	RSB	
RSB-0.0	223.4	173.9	99.4	657.4	1112.4	173.8	5.5	0.0	44.8
RSB-0.5	223.4	173.9	99.4	657.4	1112.4	173.8	5.5	7.5	29.6
RSB-1.0	223.4	173.9	99.4	657.4	1112.4	173.8	5.5	15.0	24.1
RSB-1.5	223.4	173.9	99.4	657.4	1112.4	173.8	5.5	22.6	17.2
RSB-2.0	223.4	173.9	99.4	657.4	1112.4	173.8	5.5	30.1	7.1
RSB-2.5	223.4	173.9	99.4	657.4	1112.4	173.8	5.5	37.6	4.7

3.3. Test methods

The durability-related and microstructural properties of the concrete specimens were evaluated through porosity, water absorption, rapid chloride ion penetration (RCPT), FTIR, XRD, SEM, and TG/DTG tests. Compressive strength was determined at 28 days on 100 × 100 × 100 mm cube specimens in accordance with TCVN 3118:2022 [30], and the measured values are reported in Table 3 to provide a general mechanical reference for interpreting the durability-related and microstructural results. Unless otherwise stated, all specimens were cured in water at 20 ± 2 °C until the designated testing age. For each mixture and test condition, at least three specimens were used to improve the reliability of the reported results. Porosity and water absorption were determined on 100 × 100 × 100 mm cube specimens using a procedure adapted from ASTM C642-21 [31]. The specimens were first oven-dried at 105 ± 5 °C to constant mass, cooled to room temperature, and then immersed in water until saturation. The dry mass, saturated mass, and submerged mass were recorded, and the corresponding porosity and water absorption values were calculated.

RCPT testing was carried out according to ASTM C1202-25 [32] using disk specimens of 100 mm diameter and 50 mm thickness, cut from 100 × 200 mm concrete cylinders at the testing age. Before testing, the disks were vacuum-saturated

for 24 h. Each specimen was mounted between 3% NaCl solution and a 0.3 N NaOH solution, and a constant voltage of 60 V DC was applied for 6 h. The current was recorded every 30 min, and the total charge passed was calculated from the recorded current history. For microstructural characterization, hydration was stopped at the selected age by immersing crushed specimens in isopropanol for 24 h, followed by drying at 40 °C. SEM observations were conducted on gold-coated fragments under high vacuum at an accelerating voltage of 5 kV. XRD analysis was performed on powdered samples smaller than 75 µm using Cu Kα radiation over a scan range of 10–60° 2θ, with a step size of 0.02° and a scan speed of 2°/min. FTIR spectra were collected in the range of 4000–400 cm⁻¹ using the KBr pellet technique at a resolution of 4 cm⁻¹. TG/DTG analysis was conducted on approximately 30–40 mg of powdered sample by heating from room temperature to 900 °C at a constant rate of 10 °C/min under a nitrogen atmosphere to evaluate mass-loss behavior and thermal decomposition characteristics.

4. Results and discussion

4.1. Porosity and water absorption

Fig. 5 shows that the porosity of the concrete increased consistently with increasing RSB content at both curing ages, indicating that the incorporation of RSB progressively weakened matrix compactness and promoted a more open

internal pore structure. At 28 days, the control mixture (RSB-0.0) exhibited the lowest porosity of 9.24%, whereas mixtures containing RSB showed markedly higher values of 11.15%, 12.97%, 16.03%, 18.15%, and 21.74% for RSB contents of 0.5, 1.0, 1.5, 2.0, and 2.5 vol.%, respectively. Relative to the control, these values correspond to porosity increases of approximately 20.7, 40.4, 73.5, 96.4, and 135.3%, confirming a strong dose-dependent deterioration in pore structure. A similar trend was maintained at 56 days, where porosity rose from 8.17% for RSB-0.0 to 9.99, 12.24, 14.21, 16.72, and 20.18% for the RSB-modified mixtures, representing increases of about 22.3, 49.8, 73.9, 104.7, and 147.0%, respectively, compared with the control. These results indicate that the adverse effect of RSB on porosity persisted even after prolonged curing.

Aging from 28 to 56 days reduced porosity in all mixtures, reflecting continued hydration and the gradual filling or refinement of capillary voids. However, the magnitude of reduction was relatively limited, especially at higher RSB contents. The control mixture showed a porosity reduction from 9.24 to 8.17%, equivalent to about 11.6%, while the decreases for RSB-0.5, RSB-1.0, RSB-1.5, RSB-2.0, and RSB-2.5 were approximately 10.4, 5.6, 11.4, 7.9, and 7.2%, respectively. This suggests that although later-age hydration improved the matrix to some extent, it could not fully compensate for the voids introduced by RSB incorporation. The increase in porosity with increasing RSB content may be associated with the less compact internal structure of mixtures containing bio-based particles. This effect resulted mainly from packing disturbance and internal pore development, while the influence of workability variation was limited under the controlled fresh-state conditions adopted in this study. This behavior can be attributed to the intrinsic characteristics of lignocellulosic particles, which typically exhibit lower stiffness, irregular geometry, and relatively high internal porosity compared with mineral aggregates. These

characteristics may locally disturb particle packing and create interfacial discontinuities between the organic particles and the surrounding cementitious matrix, thereby promoting the formation of additional voids and increasing overall pore connectivity. At low RSB contents, this effect remained limited, whereas beyond 1.0–1.5 vol.% the rise in porosity became more pronounced, suggesting a progressive loss of matrix densification. The observed increase in porosity with increasing RSB content is broadly in line with the dosage-sensitive behavior reported by Anandaraj et al. [20] for sugarcane bagasse fiber in concrete.

Fig. 6 shows that water absorption increased steadily with increasing RSB content at both curing ages, indicating that the incorporation of RSB reduced the resistance of the concrete to water uptake. At 28 days, the control mixture (RSB-0.0) exhibited the lowest water absorption of 3.93%, while the RSB-modified mixtures recorded higher values of 4.92%, 5.81%, 7.44%, 8.85%, and 10.59% for RSB contents of 0.5, 1.0, 1.5, 2.0, and 2.5 vol.%, respectively. Compared with the control, these values represent increases of approximately 25.2, 47.8, 89.3, 125.2, and 169.5%, confirming a strong dose-dependent rise in water absorption. A similar pattern was observed at 56 days, where water absorption increased from 3.56% for RSB-0.0 to 4.32%, 5.49%, 6.53%, 7.64%, and 9.75% for the mixtures containing RSB, corresponding to increases of about 21.3, 54.2, 83.4, 114.6, and 173.9%, respectively, relative to the control. These results indicate that the effect of RSB on water absorption remained clear even after extended curing.

From 28 to 56 days, water absorption decreased in all mixtures, suggesting that continued curing improved the internal structure to some extent and reduced the accessibility of water into the matrix. The control mixture showed a reduction from 3.93 to 3.56%, equivalent to about 9.4%, while the reductions for RSB-0.5, RSB-1.0, RSB-1.5, RSB-2.0, and RSB-2.5 were

approximately 12.2, 5.5, 12.2, 13.7, and 7.9%, respectively. However, despite this general improvement with age, the water absorption of the RSB mixtures remained substantially higher than that of the control, particularly at dosages above 1.0–1.5 vol.%. This trend is broadly consistent with

the dosage-dependent durability behavior reported by Sankeeth et al. [10] and with the observations of Zúniga et al. [22], indicating that excessive incorporation of sugarcane-derived materials can increase moisture-related vulnerability and reduce long-term durability performance.

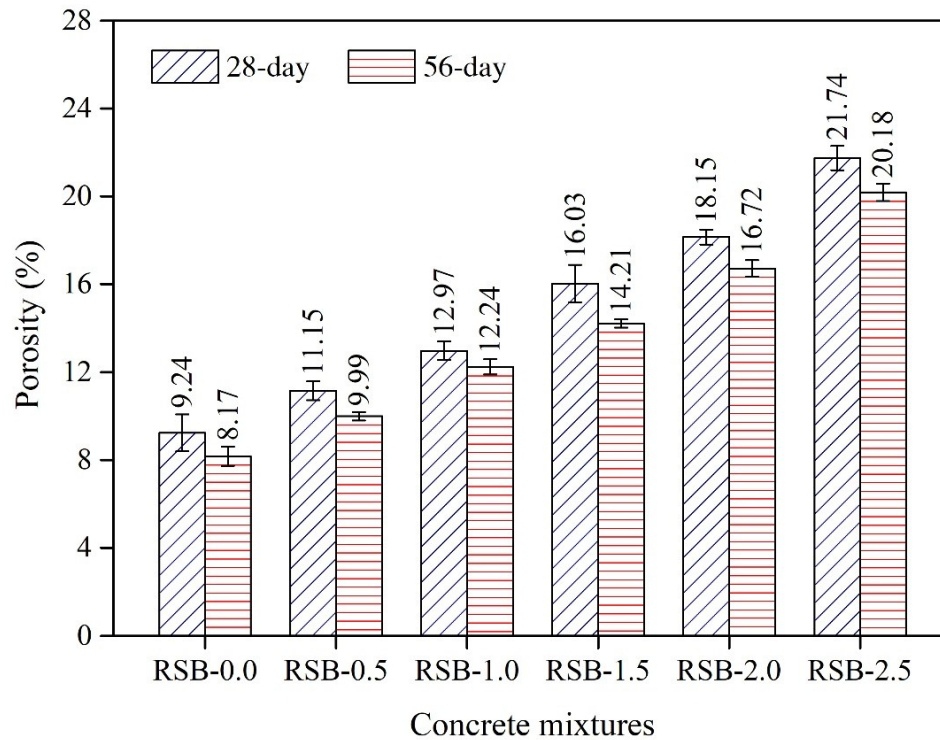


Fig. 5. Porosity of concrete specimens

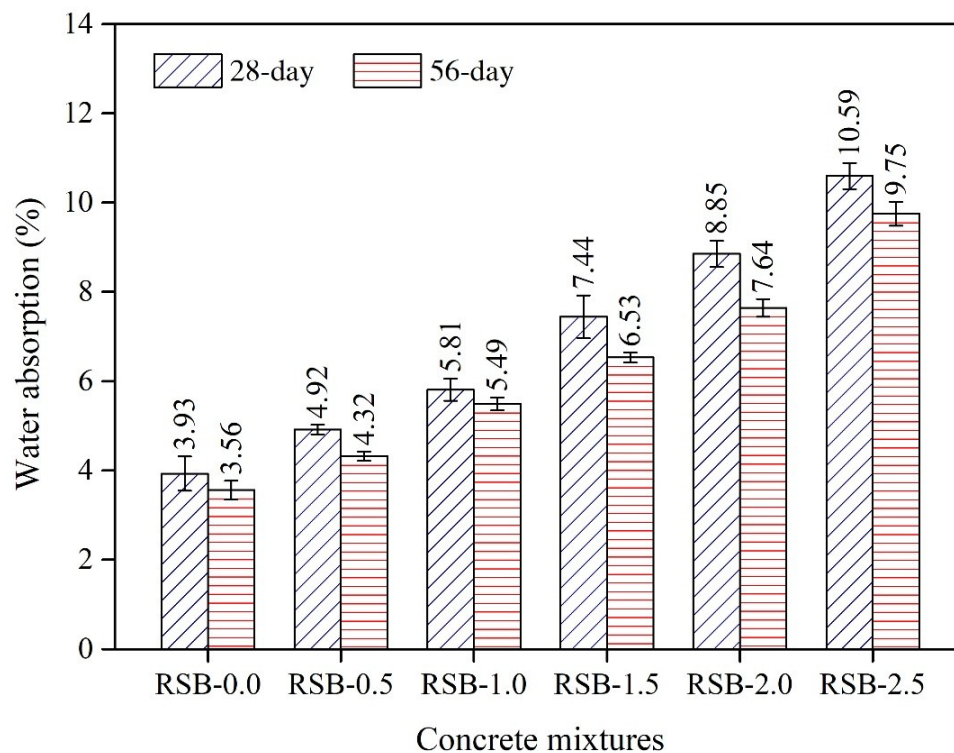


Fig. 6. Water absorption of concrete specimens

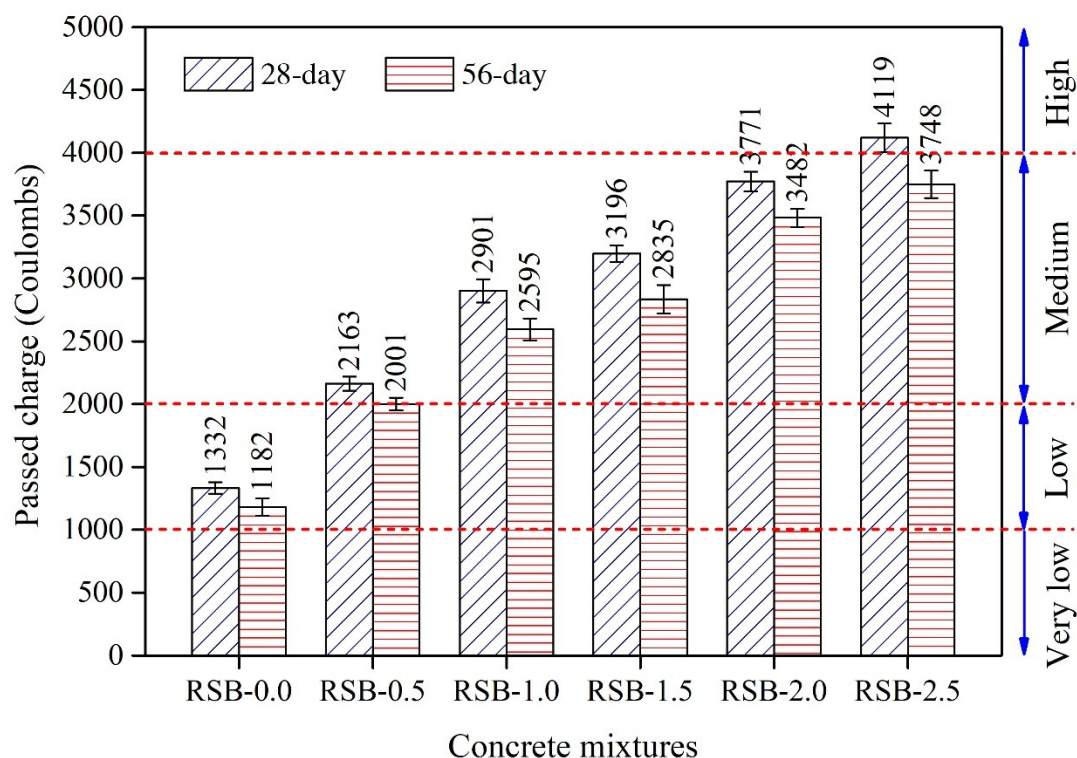


Fig. 7. RCPT of concrete specimens

4.2. Rapid chloride ion penetration

Fig. 7 shows that the charge passed increased consistently with increasing RSB content at both curing ages, indicating a progressive reduction in resistance to chloride ion penetration as the RSB content increased. At 28 days, the control mixture (RSB-0.0) recorded the lowest charge passed of 1332 Coulombs, whereas the mixtures containing RSB showed substantially higher values of 2163, 2901, 3196, 3771, and 4119 Coulombs for RSB contents of 0.5, 1.0, 1.5, 2.0, and 2.5 vol.%, respectively. Relative to the control, these values represent increases of approximately 62.4, 117.8, 139.9, 183.1, and 209.2%, confirming a strong dose-dependent increase in chloride penetrability. A similar pattern was observed at 56 days, where the charge passed increased from 1182 Coulombs for RSB-0.0 to 2001, 2595, 2835, 3482, and 3748 Coulombs for the RSB-modified mixtures, corresponding to increases of about 69.3, 119.5, 139.8, 194.6, and 217.1%, respectively, compared with the control. These results show that the influence of RSB on chloride penetration remained pronounced even after

extended curing.

From 28 to 56 days, the charge passed decreased in all mixtures, suggesting that continued curing improved the internal structure and reduced ionic transport to some extent. The control mixture showed a reduction from 1332 to 1182 Coulombs, equivalent to about 11.3%, while the reductions for RSB-0.5, RSB-1.0, RSB-1.5, RSB-2.0, and RSB-2.5 were approximately 7.5, 10.5, 11.3, 7.7, and 9.0%, respectively. Although this later-age reduction is meaningful, the RCPT values of the RSB mixtures remained markedly higher than those of the control at both ages, especially when the RSB content exceeded 1.0–1.5 vol.%. This trend is consistent with the porosity and water absorption results and suggests that increasing RSB content led to a less dense internal structure and greater ease of ion transport through the concrete. In terms of ASTM C1202-25 [32] classification, RSB-0.0 remained within the low chloride penetrability range at both ages, RSB-0.5 was in the moderate range, RSB-1.0 to RSB-2.0 remained largely within the moderate range, and RSB-2.5 reached the high penetrability range at 28

days before decreasing to the upper moderate range at 56 days. This classification further indicates that higher RSB contents were associated with a clear decline in durability-related resistance to chloride ingress. Taken together, the porosity, water absorption, and RCPT results indicate that RSB content primarily affected the accessibility and continuity of the internal pore network. This pore-structure evolution is also consistent with the reduction in compressive strength observed with increasing RSB content, as

a less compact and more connected pore network reduces the load-bearing capacity of the matrix while simultaneously facilitating moisture and ionic transport. The consistent deterioration observed across all three indicators suggests that the loss of matrix compactness was not localized but was sufficiently developed to influence both moisture uptake and ionic transport. This is an important finding because it links the durability-related response of the concrete to a common structural origin rather than to isolated test outcomes.

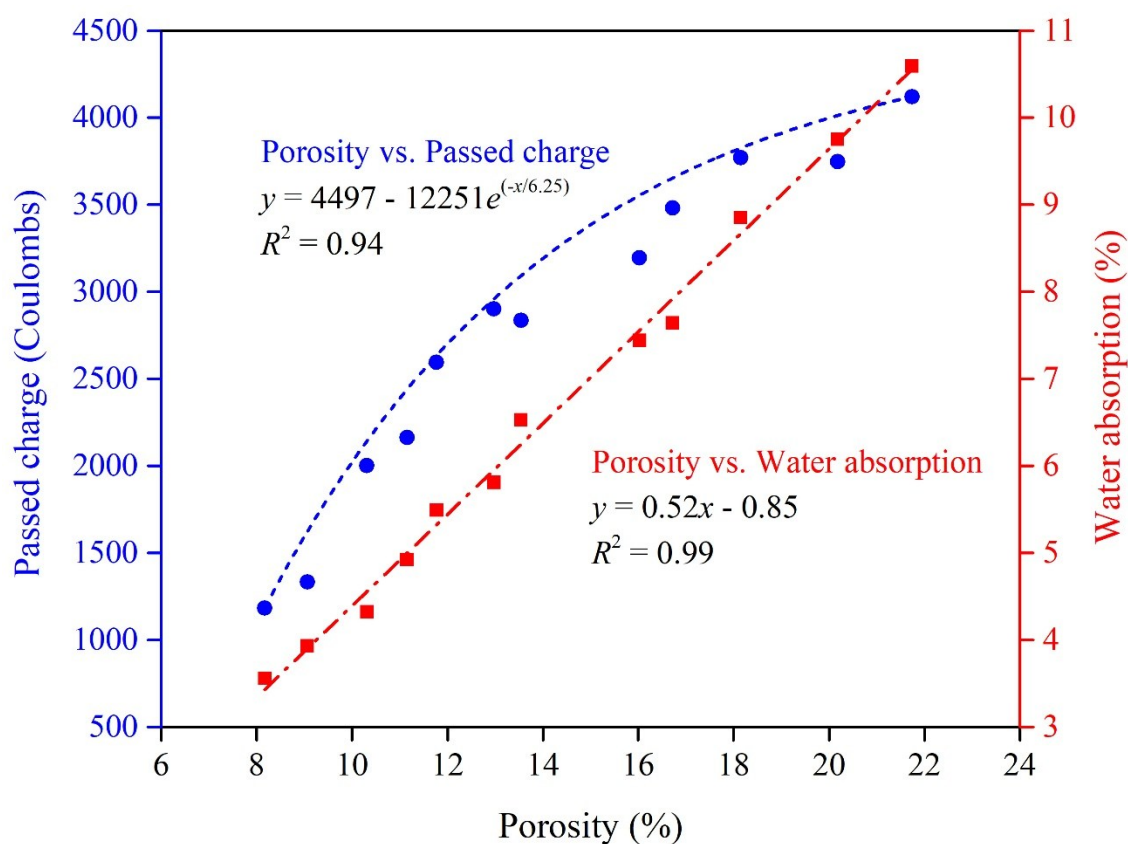


Fig. 8. Correlation among porosity, water absorption, and RCPT of concrete specimens

The relationship between porosity, water absorption, and chloride penetrability is shown in Fig. 8. The correlation analysis indicates that porosity was closely related to both water absorption and charge passed, highlighting the important role of pore structure in controlling transport-related durability properties. As porosity increased, water absorption increased almost linearly, as described by the regression equation $y = 0.52x - 0.85$ with a very high coefficient of determination ($R^2 = 0.99$), indicating a strong

proportional relationship between pore volume and water uptake. In contrast, the relationship between porosity and charge passed followed a nonlinear trend, with the exponential model $y = 4497 - 12251e^{-x/6.25}$ providing a good fit ($R^2 = 0.94$). This suggests that chloride penetrability became more sensitive to porosity as the pore structure became increasingly open. These results are consistent with the trends observed in Figs. 5–7 and indicate that the increase in porosity associated with higher RSB contents was reflected in higher water

absorption and greater chloride penetrability.

4.3. FTIR analysis

Fig. 9 presents the FTIR spectra of the concrete mixtures containing different RSB contents. In general, all mixtures exhibited similar spectral profiles, indicating that the incorporation of RSB did not fundamentally change the main chemical framework of the cementitious matrix. Nevertheless, some comparative differences can still be observed in the intensity and clarity of the characteristic bands at 1416, 986, 787, 528, and 465 cm^{-1} . The band near 1416 cm^{-1} , commonly associated with carbonate-related vibration [33], was present in all mixtures, but its feature appeared slightly broader and less distinct as the RSB content increased, particularly in the higher-RSB mixtures. Likewise, the band near 986 cm^{-1} , typically assigned to silicate-related vibration in cementitious products [2], was visible throughout the series, but its prominence was clearer in the control and lower-RSB mixtures and became somewhat weaker in the mixtures with 2.0–2.5 vol.% RSB. These observations suggest that although the same main functional groups remained present, the relative expression of some cementitious features became less pronounced at higher RSB contents.

A similar tendency was observed in the lower wavenumber region. The bands around 787, 528, and 465 cm^{-1} were detected in all mixtures [34, 35], confirming that the main mineral-related features remained generally preserved; however, the peaks tended to appear less sharp and slightly less intense in the mixtures with higher RSB contents than in RSB-0.0 and RSB-0.5. In particular, the spectral features of RSB-2.0 and RSB-2.5 appeared more subdued than those of the control mixture, while the intermediate mixtures showed a gradual transition between these two conditions. Since no major peak shift or new absorption band was observed, the FTIR results do not indicate the formation of a fundamentally different chemical system. The slight weakening and lower definition

of the characteristic bands at higher RSB contents may be associated with a less distinct expression of cementitious-related features in the hardened matrix. This trend is consistent with the increased porosity and the reduced resistance to water and chloride transport observed in the durability-related tests. This interpretation is broadly consistent with the findings of Hamcumpai et al. [14] for sugarcane-derived ash systems; however, those results are used here only as supporting literature because the present study investigates directly incorporated RSB rather than SCBA.

4.4. XRD analysis

Fig. 10 shows that all mixtures exhibited generally similar XRD patterns, indicating that the main crystalline phases remained broadly comparable after RSB incorporation. The identified phases included alite (A), mullite (M), calcite (C), and quartz (Q), with quartz-related peaks appearing at several positions across the scanned range [36]. The quartz peak near approximately $20^\circ 2\theta$ was visible in all mixtures without major variation in intensity, suggesting that this phase remained relatively stable throughout the series. In contrast, clearer differences were observed in the region around $26\text{--}30^\circ 2\theta$. The quartz peak near approximately 26.6° appeared strongest in RSB-0.5 and remained visible in the other RSB mixtures, whereas the control mixture and some higher-RSB mixes showed comparatively lower intensity. A neighboring alite-related peak in the same region was also more pronounced in RSB-0.5 and, to some extent, RSB-1.0, but became less distinct at higher RSB contents. Similarly, the calcite peak around $29.4^\circ 2\theta$ was most evident in RSB-0.5, while the other mixtures showed weaker or more comparable expression [37]. These observations suggest that the lower-RSB mixtures, especially RSB-0.5, retained sharper crystalline features in the main diffraction region.

Further differences were observed for the minor phases. The mullite-related peak near approximately $18^\circ 2\theta$ was not clearly expressed in

RSB-0.0, became more noticeable in RSB-0.5 and RSB-1.0, and then appeared less evident again at higher RSB contents, particularly in RSB-2.5. By contrast, the quartz peaks at higher angles, roughly between 37° and 51° 2θ , remained broadly similar among all mixtures, indicating limited variation in those crystalline components. Overall, the XRD results suggest that RSB addition did not introduce a fundamentally different phase assemblage, since the same major phases were still observed in all mixtures. However, the sharper and more pronounced peaks in the lower-RSB mixtures,

particularly RSB-0.5 and partly RSB-1.0, suggest clearer diffraction features within the tested range. This observation is consistent with their lower porosity and improved resistance to chloride penetration, although XRD alone does not directly quantify matrix compactness. This interpretation is broadly in line with the findings of Hamcumpai et al. [14] and Tejas and Pasla [5], who showed that sugarcane-derived additions can influence phase development and matrix quality in a dosage-dependent manner, while the overall crystalline framework remains generally comparable.

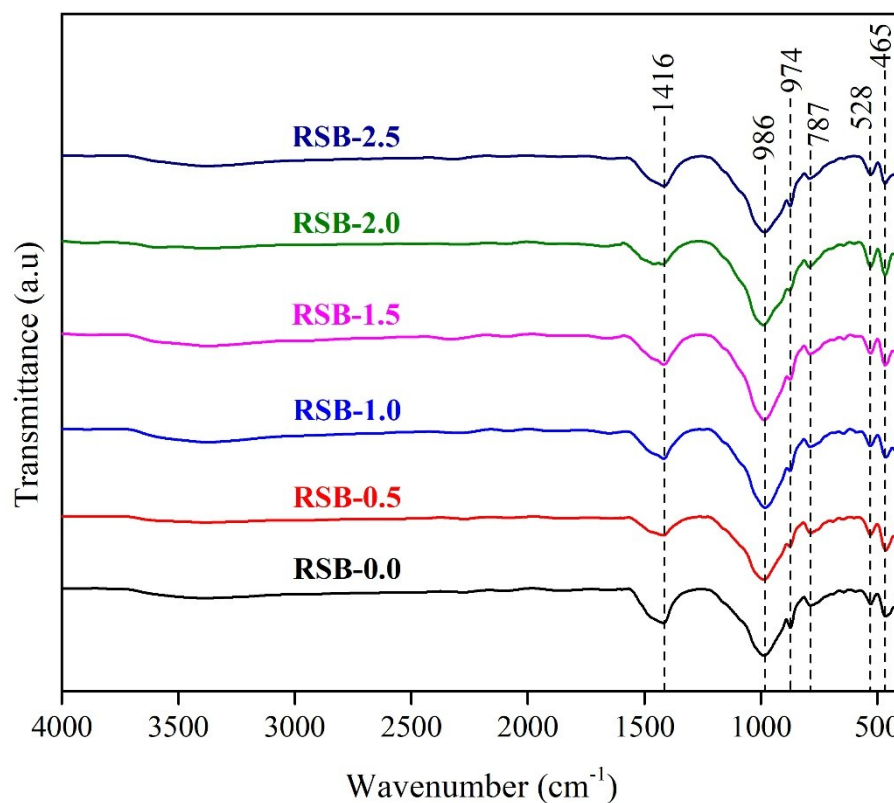


Fig. 9. FTIR spectra of concrete specimens

4.5. SEM observation

Fig. 11 shows a progressive change in microstructure with increasing RSB content. The control mixture, RSB-0.0 (Fig. 11a), exhibited the densest and most continuous matrix among the six specimens, with relatively compact solid phases, limited visible voids, and a more integrated texture. In RSB-0.5 (Fig. 11b), the matrix remained generally compact, but several rounded features and local discontinuities became more noticeable than in the control, suggesting the beginning of

microstructural heterogeneity. RSB-1.0 (Fig. 11c) still showed a relatively coherent matrix, although more elongated and irregular features could be seen embedded within the surrounding structure, giving the micrograph a rougher and less uniform appearance than RSB-0.0. Compared with RSB-0.5, the RSB-1.0 image appeared less dominated by rounded voids but more characterized by non-uniform internal features and local separation within the matrix. As the RSB content increased further, the loss of compactness became more

evident. In RSB-1.5 (Fig. 11d), the matrix appeared visibly more open than in the lower-RSB mixtures, with clearer pore spaces, a rougher surface texture, and more frequent discontinuities between adjacent solid regions. In RSB-2.0 (Fig. 11e), this trend became stronger, as large irregular solid features and more pronounced gaps could be

seen, indicating a less continuous and less densely packed microstructure. The most disrupted morphology was observed in RSB-2.5 (Fig. 11f), where a large open region, fractured-looking internal texture, and strongly heterogeneous arrangement were clearly visible, making it the least compact specimen in the series.

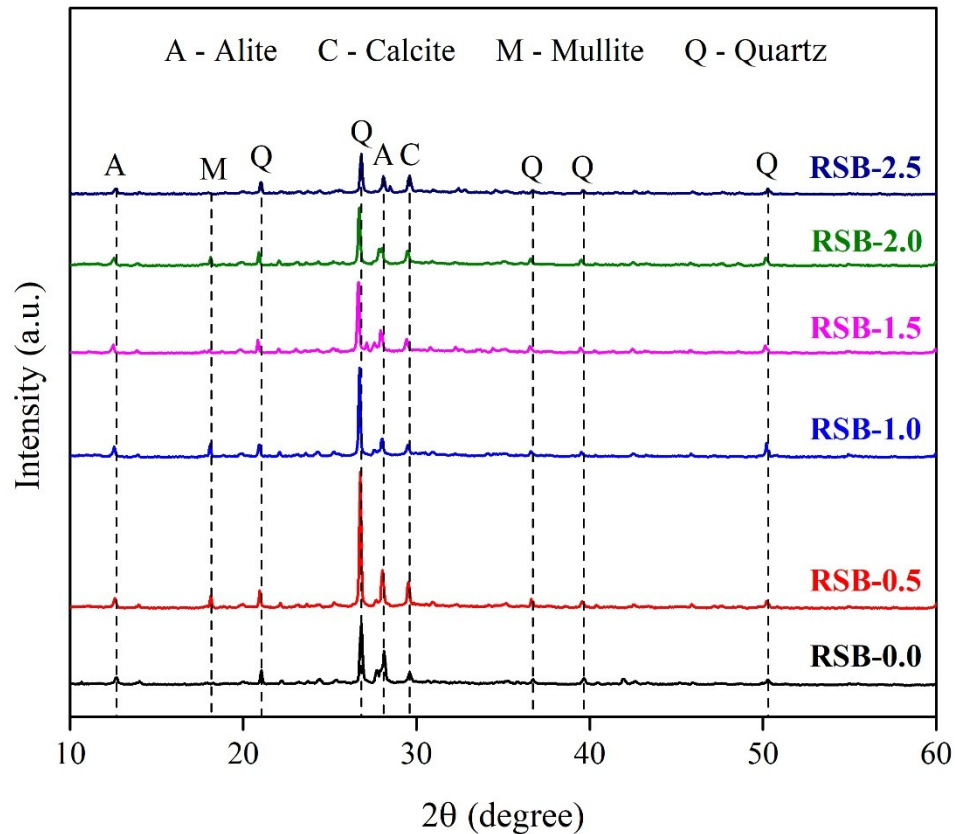
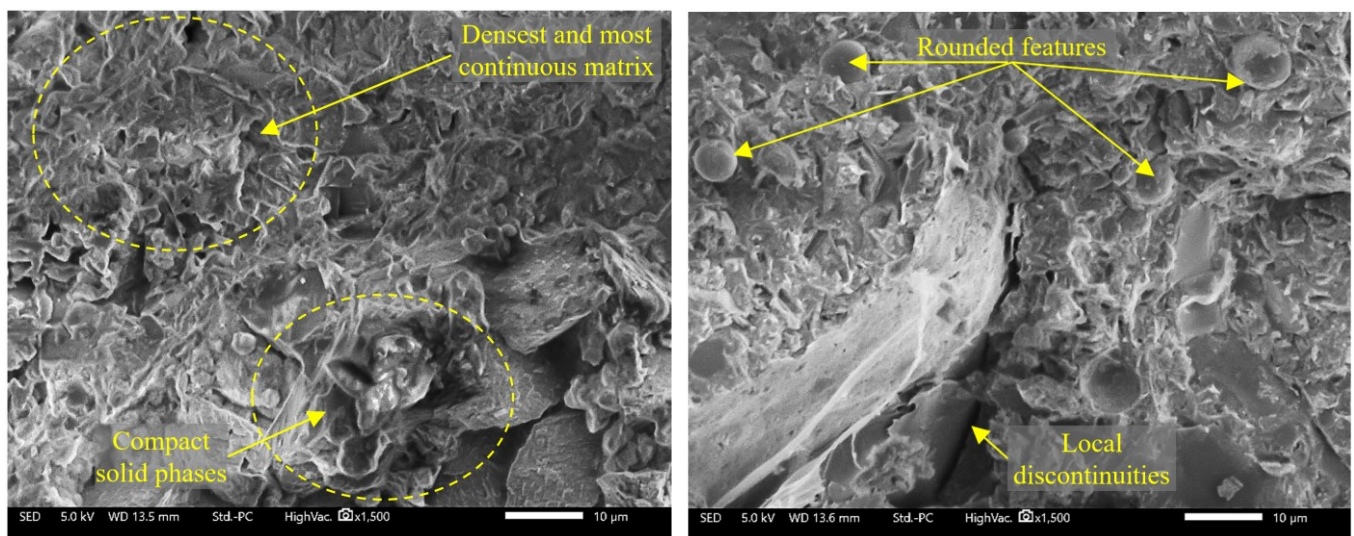


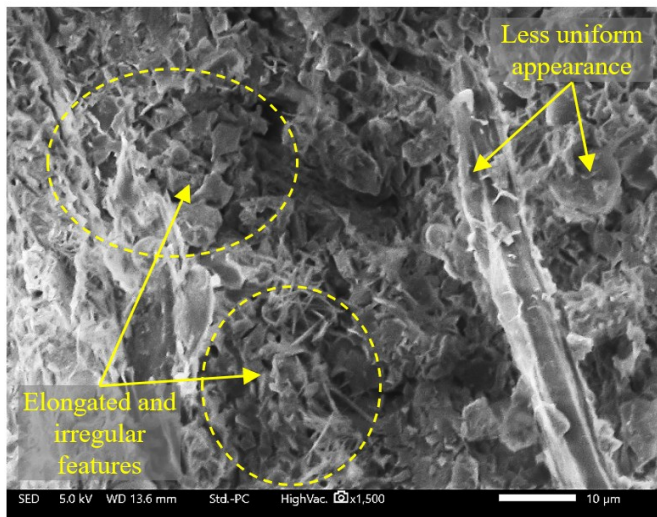
Fig. 10. XRD patterns of concrete specimens



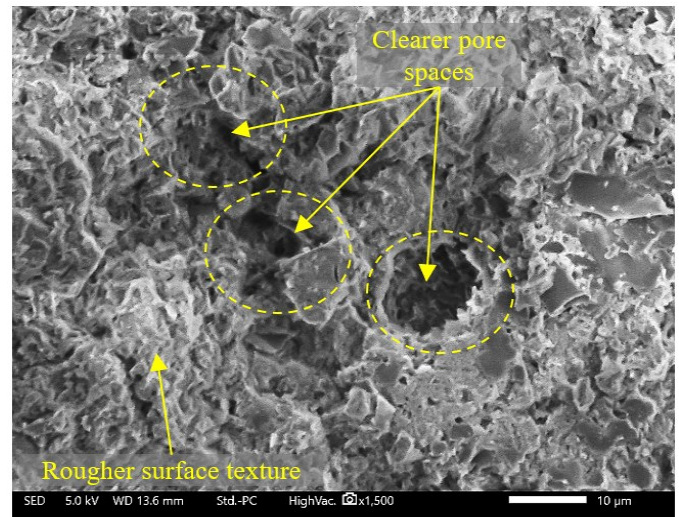
(a) RSB-0.0

(b) RSB-0.5

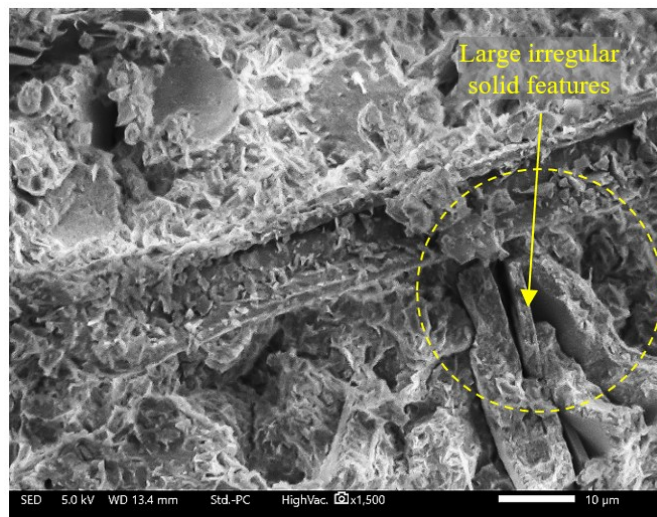
Fig. 11. SEM micrographs of concrete specimens



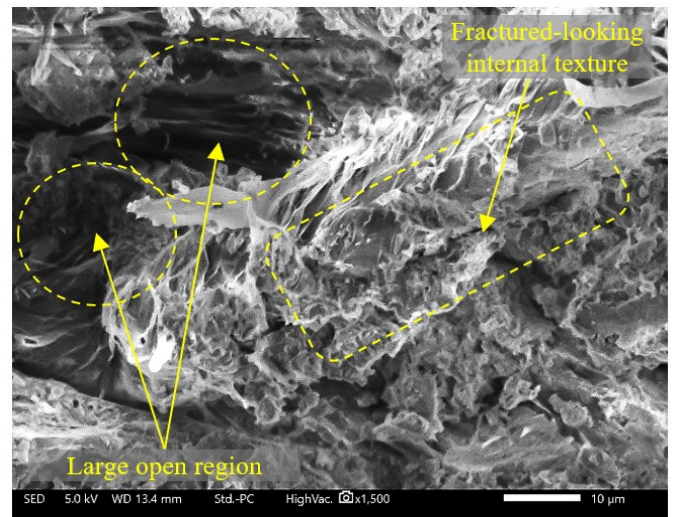
(c) RSB-1.0



(d) RSB-1.5



(e) RSB-2.0



(f) RSB-2.5

Fig. 11. (continued)

When Figs. 11a–f are compared together, the micrographs suggest a gradual transition from the relatively dense matrix of RSB-0.0 to the increasingly porous, discontinuous, and heterogeneous structure of RSB-1.5 to RSB-2.5, while RSB-0.5 and RSB-1.0 represent intermediate conditions. This visual evolution agrees well with the earlier porosity, water absorption, and RCPT results, which also showed that higher RSB contents were associated with a less dense internal structure and reduced durability-related performance. This interpretation is also broadly consistent with the findings of Hamcumpai et al. [14], who reported that low contents of sugarcane-derived ash promoted a denser and more uniform

matrix, whereas excessive content resulted in more voids, unreacted particles, and reduced compactness. It should be noted that the present SEM observations are qualitative and are intended to support the macroscopic durability trends rather than to provide a quantitative pore-structure analysis.

4.6. TG/DTG analysis

Fig. 12 shows that the incorporation of RSB changed both the decomposition pattern and the mass-loss distribution of the concrete specimens. The control mixture, RSB-0.0 (Fig. 12a), exhibited three main DTG peaks at 97.03, 436.47, and 678.51°C, with mass losses of 5.58, 1.93, and 7.52%, respectively, giving the highest total mass

loss of 15.03%. After RSB incorporation, the thermal behavior changed progressively. RSB-0.5, RSB-1.0, and RSB-1.5 (Figs. 12b–d) still showed three main decomposition stages, but the intermediate-temperature region became more pronounced. For example, RSB-0.5 showed a mass loss of 6.78% near 547.71°C, compared with only 1.93% near 436.47°C for the control, while RSB-1.0 and RSB-1.5 showed similar

intermediate-temperature peaks near 621.47 and 619.11°C, respectively. In contrast, RSB-2.0 and RSB-2.5 (Figs. 12e and 12f) exhibited four-stage decomposition behavior, with additional peaks appearing near 323–325°C and 565–566°C. Their total mass losses, 10.51 and 11.02%, were lower than those of the control, but the decomposition pattern became more distributed and more complex.

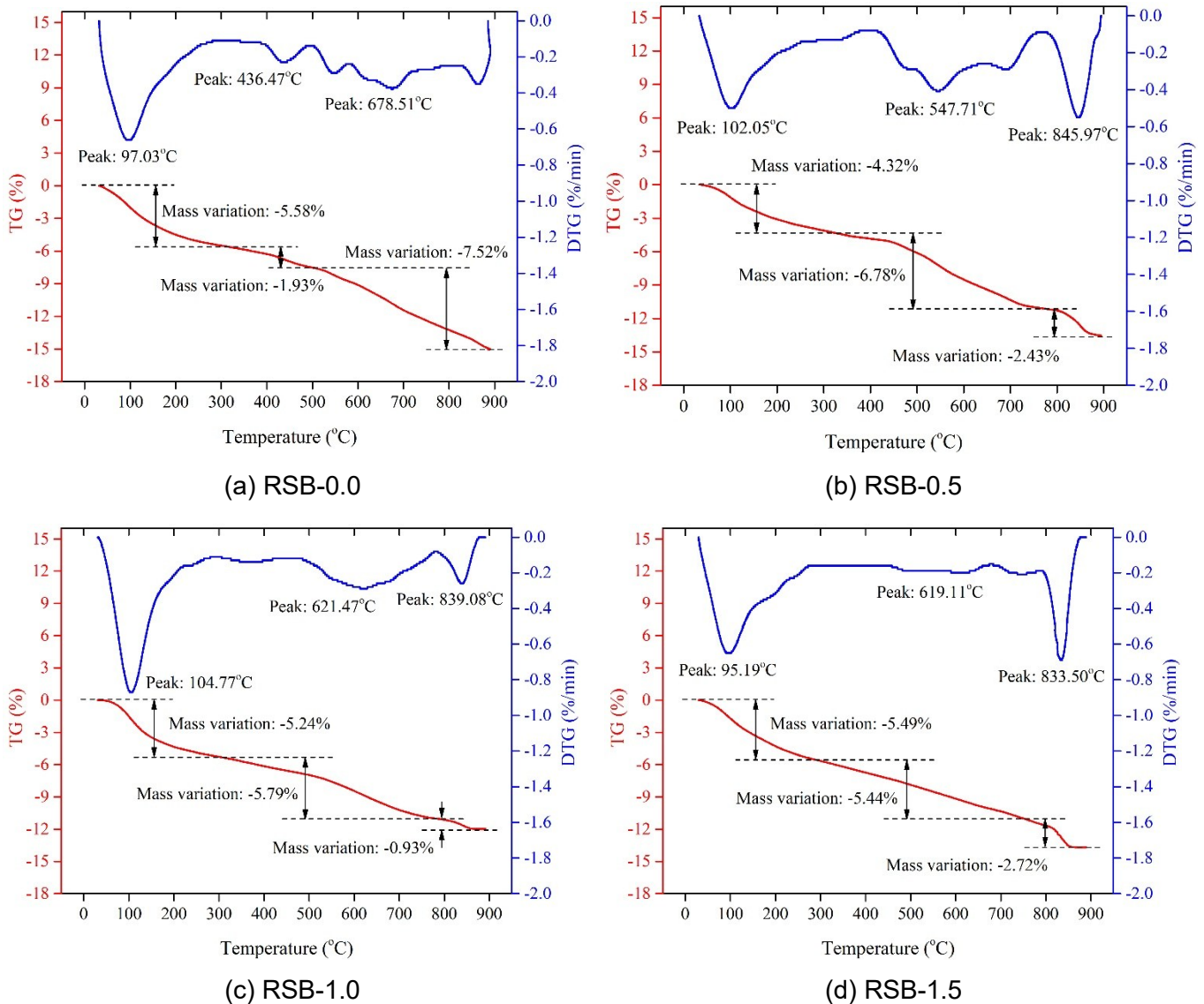


Fig. 12. TG/DTG analysis of concrete specimens

A comparison of Figs. 12a–f indicates that increasing RSB content did not simply increase or decrease total mass loss, but rather redistributed the decomposition behavior across the temperature range [5]. Therefore, the TG/DTG results should be interpreted mainly in terms of

shifts in decomposition pattern and thermal-event distribution, rather than through total mass loss alone. In the low-temperature region, the initial mass loss near 95–106°C was mainly associated with the removal of free or physically bound water and dehydration of hydration products, as

commonly reported in TG/DTG studies of cementitious materials. The mass loss observed in the temperature range of approximately 400–520°C can generally be associated with the dehydroxylation of portlandite ($\text{Ca}(\text{OH})_2$), while the region above about 520–700°C corresponds mainly to the decarbonation of CaCO_3 [38, 39]. In the present study, the control mixture showed a

more concentrated high-temperature decomposition stage, whereas the low-to-moderate RSB mixtures showed stronger intermediate-temperature decomposition. At higher RSB contents, the emergence of four-stage decomposition suggests a more heterogeneous internal matrix and a more distributed thermal response.

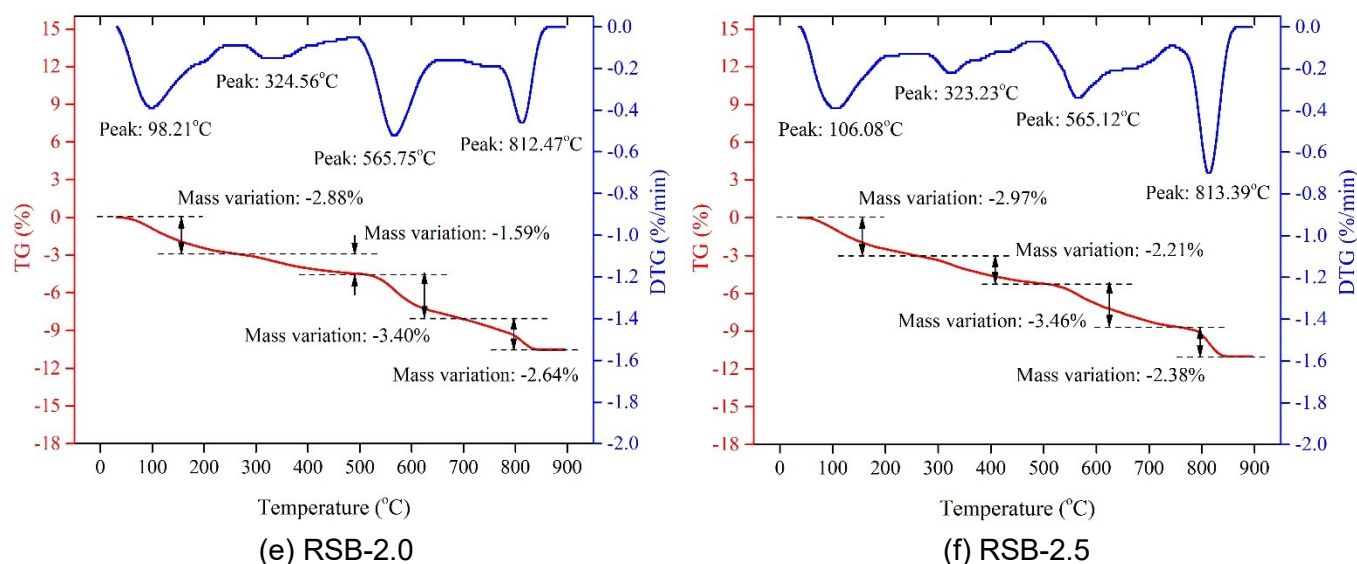


Fig. 12. (continued)

This interpretation agrees well with the SEM observations, which showed a progressively more irregular and discontinuous morphology with increasing RSB content, and it is also consistent with the porosity, water absorption, and RCPT results indicating reduced matrix compactness and durability-related performance at higher RSB contents. These findings are broadly consistent with the view that changes in thermal decomposition pattern reflect modifications in the internal constitution of sugarcane-derived cementitious systems, although the present TG/DTG results are interpreted qualitatively [5].

5. Conclusions

This study evaluated the influence of RSB on the durability-related performance and microstructural characteristics of concrete. Based on the experimental results, the following conclusions are drawn:

Increasing RSB content progressively

reduced the resistance of concrete to fluid and ionic transport, as reflected by simultaneous increases in porosity, water absorption, and chloride penetrability. Higher RSB contents led to marked increases in porosity, water absorption, and chloride penetrability at both 28 and 56 days, indicating a clear loss of matrix compactness and a greater susceptibility to moisture and chloride ingress.

The durability indicators were strongly interrelated. Water absorption increased almost linearly with porosity, while chloride penetrability also rose with increasing porosity, indicating that pore-structure development was closely associated with the resistance of the tested concretes to water and ionic transport.

Microstructural analyses generally supported the durability results. FTIR and XRD showed that the main chemical and crystalline features of the cementitious matrix were retained after RSB

incorporation, although several characteristic bands and peaks became less distinct at higher RSB contents. SEM further revealed a gradual transition from a relatively dense and continuous matrix in the control mixture to a more porous, discontinuous, and heterogeneous structure in mixtures with elevated RSB contents. TG/DTG results also indicated that high RSB contents altered the thermal decomposition pattern and were associated with a more heterogeneous internal constitution.

When all results are considered together, RSB contents above approximately 1.0–1.5 vol.% caused a clear deterioration in matrix compactness and in resistance to water and chloride ingress. In contrast, lower dosages, particularly 0.5–1.0 vol.%, caused less severe deterioration than higher RSB contents and therefore represent the more technically feasible range among the mixtures investigated in this study. This range may be considered a preliminary practical dosage window for applications requiring moderate durability performance under similar material and curing conditions.

Based on the overall findings, the most technically feasible RSB content range in this study is 0.5–1.0 vol.%, although measurable strength loss still occurred relative to the control mixture. However, this conclusion is limited to the specific RSB source, treatment procedure, mixture composition, and laboratory exposure conditions considered herein. Future studies should examine source variability, pretreatment conditions, particle-size characteristics, and long-term durability under more aggressive service environments in order to confirm the broader applicability of this dosage range.

Declaration of Generative AI

During the preparation of this work, the authors did not use Generative AI and AI-assisted technology tools in order to generate the content of the manuscript.

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