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A review of recycled micro-powder concrete: material treatment, performance and mechanism

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ABSTRACT

Recycled micro-powder (RP), composed primarily of recycled concrete powder and recycled brick powder derived from construction and demolition waste, has emerged as a promising sustainable supplementary cementitious material in concrete production. Owing to its inherent pozzolanic reactivity and micro-filler effect, RP contributes to refining pore structures and enhancing both the fresh and hardened properties of cement-based materials. This review provides a comprehensive overview of the physicochemical characteristics and hydration potential of RP, critically evaluating its effects on workability, mechanical performance, and durability. Furthermore, the environmental and economic implications of RP utilization are discussed, emphasizing its potential to reduce energy consumption, lower carbon emissions, and conserve natural resources. Finally, key research gaps are identified, and future directions are proposed to advance the practical application of RP in developing low-carbon, sustainable concrete.

1. Introduction

The rapid pace of urbanization and the continued expansion of the construction industry have led to an unprecedented demand for concrete, now the most widely used construction material globally. In China alone, the annual production of concrete is estimated to exceed 20 billion tons (Mehta and Meryman, 2009), with Portland cement serving as the primary binder. However, cement manufacturing is both energy-intensive and environmentally damaging, accounting for a significant share of global carbon dioxide (CO_2) emissions. Consequently, it is widely recognized as a major contributor to anthropogenic greenhouse gas emissions and climate change. Simultaneously, the construction sector generates vast quantities of construction and demolition (C&D) waste (Lei et al., 2023). In 2020, China produced approximately 3.039 billion tons of C&D waste, of which up to 80% consisted of inorganic components such as waste concrete and bricks. Conventional disposal methods, particularly landfilling, not only fail to recover valuable resources but also pose severe environmental risks. As a result, the dual objectives of resource recovery and carbon emission reduction—while maintaining the performance of construction materials—have become urgent challenges in developing sustainable and green building materials (Puertas et al., 2006; Kulovaná et al., 2016; Yang et al., 2022a; Zhan and He, 2019).

Recycled fine powder (RP), also known as recycled micro powder, typically has a particle size of less than 75 μm. It is an unavoidable byproduct generated during the crushing and screening of construction waste and mainly includes recycled concrete powder (RCP) and recycled brick powder (RBP) (Kumar et al., 2013). As a potential supplementary cementitious material (SCM), the effective utilization of RP holds significant promise for promoting low-carbon and circular construction practices (Kwon et al., 2015). RP is rich in SiO_2, Al_2O_3, and CaO, which confer a certain degree of latent pozzolanic reactivity (Baronio and Binda, 1997; Otsuki et al., 2003). Under alkaline conditions, residual unhydrated cement particles in RP may undergo secondary hydration, while active oxide phases can react with $Ca(OH)_2$ (CH) to form additional cementitious hydrates (Hu and He, 2007). Recent studies have

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reported that, when the replacement level of cement with RP is maintained within 10%–30% and appropriate activation techniques-such as mechanical grinding, thermal treatment, or chemical activation-are employed, the resulting concrete can maintain or even enhance its later-age compressive and flexural strengths while exhibiting improved pore structure (Poon and Chan, 2006; Likes et al., 2022). In terms of durability, the incorporation of RP has been shown to enhance resistance to chloride ion penetration, freeze–thaw damage, and sulfate attack. Some investigations have also noted its potential to mitigate carbonation. However, excessive RPs content or insufficient activation may lead to performance degradation due to its low reactivity or the introduction of porosity. Microstructural analyses, including scanning electron microscopy (SEM) and mercury intrusion porosimetry (MIP), indicate that activated RP promotes the formation of C-S-H gels, refines pore size distribution, improves the interfacial transition zone (ITZ), and enhances overall matrix densification and bonding strength (He et al., 2022). Conversely, untreated RP may contain inert phases and exhibit low reactivity, thereby acting as defects or weak interfaces within the hardened matrix.

A substantial body of review articles and systematic studies has been published on the application of RPs in cement-based systems (Yang et al., 2022b). Existing reviews predominantly focus on either RCP, emphasizing its hydration behavior and strength development (Lin et al., 2023), or RBP, highlighting its pozzolanic reactivity and mineralogical transformation mechanisms (Sallı Bideci et al., 2024). Although these studies have significantly advanced the field, several limitations remain evident in the current literature. First, RCP and RBP are commonly investigated in isolation, with limited systematic and comparative analysis. Second, activation methods are largely presented in a descriptive and categorical manner, lacking a unified framework that links activation strategies with microstructural evolution and macroscopic performance. Third, most studies emphasize empirical observations, whereas comprehensive mechanistic interpretations are relatively scarce. Finally, holistic assessments of environmental benefits, particularly those based on Life cycle assessment (LCA), remain insufficient. To clearly differentiate the present work from recent publications, representative review articles published between 2023 and 2025 were critically examined and compared (Aquino Rocha and Toledo Filho, 2023; Tang et al., 2020; Ye et al., 2022). In contrast to previous studies, this review presents an integrated, comparative, and mechanism-oriented synthesis of RCP and RBP within a unified analytical framework. It systematically elucidates RP-modified concrete from the perspectives of physicochemical characteristics, activation strategies, and their influences on workability and durability. Specifically, this review (i) compares the fundamental differences between RCP and RBP in terms of chemical composition, mineralogical phases, and reactivity; (ii) establishes linkages between activation techniques and microstructure-macro-performance relationships; (iii) clarifies the mechanisms governing strength development and durability enhancement; and (iv) identifies critical knowledge gaps and future research directions.

As an environmentally benign SCM, recycled fines exhibit considerable potential for sustainable concrete production (Olofinnade et al., 2018). Accordingly, this review aims not only to synthesize the existing literature but also to provide a more comprehensive and mechanistically informed perspective on RP-based concrete systems.

2. Review methodology

A systematic, transparent, and reproducible review protocol was adopted to comprehensively synthesize research on RPs derived from C&D waste, including RCP and RBP. The review process followed established principles for systematic literature reviews in construction materials research, with explicit identification, screening, eligibility, and inclusion stages. The literature search was conducted using Web of Science (WoS), Scopus, and Google Scholar, covering publications from January 2005 to September 2025. This time span was selected to capture both early exploratory studies on RPs and recent advances in activation technologies, performance optimization, and environmental assessment. A combination of controlled vocabulary and free-text terms was applied to titles, abstracts, and author keywords. The main search terms included: recycled concrete powder, recycled brick powder, recycled fine powder, waste concrete powder, brick powder as SCM, ceramic powder cement, pozzolanic activity, carbonation, carbon curing, carbon sequestration, thermal activation, mechanical activation, chemical activation, alkali activation, cement replacement, and durability. Boolean operators were used to refine the search and avoid irrelevant records.

The study selection procedure is summarized in Fig. 1. The initial database search yielded 1248 records (WoS: 412; Scopus: 536; Google Scholar: 300). After removing 327 duplicate records, 921 unique publications were retained for further screening. In the first screening stage, titles and abstracts were reviewed to exclude studies that were clearly irrelevant to RPs in cementitious systems. This resulted in the exclusion of 563 records, mainly due to: (i) exclusive focus on recycled aggregates without powder involvement, (ii) unrelated ceramic or mineral powders not derived from C&D waste, or (iii) applications outside cement-based materials. The remaining 358 full-text articles were assessed for eligibility. Based on predefined inclusion and exclusion criteria, 190 studies were further excluded due to insufficient experimental detail, lack of methodological transparency, non-peer-reviewed status, or absence of performance-related analysis. Ultimately, 168 studies were deemed eligible and included in the qualitative synthesis.

Studies were included if they met all of the following criteria: (i) peer-reviewed journal articles or doctoral dissertations; (ii) focused on RCP, RBP, or hybrid RP; (iii) investigated material characteristics, activation methods, hydration behavior, mechanical performance, durability, carbonation behavior, or environmental indicators in cementitious systems; (iv) published in English or Chinese. The following were excluded: conference abstracts, patents, non-peer-reviewed reports, studies dealing solely with recycled aggregates without powder utilization, and papers lacking sufficient experimental or analytical detail. From each eligible study, standardized information was extracted, including: source and type of RP; mineralogical and chemical composition; particle size distribution; activation method; mixture proportions and replacement ratios; testing protocols; key performance indicators (strength, durability, and microstructure); and available environmental metrics (e.g., CO_2 uptake and energy demand) where reported. A qualitative comparative synthesis approach was then applied to identify: (i) intrinsic differences in reactivity and performance between RCP and RBP; (ii) relationships between activation techniques and hydration mechanisms; (iii) performance patterns across mechanical and durability properties. Bibliometric visualization was conducted using VOSviewer, and Fig. 2 present the density maps of major contributing authors and high-frequency keywords.

3. Physicochemical properties of RP

RP, produced as a byproduct during the processing of C&D waste, can be broadly classified into two categories based on its source material: RCP and RBP. The chemical composition of RP primarily consists of SiO_2, Al_2O_3, and CaO, as confirmed by X-ray diffraction (XRD) analysis (Fig. 3) (Liu et al., 2014). The specific chemical compositions and physical properties of RCP and RBP are detailed in Table 1 (Yang et al., 2020, 2022b; Olofinnade et al., 2018; Wang Haijin, 2015; Chen et al., 2013; Liu Li et al., 2021; Kang and Li, 2019; Cantero et al., 2020a; Bektas, 2007; Yu et al., 2017; Li et al., 2019; Kinuthia and Nidzam, 2011; Xiaolu et al., 2016; Luo et al., 2022). These oxides are indicative of latent pozzolanic reactivity (Shi et al., 2005), suggesting that RP possesses potential as a SCM capable of participating in secondary hydration reactions.

RCP is typically characterized by a fine particle size and a highly

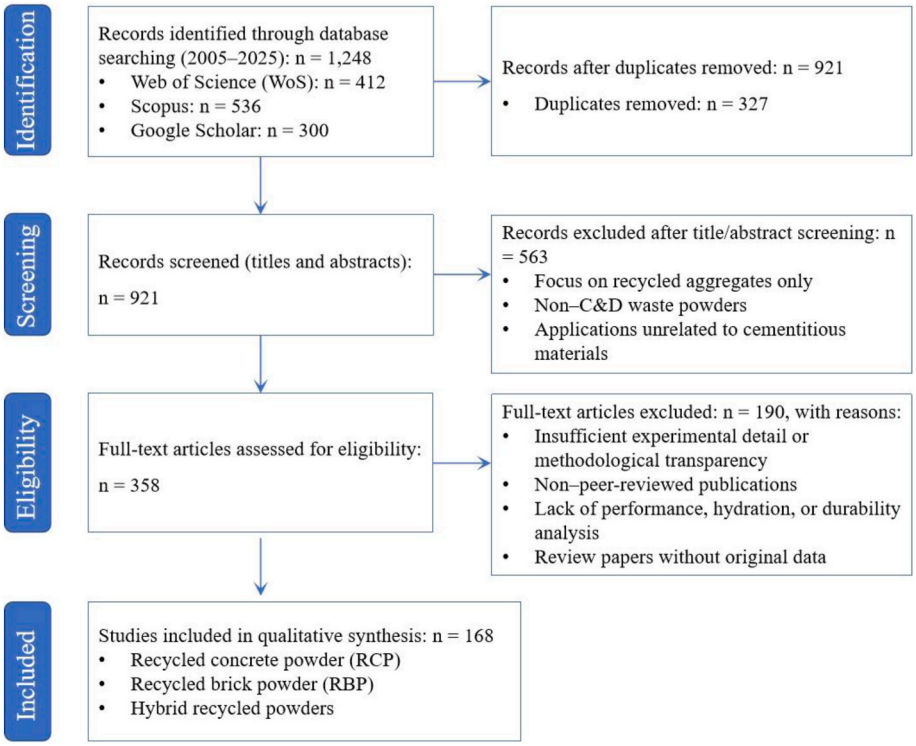

Fig. 1. PRISMA flow diagram for the literature review on RP in cement-based materials.

porous microstructure. As illustrated in Fig. 4 (Liu et al., 2022; Wu et al., 2022a; Singh et al., 2019), the surface morphology of RCP particles reveals fractured planes and adhered fine particles, which are remnants of the original cementitious matrix. Mineralogical analysis indicates the presence of residual unhydrated clinker phases, such as belite (C_2S) and alite (C_3S), along with hydration products including C-S-H gels. These constituents provide the basis for secondary hydration, contributing to the material's potential for continued strength development. In contrast, RBP exhibits distinct morphological and chemical features. SEM images (Fig. 5) demonstrate that RBP particles are predominantly amorphous with a glassy texture, composed mainly of aluminosilicate phases (Likes et al., 2022). Although this amorphous structure exhibits limited reactivity under ambient conditions, it can be chemically activated-particularly in alkaline environments (Zhao et al., 2020a).

The presence of reactive mineral phases, combined with the favorable physical characteristics of both RCP and RBP, underscores their potential as viable SCMs. Their reactivity, however, is strongly influenced by factors such as phase composition, degree of crystallinity, and surface area. To improve the reproducibility and standardization of research on RPs, this study refers to the JGT 573–2020 standard to establish a recommended set of performance metrics. The proposed framework encompasses essential material characteristics, including particle fineness, water demand, activity index, flow retention, methylene blue (MB) value, dimensional stability, moisture content, and key chemical constituents (chloride and sulfate content). These parameters provide a rigorous basis for quality assessment, facilitate reproducible experimental comparisons, and support the practical application of RPs in engineering contexts. A comprehensive summary of the recommended metrics is presented in Table 2.

4. Activation of RP

The activation methods for RP primarily include physical and chemical approaches. This study focuses on previously reported activation methods, such as mechanical grinding, Chemical Activation, thermal treatment, and carbonation. To strengthen the conceptual framework of RP activation, Fig. 6 presents a cause-effect map that explicitly links treatment methods to microstructural parameters and macroscopic performance. As illustrated in the map, each activation method drives a distinct set of microstructural transformations-including changes in amorphous content, SSA, particle morphology, ITZ characteristics, and hydration product assemblages (e.g., C-S-H, AFt, carboaluminates)-which collectively determine the reactivity and engineering performance of RP-blended systems.

4.1. Physical activation

Physical activation, particularly through mechanical grinding, is one of the most widely employed strategies to enhance the reactivity of RP. Among these methods, ball milling is commonly employed to induce microstructural modifications that improve the material's pozzolanic performance. Ball milling facilitates the removal of surface layers from residual unhydrated cement particles, re-exposing reactive clinker phases and promoting further hydration. Concurrently, mechanical impact disrupts the crystalline framework of relatively inert x-SiO_2 tetrahedra, transforming them into a disordered, reactive amorphous phase that enhances pozzolanic behavior (Kumar et al., 2008). During grinding, CH on particle surfaces may react with ambient CO_2 to form $CaCO_3$. The nucleation properties and weak alkalinity of $CaCO_3$ further facilitate cement hydration by acting as heterogeneous nucleation sites (Binici et al., 2007).

As shown in Fig. 7, the particle size of RCP decreases significantly with prolonged grinding time, accompanied by a corresponding increase in specific surface area, thereby improving reactivity (Yang et al., 2022b). However, this enhancement is nonlinear. Beyond an optimal milling duration, reactivity plateaus or declines slightly due to particle agglomeration. Zhang et al. (Lin, 2016) observed that a 30-min milling period drastically reduced coarse particles but induced agglomeration thereafter. Ma et al. (2024) demonstrated that after 180 min of grinding, particle size and surface area stabilized, indicating a dynamic "fracture-agglomeration" equilibrium. At particle sizes below 10 μm, van der Waals forces and electrostatic interactions increase markedly,

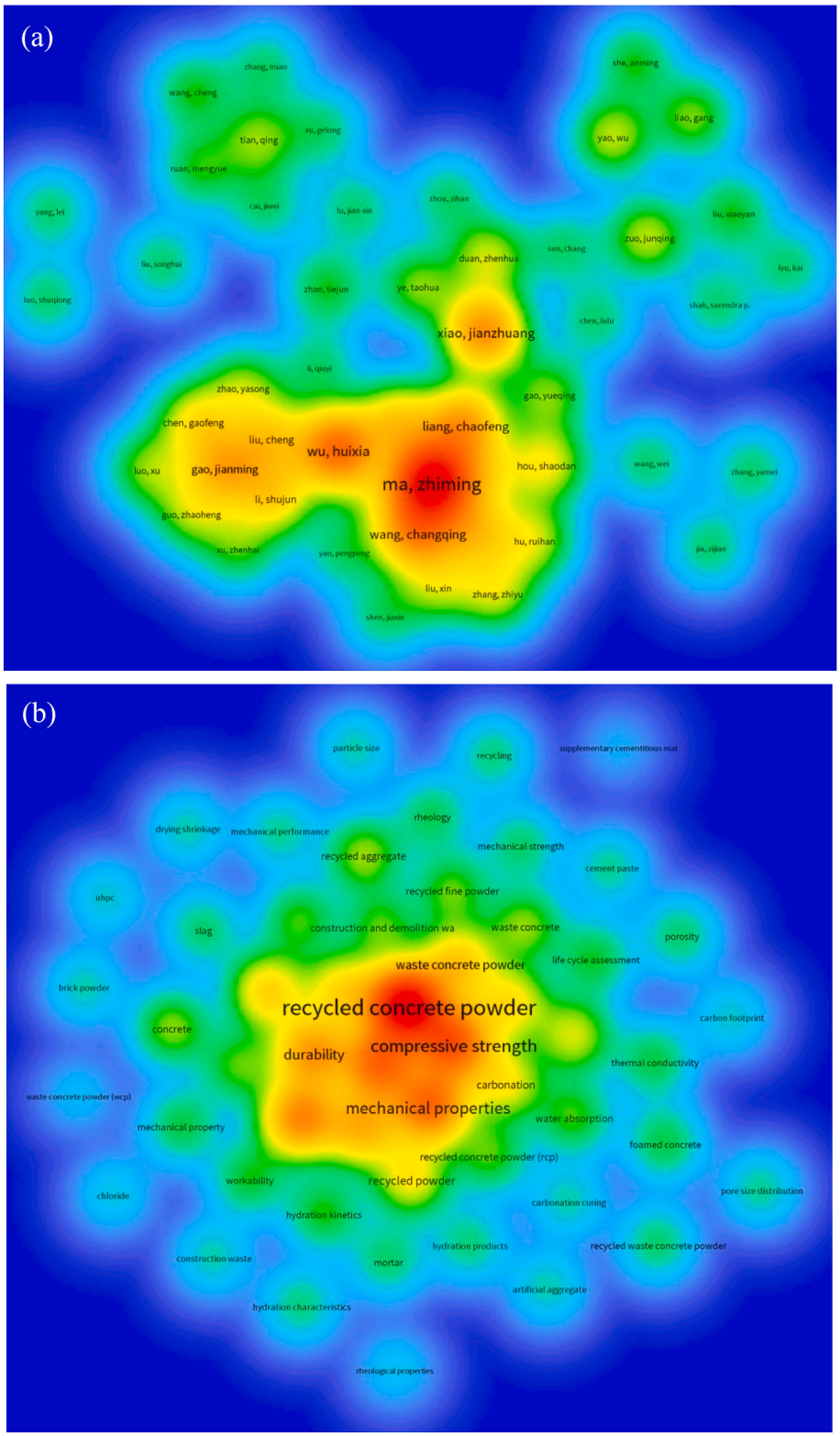

Fig. 2. Density map identifying (a) authors and (b) keywords with most publications (VOSviewer software).

promoting aggregation. This agglomeration hinders reactive site exposure, increases water demand, and compromises workability in cementitious mixtures. Li et al. (Li and Kang, 2019) reported reduced SiO_2 crystalline peak intensity and CH-to-$CaCO_3$ transformation after prolonged milling via XRD analysis, though mineralogical composition remained unchanged. These findings confirm that physical activation primarily modifies particle size, surface area, and amorphization rather than inducing phase transformations.

RBP also responds to mechanical activation but exhibits distinct behavior due to its composition. Lou et al. (2019) found that mortars with RBP showed increased 7-day compressive strength with extended grinding, but 28-day strength peaked at 60 min before declining, likely due to agglomeration-induced reactivity loss. Yu et al. (2017) compared ultrafine jet milling (RBP-I) and vibratory ball milling (RBP-W). SEM

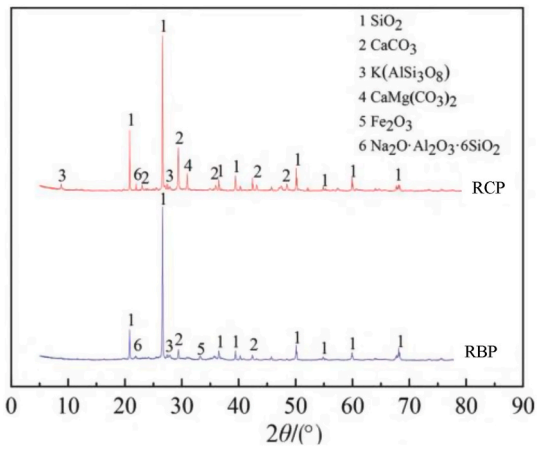

Fig. 3. XRD patterns of RP (Liu et al., 2014).

analysis revealed RBP-W had uniform particle distribution, smooth surfaces, and rounded edges, whereas RBP-I particles were irregular with rough surfaces and adhered fines (Fig. 8). Although compressive strength differences were modest, RBP-W mortars exhibited denser microstructures and marginally superior strength, underscoring the influence of activation technique on RBP's microstructural properties.

In summary, physical activation effectively enhances RP's structural properties and specific surface area, improving its latent reactivity and performance in cement-based materials. However, grinding duration and method require careful optimization. Excessive milling causes particle agglomeration, reduced reactivity, and compromised workability. Thus, selecting optimal activation parameters is critical to maximizing RP's utilization efficiency in sustainable construction.

4.2. Chemical activation

Chemical activation represents a key strategy for enhancing the reactivity of RP by chemically modifying its surface structures and

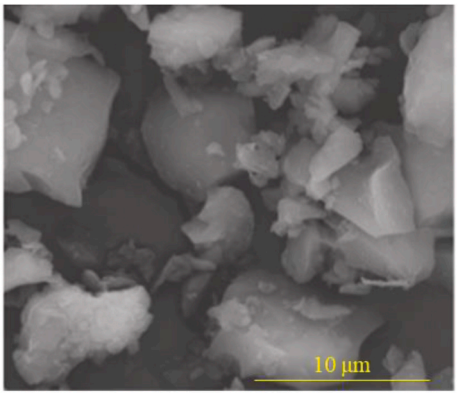

Fig. 5. SEM image of RBP (Likes et al., 2022).

Table 1
Chemical composition and physical properties of RCP,RBP, Fly ash and granulated blast furnace slag (Yang et al., 2020, 2022b; Olofinnade et al., 2018; Wang Haijin, 2015; Chen et al., 2013; Liu Li et al., 2021; Kang and Li, 2019; Cantero et al., 2020a; Bektas, 2007; Yu et al., 2017; Li et al., 2019; Kinuthia and Nidzam, 2011; Xiaolu et al., 2016; Luo et al., 2022).

Category		RCP	RBP	Fly ash	granulated blast furnace slag
Chemical composition (%)	SiO_2	37.8–54	49.8–63.1	43–45.1	27–32.3
	Al_2O_3	11~19.2	12.2–19.8	24.2–35.3	8.4–16.0
	CaO	13.8–29.3	2.0–13.5	5.1–5.6	38.2–45.5
	Fe_2O_3	2.2–4.7	2.6–6.8	2.7–6.4	1.0–10.2
	K_2O	3.2–3.8	2.0–4.6	0.5–1.2	0.25–0.7
	MgO	1.1–2.7	1.3–2.1	0.6–1.3	5.2–11.0
	Na_2O	1.4–1.8	1.2–1.7	0.03–0.7	0.2–0.3
	SO_3	0.5–1.8	0.3–0.4	1.6–2.1	0.1–1.45
Physical properties	Apparent density ($g{\cdot}cm^{-3}$)	2.32–2.65	2.42–2.62	2.2–3.1	2.55–2.8
	Bulk density ($g{\cdot}cm^{-3}$)	0.82–0.92	1.81–1.86	0.85–1.2	1.25–1.35
	Specific surface area (SSA, $m^2{\cdot}kg^{-1}$)	245–750	340–856	350–435	400–550
	Activity index (%)	54.8–68.5	58–69	>70%	≥90%

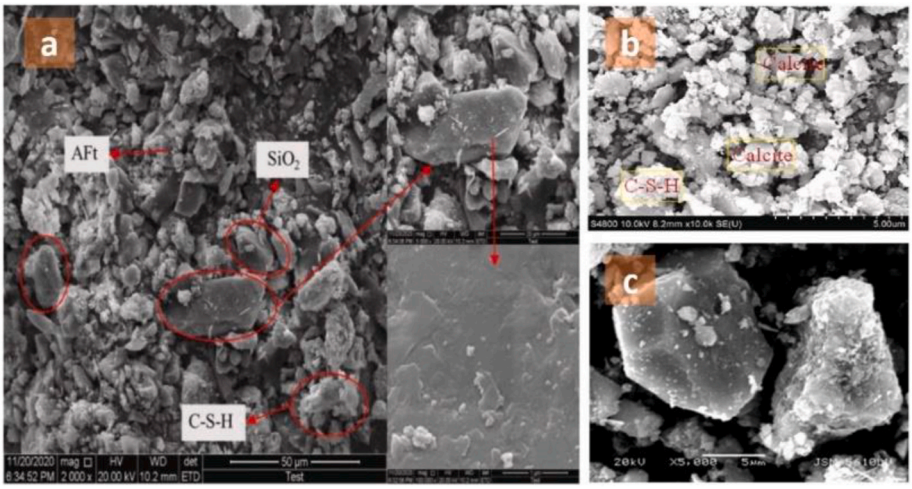

Fig. 4. Microstructure and RCP components: (a) hydrated products (Liu et al., 2022), (b) $CaCO_3$ (Wu et al., 2022a) and (c) SiO_2 (Singh et al., 2019).

Table 2
Recommended technical indicator for RPs.

Parameter	Grade I	Grade II
Fineness (residue on 45 μm sieve)/%	≤30.0	≤45
Water demand ratio/%	≤105	≤115
Activity index/%	≥70	≥60
Flow loss after 2 h/mm	≤40	≤60
Methylene blue (MB) value	≤1.4	
Dimensional stability (boiling method)	Pass	
Moisture content/%	≤1.0	
Cl^- content (mass fraction)/%	≤0.06	
SO_3 content (mass fraction)/%	≤3.0	

promoting the dissolution of latent reactive components. This process is typically achieved through the introduction of alkaline agents, salts, or other chemical activators that trigger secondary hydration or geopolymerization reactions (Ge et al., 2012). Based on the primary cations involved, chemical activators are categorized into sodium-based, calcium-based, and composite systems, each characterized by distinct activation mechanisms and application contexts. The effects of different chemical activators on RCP and RBP are summarized in Table 3.

4.2.1. Sodium-based activators

Sodium-based activators-such as NaOH, $Na_2SiO_3{\cdot}9H_2O$, Na_2SO_4, Na_2CO_3, and $NaHCO_3$-primarily enhance system alkalinity (Guo-Jun et al., 2005). Elevated pH disrupts Si-O and Al-O bonds in the amorphous phases of RP, promoting the release of reactive silicate and aluminate species that form hydration products like C-S-H and C-A-H gels (Dugat et al., 1996; Zhai et al., 2017). For RCP, which retains unhydrated cement particles and hydration products, NaOH enhances the dissolution of reactive constituents and stimulates secondary C-S-H gel precipitation, improving mechanical performance (Li et al., 2013). A threshold effect occurs: moderate NaOH dosages (0.75–4.8%) enhance strength, while excessive alkalinity reduces Ca^{2+} availability and suppresses silicate polymerization, impairing hydration (Aydın, 2013). $Na_2SiO_3{\cdot}9H_2O$ provides alkalinity and supplemental silica, fostering stable geopolymeric or hybrid C-S-H networks. Optimal dosages (~5%) avoid microstructural loosening from overreaction (Yan et al., 2013). Na_2SO_4 acts as a sulfate donor, promoting ettringite (AFt) formation via reaction with C_3A phases. A 3.5% addition improves compressive strength by up to 25% compared to controls (He et al., 2010).

RBP, rich in amorphous SiO_2 and Al_2O_3 but deficient in calcium, sodium-based activation is highly effective. NaOH accelerates Si-O-Al bond depolymerization, yielding 28-day compressive strengths up to 40 MPa at 0.5% dosage (Shi and Day, 1999). A NaOH dosage of 0.5% has been reported to triple the depolymerization rate of Si-O-Al bonds, yielding compressive strengths up to 40 MPa at 28 days. The use of $Na_2SiO_3{\cdot}9H_2O$ further increases gel formation by supplying reactive silicates; however, excessive dosages (>10%) may disrupt gel integrity due to kinetic imbalance. In addition, Na_2SO_4 contributes both sulfate and sodium ions (Jin et al., 2019), promoting early AFt formation Eq. (1) (Tian et al., 2020). and enhancing strength more effectively than $CaSO_4$

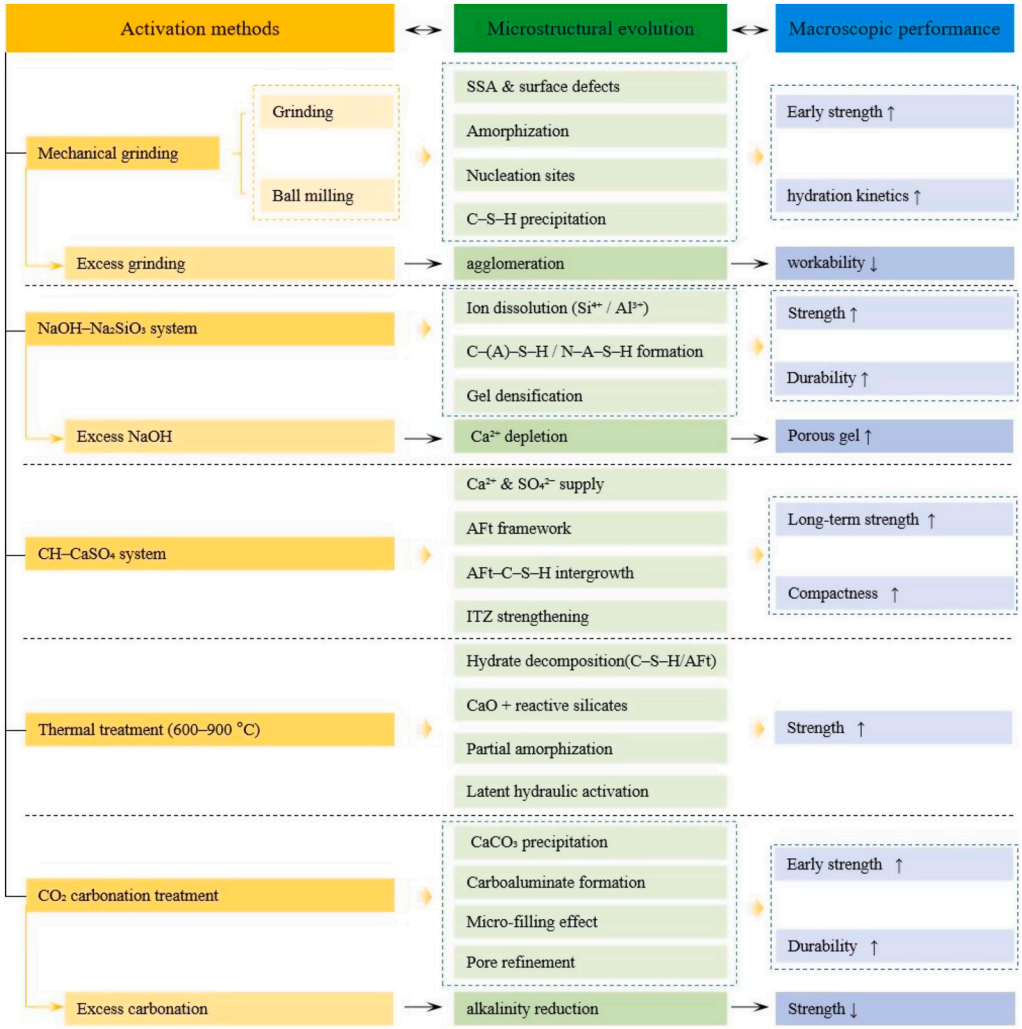

Fig. 6. A schematic illustration of the relationships among RP treatment methods, microstructural characteristics, and macroscopic performance.

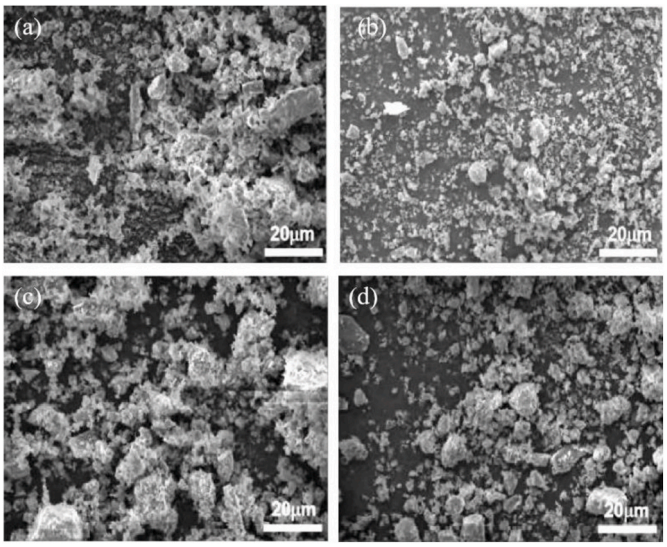

Fig. 7. SEM images of RCP after grinding time (a)10h, (b)20h, (c)30h and (d) 40h (Yang et al., 2022b).

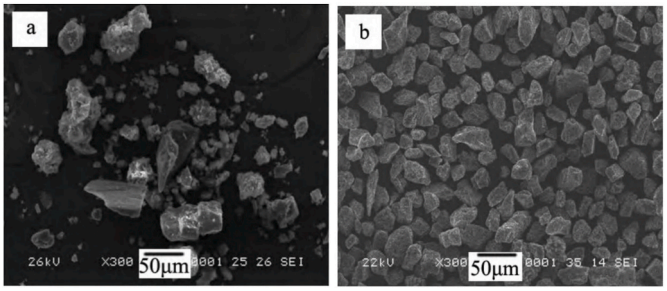

Fig. 8. SEM images of RP crushed by mechanical force (a)RBP-I and (b)RBP-W (Yu et al., 2017).

(He et al., 2010). Mild alkalis like Na_2CO_3 and $NaHCO_3$ offer sustained alkalinity release and improved workability (Guo-Jun et al., 2005).

$$AlO_2^- + Ca^{2+} + OH^- + SO_4^{2-} \rightarrow 3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O \quad (1)$$

4.2.2. Calcium-based activators

Calcium-based activators-such as CH, $CaSO_4$, and $CaCl_2$-increase alkalinity and Ca^{2+} concentration, promoting C-S-H/AFt formation and matrix densification. These activators are particularly effective in high-substitution systems.

In CaO-rich RCP, CH supplementation facilitates residual C_3S/C_2S hydration and silica/alumina interaction with Ca^{2+}, forming cementitious phases (Yang et al., 2022b). At 70–80% RCP replacement, CH-activated systems exhibit superior strength to NaOH-activated ones. Sulfate and chloride sources (e.g., $CaSO_4$, $CaCl_2$) refine pores via AFt and calcium chloroaluminate hydrates (e.g., Friedel's salt) (Fang et al., 2002), though chloride use requires caution in reinforced concrete.

For RBP, characterized by low CaO content, calcium-based activators are essential to compensate for the lack of calcium. CH provides the Ca^{2+} required for the formation of C-S-H, C-A-H, and AFt gels, substantially enhancing reactivity and mechanical properties (Yang, 2017). At a 30% RBP replacement ratio, the inclusion of 1% CH has been shown to increase 28-day compressive strength by approximately 30%. Similarly, $CaSO_4$ enables ternary synergy between SO_4^{2-}, Al^{3+}, and Ca^{2+} ions (Fang et al., 2002), promoting AFt formation even under low-temperature curing conditions (e.g., 0 °C), with early strength improvements up to 40%. Nevertheless, $CaSO_4$ tends to be less effective than Na_2SO_4, resulting in strength reductions of up to 12.7%. $CaCl_2$ also enhances early strength development in RBP systems, but its use must be carefully managed to mitigate long-term durability issues related to chloride ingress.

4.2.3. Composite activators

Composite activator systems combine the benefits of different chemical species to achieve synergistic effects in activating RP (Tian et al., 2020). These synergistic behaviors can generally be attributed to three coupled mechanisms: (i) enhanced alkalinity that accelerates the dissolution and depolymerization of aluminosilicate phases (ii) increased availability of key ions (e.g., Ca^{2+}, SO_4^{2-}, SO_3^{2-}), that participate directly in C-S-H, C-A-S-H or N-A-S-H formation, and (iii) stabilization of early gels through charge balancing or cross-linking, which improves structural integrity.

For RCP, the NaOH-$Na_2SiO_3 \cdot 9H_2O$ system is particularly effective: NaOH raises the pH and promotes bond cleavage, while NaOH-$Na_2SiO_3 \cdot 9H_2O$ supplies reactive silicate to promote C-S-H precipitation and stabilize the gel network (Vásquez et al., 2016). Optimal performance has been observed at NaOH $\leq$2.4% and NaOH-$Na_2SiO_3 \cdot 9H_2O$ = 10%; beyond this threshold, excessive alkalinity disrupts early gel densification. NaOH-Na_2CO_3 systems show more complex interactions. At Na_2CO_3 < 5%, the additional OH^- enhances dissolution, but higher Na_2CO_3 concentrations buffer the pH and suppress hydrolysis, reducing strength. In NaOH-CH systems, CH mainly provides Ca^{2+} to promote C-S-H formation and stabilize silicate-rich gels (Ren et al., 2020). A combined dosage of 4.8% NaOH and 15% CH yields compressive strengths up to 28.23 MPa, confirming that NaOH governs

Table 3
Effect of activator on RCP and RBP.

Activator type	Applicable RPs	Optimum dosage	Enhancement effect	Action characteristics
NaOH	RBP	0.5%–4.8%	10.5%–30%	High pH depolymerization of silica-alumina network
$Na_2SiO_3 \cdot 9H_2O$	RCP/RBP	5%	15%–25%	Silicon source supplementation + alkali excitation
Na_2SO_4	RCP	3%	20%–25%	Dual action: SO_4^{2-} reacts with C_3A to generate AFt; Na^+ alkali excitation increases the depolymerization rate
$CaSO_4$	RBP	3.5%	18%–22%	At low temperature (0 °C), SO_4^{2-}-Al^{3+}-Ca^{2+} synergistically generates AFt skeleton, but the reaction activity is lower than Na_2SO_4
CH	RCP	1%–3.5%	20%–35%	Calcium source supply + pH adjustment
$CaCl_2$	RCP	3.5%	25%	Osmotic pressure destruction + chloroaluminate generation
NaOH/ $Na_2SiO_3 \cdot 9H_2O$	RCP	NaOH≤2.4% +Na_2SiO_3 10%	35%–40%	Alkalinity regulation and silicon source synergy, C-S-H and geopolymer co-generation
NaOH/$CaSO_4$	RCP	1:2 (3% Total dosage)	32%–38%	NaOH accelerates Si/Al dissolution, $CaSO_4$ promotes AFt growth
Na_2SO_4/CH	RCP	2% + 1.5%	40%–45%	Na_2SO_4 excites C_3A, CH provides Ca^{2+} to strengthen C-S-H
Na_2SiO_3/ $CaSO_4 \cdot 2H_2O$	RBP	Total dosage <2.0%	25%–28%	Silicon source supplementation and sulfate excitation synergistically increase the Al_2O_3 conversion rate to 78%
Na_2SO_4/$CaSO_4$	RBP	1.5% + 1.5%	30%	SO_4^{2-} dual source supply accelerates AFt nucleation

initial dissolution while Ca^{2+} contributes to gel stabilization (Zixiu, 2018). NaOH-$CaSO_4$ systems also perform well, where a 1:2 ratio and 3% total dosage optimize both early dissolution and sulfate-regulated gel structure development (Rulin, 2011). Similar synergistic effects appear in Na_2SO_4-CH and Na_2SO_4-$CaCl_2$ systems, where complementary ion supply enhances both hydration kinetics and gel stability under pozzolanic or blended conditions.

For RBP-characterized by low CaO and high SiO_2-stronger alkali activation combined with external Ca^{2+} or SO_4^{2-} sources is required to balance charge and form stable gels. Systems such as $Na_2SiO_3{\cdot}9H_2O$-$CaSO_4{\cdot}2H_2O$ have demonstrated superior performance, where moderate activator dosages ($\leq$2%) increase dissolution while $CaSO_4{\cdot}2H_2O$ promotes Ca-bridged gel formation. Higher dosages overactivate dissolution, destabilizing the early network.Na_2SO_4-$CaSO_4{\cdot}2H_2O$ systems also outperform single activators by accelerating aluminosilicate–calcium interactions and improving mechanical properties (Guoqiang, 2009).

Overall, chemical activation enhances RP reactivity through dissolution–depolymerization processes, ionic supplementation, and gel structure stabilization. Sodium-based activators (e.g., NaOH, Na_2SiO_3) are better suited for aluminosilicate-rich RBP, whereas calcium-bearing activators (e.g., CH, $CaSO_4$) align with Ca-rich RCP. Composite activator systems maximize performance by simultaneously boosting alkalinity, enriching reactive ions, and stabilizing early hydration/geopolymer gels.

4.3. Thermal treatment

Thermal treatment has been reported as an effective method for enhancing the cementitious activity of RP by inducing phase transformations, decomposing stable phases, and releasing latent reactive components. RCP exhibits considerable potential for thermal activation due to the presence of residual hydration products and unreacted cement particles (Deng and Wu, 2024). Upon heating, C-S-H gel undergoes dehydration and decomposition, forming reactive silicate phases such as C_2S (dicalcium silicate) in the range of 550–750 °C. CH begins to decompose around 500 °C, yielding CaO, while AFt transforms into CaO and Al_2O_3 at approximately 550 °C. $CaCO_3$ decomposes at higher temperatures (~840 °C), further contributing to reactive CaO formation. These reactions collectively enhance RCP's latent hydraulic reactivity by generating mineral phases capable of participating in hydration processes. TG-DSC analyses confirm these phase transformations, indicating progressive decomposition of hydration products with increasing temperature (Bogas et al., 2019). Microstructural analysis reveals that moderate thermal treatment (300–400 °C) results in a denser matrix due to the breakdown of CH, C-S-H, and calcite (Fig. 9), leading to pore refinement (Wu et al., 2021a). Between 400 and 1000 °C, further densification occurs due to the formation and sintering of new surface phases (Wu et al., 2021a; Ma et al., 2022). However, at temperatures approaching 1200 °C, RCP particles soften, and hydration products are almost entirely absent. While softening enhances powder flowability, it reduces nucleation sites, diminishing hydration efficiency in cementitious matrices (Ma et al., 2022; Wu et al., 2021b).

Thermal treatment significantly alters RCP's particle morphology. As temperature increases, particles become finer and more spherical (Fig. 10). However, above 600 °C, partial sintering and agglomeration occur, reducing specific surface area (Wu et al., 2021b; Real et al., 2020). Zhang et al. (2022) observed that RCP particles treated below 800 °C remain relatively coarse. Particle size analyses indicate a general decrease in median particle size (D_{50}) from 400 °C to 900 °C, particularly between 800 and 900 °C, driven by dehydration and decarbonation (Real et al., 2020; Serpell and Lopez, 2015). A temporary D_{50} increase between 600 and 800 °C suggests particle agglomeration, followed by fragmentation at higher temperatures (Real et al., 2020). Sui et al. (2020) reported similar trends, attributing size changes to C-S-H decomposition and raw material porosity. These findings highlight that particle size dynamics during thermal treatment are governed by multiple interacting factors.

Unlike RCP, RBP originates from fired clay bricks and consists of crystalline SiO_2 and thermally stable aluminosilicates. TG–DSC analyses reveal minimal endothermic/exothermic activity in RBP between 0 and 1000 °C, indicating limited phase transitions (HT, 2020). Above 800 °C, partial Si-O and Al-O bond disruption converts the aluminosilicate framework into a metastable amorphous structure, enhancing reactivity via calcium ion exchange and gel formation. Although thermal activation effects on RBP are modest, interfacial bonding and matrix porosity improve. Kang et al. (2019) demonstrated that RCP particles (<0.16 mm) treated at 800 °C for 2 h achieved 28-day compressive strengths of 44.6 MPa at 10% replacement—comparable to control samples. Microstructural analysis confirmed denser, less porous matrices with treated RCP.

Thermal treatment enhances RP reactivity by decomposing stable phases and impurities, facilitating renewed hydration. RCP, with residual cementitious phases, responds optimally between 600 and 900 °C. RBP, due to its crystalline composition, benefits minimally but exhibits improved surface reactivity at high temperatures. The efficacy of thermal treatment depends on mineralogical composition, initial porosity, and treatment parameters.

4.4. Carbonation treatment

Carbonation treatment has emerged as a promising technique for enhancing the reactivity of RPs. Under controlled CO_2 exposure, RCP reacts to form stable $CaCO_3$ phases and secondary products such as C-S-H, thereby improving its potential as a SCM (Mehdizadeh et al., 2021; Monkman et al., 2016). XRD analysis of carbonated RCP reveals distinct peaks corresponding to $CaCO_3$, including polymorphs such as aragonite and dolomite (Lu et al., 2018). Carbonation reactions progressively transform original hydration products-such as CH, AFt, C_2S, and

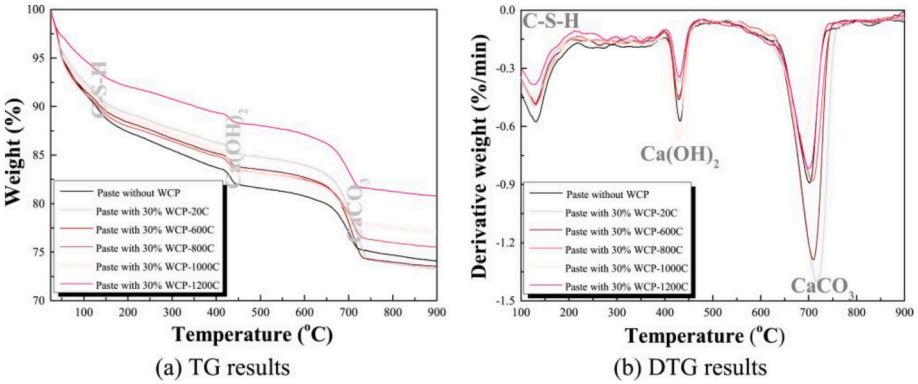

Fig. 9. Hydration products of paste including thermal-activated RCP by TG (Wu et al., 2021a).

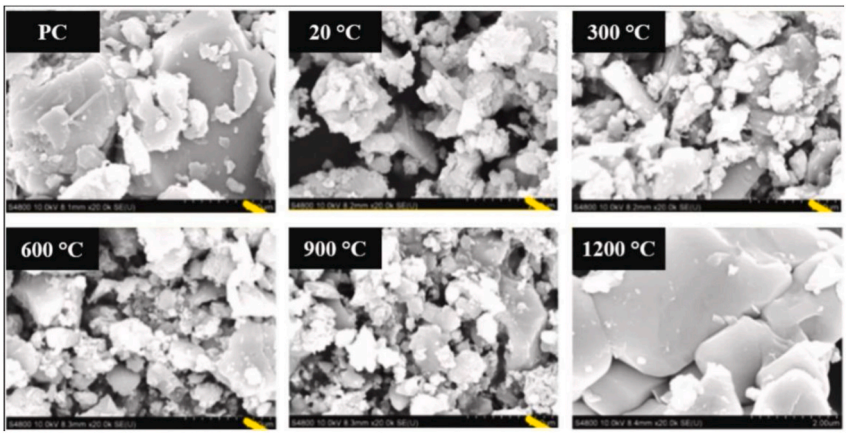

Fig. 10. Microstructure of thermal-treated RCP (Wu et al., 2021b).

C_3S-into stable carbonate phases. This process is validated by TG–DTG analysis, showing a mass loss shift from 100 to 500 °C (dehydration of CH and C-S-H in untreated RCP) to 550–950 °C ($CaCO_3$ decomposition) in carbonated samples (Mehdizadeh et al., 2021; Kaliyavaradhan et al., 2022). High-crystallinity $CaCO_3$ forms within 30 min of carbonation at 100 °C, underscoring process efficiency (Wu et al., 2022b). Carbonation

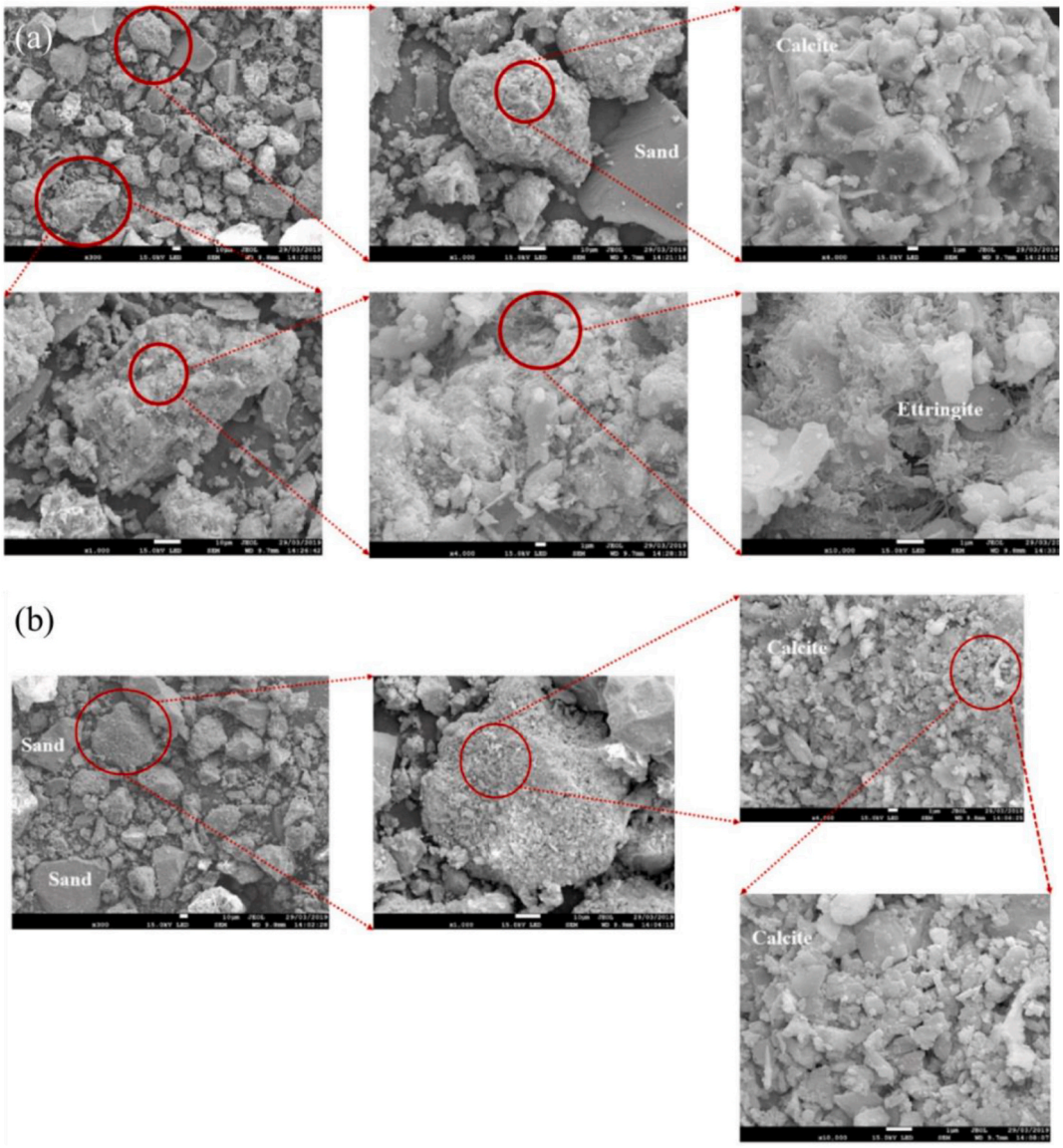

Fig. 11. SEM images of RCP (a) before and (b) after carbonation (Kaliyavaradhan et al., 2022).

also refines particle morphology and size distribution. Image analysis demonstrates uniform particle distribution due to fine $CaCO_3$ precipitation (Fig. 11) (Kaliyavaradhan et al., 2022; Ashraf, 2016). Post-carbonation, RCP particles exhibit denser surfaces, reduced porosity, and regular morphologies. These features stabilize a $CaCO_3$–silica gel composite system, enhancing nucleation and hydration product growth (Wu et al., 2021c; Kaliyavaradhan et al., 2020). $CaCO_3$ polymorphs (e.g., aragonite, calcite) formed between 20 and 140 °C improve structural compactness and durability. Mechanically, carbonation substantially enhances early-age compressive strength. Gains of 75–100% are reported under 140 °C carbonation (Kaliyavaradhan et al., 2022), attributed to calcium carboaluminate hydrates from $CaCO_3$ and tricalcium aluminate (C_3A) reactions. By 28 days, calcite nucleation stabilizes, limiting further strength gains (Hargis et al., 2014).

In contrast, research on RBP carbonation is still limited, despite its widespread availability and potential. RBP is primarily composed of SiO_2 and Al_2O_3, with amorphous phases and free lime that enable pozzolanic reactions under CO_2 exposure. Carbonation of RBP can promote the formation of $CaCO_3$ polymorphs (calcite, aragonite, vaterite) and carbonate–aluminate compounds, refine pore structure, reduce permeability, and improve particle uniformity and matrix packing. To systematically investigate RBP carbonation, standardized experimental protocols are recommended: CO_2 concentration of 5–20 vol%, temperatures of 20–140 °C, relative humidity of 50–80%, and exposure durations from 0.5 to 24 h. As discussed in Section 4.1, mechanical pregrinding enhances surface reactivity by exposing residual clinker phases and inducing amorphization, which in turn accelerates carbonation kinetics (Kumar et al., 2008; Binici et al., 2007). Measurable parameters for RBP carbonation should include: (i) identification of $CaCO_3$ polymorphs via XRD or Raman spectroscopy; (ii) particle size distribution post-carbonation to monitor refinement and agglomeration; (iii) pore structure and connectivity through MIP; (iv) TG–DTG for carbonation extent and thermal stability; (v) SEM imaging to assess surface densification and microstructural uniformity; (vi) compressive strength, hydration heat, and reaction kinetics to quantify improvements in cementitious performance.

Overall, carbonation enhances RP reactivity through mineralogical transformations and microstructural refinement. While RCP exhibits rapid early-age strength gains, RBP demonstrates considerable but underexplored potential. Future research should focus on elucidating RBP carbonation mechanisms, optimizing processing conditions, and establishing quantitative links between mineralogical changes, microstructure evolution, and macroscopic performance.

5. Effect of RP on concrete performance

5.1. Workability

RP, owing to their high porosity and irregular, rough microstructure, typically exhibit increased SSA and water demand, which can negatively impact the flowability of concrete. In this study, the flowability of concrete is systematically evaluated from four aspects: particle size and fineness, water absorption and pore structure, w/b ratio and chemical admixtures, and rheological characterization. Additionally, a comparative analysis of the influences of RCP and RBP on concrete flowability is conducted, as summarized in the accompanying Table 4.

5.1.1. Particle size and fineness

Numerous studies have demonstrated that RCP can improve the flowability of cement-based materials when ground to an appropriate fineness and incorporated at low to moderate replacement levels. Increasing the RCP content from 5% to 30% has been reported to raise initial slump by up to 52% and flow spread by approximately 26.5%, while simultaneously mitigating slump loss. Similarly, in mortar systems, Ma and Wang (2013) observed that replacement of cement with 40% RCP increased flowability by nearly 40%, which was primarily attributed to the micro-filling effect and improved particle packing induced by fine RCP particles.

Table 4
Comparison of fresh-state behavior between RCP and RBP.

Parameter	RCP	RBP
Particle morphology	Relatively rounded, smoother surface texture	Highly angular, irregular, rough surface
Internal porosity	Low to moderate	High, with open pore structure
Water absorption capacity	Low to moderate	High
Packing and filling effect	Favorable; improves particle packing density	Limited; ineffective filling
Interparticle friction	Relatively low	High
Rheological characterization	Reduced yield stress and plastic viscosity; relatively flatter τ–γ	Increased yield stress and viscosity; steeper τ–γcurves
Fluidity	Often improves at low to moderate replacement levels	Generally reduces flowability
Chemical admixtures	Moderate adsorption competition	Strong physical adsorption within internal pores
Hydration effect	Weak acceleration or dilution-type behavior	Promotes early hydration
Overall influence on flowability	Flow-enhancing at optimized dosages	Usually detrimental to flowability

Nevertheless, contradictory findings have also been reported. Moon et al. (Moon, 2008) observed a decline in mortar flowability with increasing RCP dosage, with flow values decreasing by a factor of 1.46–1.50. For RBP systems, Bektas et al. (2008) and Kartini et al. (2012) showed that both overly coarse and ultra-fine RBP negatively affect fresh properties. Bektas (Bektas et al., 2009) further emphasized that neither extreme is conducive to optimal packing, as coarse particles increase internal friction while overly fine particles significantly elevate water demand. Consequently, an optimal fineness range exists for RCP in which flowability can be maximized, whereas the effective "packing window" for RBP is substantially narrower due to its distinct mineralogical composition and porous microstructure.

5.1.2. Water absorption and pore structure

Water absorption is a critical parameter governing effective water availability in cementitious systems containing RPs. RCP generally exhibits relatively low water absorption owing to the presence of dense hydrated cement paste particles and residual unhydrated clinker phases. As a result, it may behave similarly to low-calcium fly ash with respect to water demand. In contrast, RBP is characterized by a highly porous microstructure and strong capillary absorption capacity, which markedly reduces the amount of free water available for lubrication and flow. Zhu et al. (Zhu et al., 2016) reported that the incorporation of 50% RBP increased the standard consistency water demand by 7.2%, indicating substantial internal water consumption. Correspondingly, higher RBP contents were associated with shortened initial setting times, reflecting accelerated early hydration caused by an increase in ionic concentration in the pore solution.

From a water-distribution perspective, RCP acts primarily as a mild water diluent, tending to preserve free water within the system, whereas RBP behaves as a pronounced water sink, intensifying competition between cement particles and RPs for available mixing water. This fundamental distinction accounts for the contrasting effects of RCP and RBP on the flowability of cementitious mixtures.

5.1.3. Chemical admixtures and w/b ratio

Flowability responses to RPs are significantly conditioned by the w/b ratio. Under constant w/b conditions, slump loss in RBP-based mixtures remained limited at low dosages (a 5% reduction from 10% to 20%), but at higher replacement levels of 30%–40%, slump reductions reached up to 16%. Kim and Choi (2012) reported that although RCP replacement

reduced paste viscosity by 23%–62% at dosages ranging from 15% to 45%, mortar flowability decreased by 14%–30% due to strong adsorption effects on cement particles. The adsorption coefficient increased by 10.9%–71.7%, suggesting that RCP may compete with superplasticizers for adsorption sites. The performance of chemical admixtures, particularly polycarboxylate ether-based superplasticizers, is therefore highly sensitive to both the type and dosage of RPs. In RCP-containing systems, excessive adsorption of admixture molecules onto particle surfaces may attenuate dispersion efficiency by limiting the availability of effective dispersing chains in the pore solution. In contrast, in RBP-based systems, superplasticizers are prone to partial immobilization within the porous structure of brick powder particles, resulting in a diminished water-reducing effect. These observations indicate that the incorporation of RPs necessitates not only careful control of replacement ratio but also the rational selection and optimization of admixture type and dosage to ensure adequate dispersion and flowability.

5.1.4. Rheological characterization

Li et al. (2025) demonstrated that the rheological properties of cement paste are highly sensitive to the incorporation of RCP. As the RCP content increases from 0% to 25%, the paste exhibits elevated water absorption, packing density, and superplasticizer adsorption, while interparticle spacing decreases, resulting in marked increases in both yield stress and plastic viscosity. These effects are primarily attributed to intensified colloidal interactions, reduced dispersant efficiency, and a decrease in free water content. Deng et al. (2023) further elucidated the influence of RCP particle size (Fig. 12), reporting that for fine RCP (RCP-F, <0.045 mm) at 30 vol%, the 10-min yield stress (τ_0) and plastic viscosity (η_p) increase by approximately 107.3%–162.5% and 200%–309.1%, respectively, relative to the control. In contrast, pastes incorporating medium (RCP-M, <0.075 mm) and coarse (RCP-C, <0.15 mm) powders display smaller variations in τ_0 (9%–39%) and η_p (4%–78%), with both parameters tending to decrease as dosage increases. The shear response of the paste is also strongly particle-size dependent: RP systems tend to exhibit shear-thickening behavior, whereas coarse-powder systems are more prone to shear-thinning. After 60 min of hydration, the relative increase in η_p differs significantly among groups: approximately 43.2% for the control, 15% for the 10 vol% RCP-C paste, and 50.4% for the 10 vol% RCP-F paste.

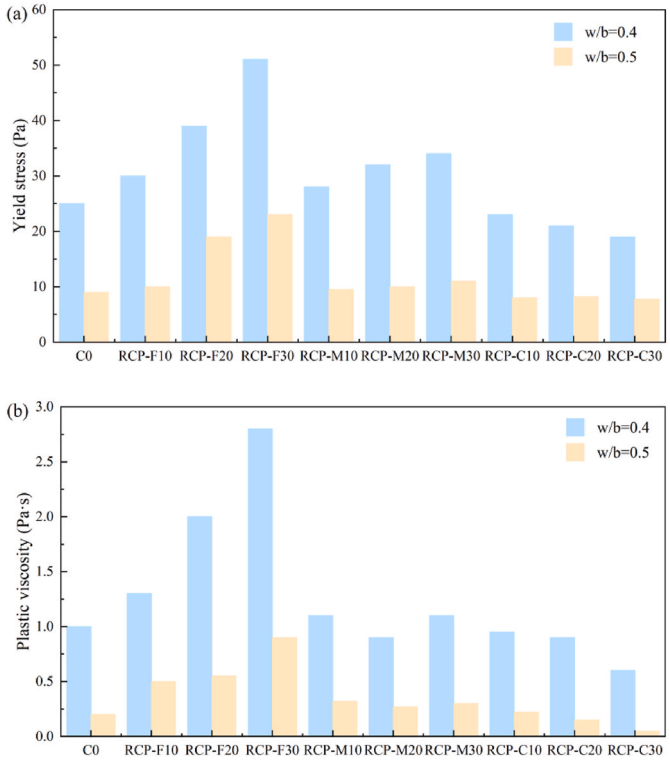

Fig. 12. Effects of RCP with different particle sizes on paste rheological properties: (a) Yield stress; (b) Plastic viscosity.

Xie et al. (Li et al., 2023; Xie et al., 2020), employing the Yodel model, systematically investigated the effects of RCP and RBP on cement paste rheology in the presence of superplasticizers. Their findings indicate that at constant flowability, increasing RCP or RBP content to 30% raises superplasticizer demand by 11.7%–71.7% while reducing yield stress by 17.7%–83.2%, with RBP inducing a more pronounced reduction. Furthermore, under equivalent rheological conditions, the incorporation of 10% RP reduces yield stress, whereas increasing the dosage to 20% and 30% results in substantial increases, ranging from 11% to 599%, suggesting a clear dosage-threshold effect on the rheological behavior of cement pastes containing RPs.

5.2. Mechanical properties

RCP consists predominantly of hydrated and partially unhydrated cementitious phases, along with residual inert aggregates (Rocha and Toledo Filho, 2024). Compared to conventional SCMs, RCP typically exhibits lower intrinsic reactivity and inferior physical performance. Nonetheless, at low replacement levels (generally ≤10%), RCP can enhance mechanical properties through its micro-filler effect, which improves particle packing and reduces pore connectivity (Song et al., 2022). Additionally, limited pozzolanic activity—primarily involving reactions between residual CH and the amorphous phases in RCP—can contribute to the formation of additional C-S-H gel, thereby promoting strength development. Several studies have reported that replacing cement with 10% RCP can increase the 28-day mortar flexural strength by more than 50% (Kasami et al., 2001), largely attributed to the nucleation-enhancing role of $CaCO_3$ present in RCP. $CaCO_3$ facilitates the hydration of C_3S and C_3A, accelerating the formation of early C-S-H gel and enhancing matrix densification (Bonavetti et al., 2001). However, at higher replacement levels, the mechanical performance typically declines due to RCP's high specific surface area and limited reactivity, which increase water demand and hinder complete hydration (Horsakulthai, 2021). As a result, porosity increases and strength is reduced. Various activation strategies—including the use of chemical activators such as CH, NaOH, or $Na_2SiO_3{\cdot}9H_2O$—have been explored to enhance the reactivity of RCP and improve its cementitious performance (Kasami et al., 2001; Ahmari et al., 2012). Nevertheless, the effectiveness of these activators tends to diminish with increasing RCP content. Florea et al. (2014) demonstrated that thermally treated RCP, when blended with slag and cement, improved 28-day mortar compressive strength by 14.7%–20.1%, indicating the potential of RCP as a partial cement substitute when properly processed and activated.

RBP, derived from crushed clay bricks, exhibits higher pozzolanic reactivity than RCP due to its greater amorphous aluminosilicate content. When incorporated into cementitious systems, RBP contributes to mechanical performance through both physical and chemical mechanisms. Physically, it improves packing density via micro-filler effects, reducing porosity and refining the pore structure (Sun et al., 2014). Chemically, RBP reacts with CH to form additional secondary C-S-H gel, which enhances matrix continuity and mechanical integrity (Kim and Choi, 2012; Ge et al., 2015). Moreover, RBP possesses internal curing capacity by retaining moisture and gradually releasing it during hydration, thereby sustaining long-term strength development—particularly under conditions of low internal humidity. Nevertheless, inconsistent findings have been reported regarding the mechanical effects of RBP. Several studies (Letelier et al., 2017; Katzer, 2013) indicate that at replacement levels exceeding 10%, the high fineness and water demand of RBP can adversely affect early-age strength by disrupting the pore structure, increasing macroporosity, and reducing the proportion of beneficial fine pores (Zeghad et al., 2017; Naceri and Hamina, 2009; O'farrell et al., 2001). For instance, 28-day

compressive strength reductions of 4.9%–22.3% have been observed at RBP replacement levels of 10%–30% (Cha et al., 2016). However, synergistic improvements in mechanical performance can be achieved when RBP is combined with other reactive SCMs such as fly ash or ground granulated blast-furnace slag. In such blended systems, the formation of low-alkalinity C-S-H gels reduces CH content and disrupts the equilibrium of the cement hydration system, thereby stimulating further hydration reactions and enhancing both strength and durability.

In conclusion, both RCP and RBP exhibit potential as sustainable mineral admixtures for improving the mechanical performance of cement-based materials. RCP primarily contributes through filler effects and limited latent reactivity, making it more suitable for low-level replacement scenarios. In contrast, RBP demonstrates higher pozzolanic activity and internal curing capacity, offering greater potential in blended or hybrid systems. To fully exploit the performance and sustainability benefits of RPs, careful consideration must be given to their particle characteristics, chemical reactivity, activation strategies, and curing conditions in the design of high-performance, low-carbon cementitious materials.

5.3. Durability

5.3.1. Chloride permeability

Table 5 summarizes the effects of RCP and RBP on the chloride penetration resistance of concrete. Overall, the performance of RCP-modified concrete shows substantial variability. As the RCP content increases, the electric flux typically decreases at first and then rises, with an optimal replacement level of approximately 10%. At high dosages, fine RCP may even exacerbate chloride transport; for instance, a 50% replacement increases the chloride diffusion coefficient by 42.8% (Qian et al., 2020). In contrast, RBP refined to a D50 below 8.5 μm markedly enhances resistance to chloride ingress, with 10% and 20% replacement levels reducing the diffusion coefficient by 31.7% and 48.15%, respectively (Ortega et al., 2018). This improvement is primarily attributed to the pozzolanic reactivity of RBP and its beneficial effects on pore-structure densification. Blended RCP–RBP systems demonstrate synergistic improvements at low to moderate replacement levels. However, when the total powder content becomes excessive, the diffusion coefficient increases sharply, reflecting weakened interfacial bonding and greater pore connectivity within the matrix (Ma et al., 2019).

5.3.2. Freeze-thaw resistance

Zhao et al. (2020b) reported that, at a water–binder ratio of 0.35, concrete incorporating 30% RP demonstrated the most favorable frost resistance. After 175 freeze–thaw cycles, the specimen exhibited a mass loss of only 2.64% and retained 62.47% of its relative dynamic modulus of elasticity. In contrast, under comparable conditions, ordinary concrete and fly ash concrete could withstand only 50 and 75 freeze–thaw cycles, respectively. Nevertheless, contrasting results have been documented. Ma et al. (2019) found that the relative dynamic modulus of elasticity declined continuously with the progression of freeze–thaw cycles for all mixes. Moreover, the inclusion of RCP further accelerated this degradation, suggesting a detrimental effect of RCP on freeze–thaw durability. After 75 cycles, the relative dynamic modulus of specimens containing 15%, 30%, and 45% RCP decreased to 0.95, 0.88, and 0.28 times that of the control mixture, respectively. The freeze–thaw durability of RCP-containing mortar can be significantly enhanced through the use of chemical activators. Improvements in pore structure and hydration kinetics contribute to reduced mass loss and higher retention of dynamic modulus under cyclic freezing and thawing conditions (Qin and Qun-Ling, 2017). Wei et al. (2024) demonstrated that thermally activated RCP substantially improved the freeze–thaw resistance of concrete, showing greater endurance over repeated cycles, lower mass loss, and reduced degradation of dynamic modulus compared to untreated RCP. Based on their experimental results, a predictive model (Eq. (2)) was developed to assess freeze–thaw durability, incorporating the number of cycles (n) and fatigue life (N) as key variables. The model exhibited excellent predictive performance ($R^2 > 0.98$), surpassing that of conventional models (Eq. (3)), as illustrated in Fig. 13.

$$D_n = a + be^{cn} \tag{2}$$

$$D_n = 1 - \frac{1 - \beta lgN}{1 - \beta \lg(N - n)} (0 < n < N) \tag{3}$$

Where β, a, b, and c are empirical fitting parameters.

5.3.3. Sulfate attack resistance

In sulfate-rich environments, RBP has demonstrated beneficial effects on chemical durability. Sulfate resistance tests indicate that mortar specimens incorporating up to 30% RBP exhibit enhanced resistance to sulfate attack (O'farrell et al., 2001). This improvement is attributed to the appropriate levels of SO_3 and CaO present in the glassy phase of RBP. The controlled release of CaO promotes the formation of secondary C-S-H and minor amounts of hydrated calcium aluminates, contributing to matrix densification and enhanced chemical resistance. However, excessive CaO content (e.g., >10%) may increase the risk of ettringite formation due to subsequent reactions with sulfates, potentially resulting in expansion and degradation. Additionally, the favorable particle size distribution of RBP facilitates uniform dispersion within the matrix and along aggregate surfaces, providing nucleation sites for hydration products. Its pozzolanic activity further contributes to CH consumption, the formation of low-alkalinity C-S-H gel, and capillary pore refinement (Nasvi et al., 2013), thereby reducing permeability and the amount of freezable water.

Table 5
Chloride diffusivity of RPs concrete.

Type	Particle size (D50), μm	Dosage, %	Electric flux, C	Chloride diffusion coefficient, 10^{-12} m/s	Ref.
RCP	4	0–50	/	2.01 → 2.87	Qian et al. (2020)
	18	0–30	857 → 1767	/	Zhao (2019)
	/		2979 → 1978→3537		Lv et al. (2009)
			1910 → 1777→2944		
			1700 → 2400→2208		
RBP	8.5	0–20	/	1.89 → 0.98	Ortega et al. (2018)
	19.6	0–30	857 → 1861	/	Zhao (2019)
	<60*		1306 → 1202→1706		Zheng (2012)
	<100*		1306 → 1281→1758		
	/		/	2.81 → 2.76→5.07	Castillo et al. (2020)
RCP + RBP	12.5	0–45	/	6.9 → 4.98→5.72	Ma et al. (2019)
	<16*	0–40		4.2 → 2.4→14.5	Xue et al. (2016)
	5.94	0–10		12 → 14.5	Rocha and Sousa-Coutinho (2018)
	11	0–30		0.11 → 0.122→0.086	Mao et al. (2020)

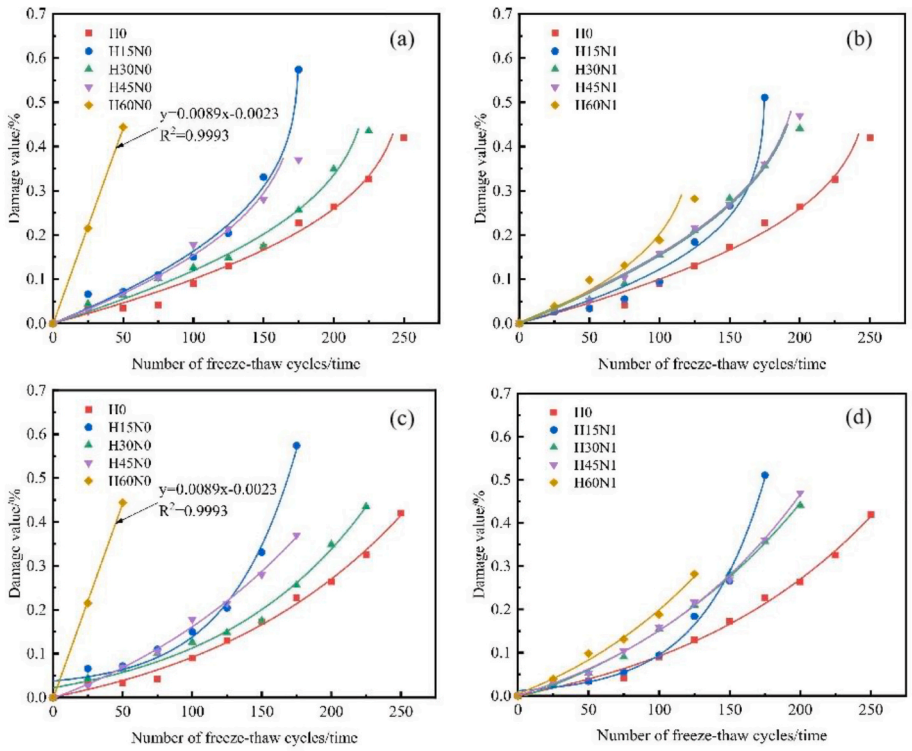

Fig. 13. Fitting curves of the damage under freeze–thaw cycles (a)Inactivated RCP concrete specimens based on Eq. (3), (b)Thermally activated RCP concrete specimens based on Eq. (3), (c)Inactivated RCP concrete specimens based on Eq. (2) and (d)Thermally activated RCP concrete specimens based on Eq. (2) (Wei et al., 2024).

5.3.4. *Carbonation resistance*

Feng et al. (Feng Tai and Guiyun, 2015) reported that the incorporation of 10% RCP significantly improves the carbonation resistance of concrete, reducing carbonation depth by 7.24% relative to the control. The carbonation resistance can be further enhanced through treatments such as $Na_2SiO_3{\cdot}9H_2O$ addition or particle grinding and refinement (Ryu et al., 2012; Bernal, 2015), in agreement with the observations of Pavlu et al. (Pavlů and Šefflová, 2017) and Kim (2017). Conversely, specimens containing 20% and 30% RCP showed increased carbonation depths of 32.6% and 45.8%, respectively. This trend is primarily attributed to the dual role of moderate RCP content: it acts as a mineral filler while promoting secondary hydration, thereby increasing matrix densification and enhancing carbonation resistance. Excessive RCP content, however, introduces interconnected pores within the coarse particles, elevating the water demand for hydration and consequently impairing the concrete's carbonation performance.

5.3.5. *Other durability*

Several studies have also demonstrated the potential of RBP to mitigate alkali–aggregate reaction (AAR)-induced expansion. Bektas and Wang et al. (Bektas and Wang, 2012) found that incorporating RBP leads to the formation of low-Ca, high-alkalinity C-S-H gels, which lower the concentration of free alkalis available for deleterious reactions. The pozzolanic activity of RBP further refines the pore structure and restricts ion mobility. By consuming CH and reducing the pH of the pore solution, RBP effectively impedes alkali ingress into silica-rich aggregates, thereby reducing the risk of expansive gel formation and AAR-related deterioration (Turanli et al., 2003).

5.4. *Volume stability*

Compared to conventional mineral admixtures such as slag or limestone, self-compacting concrete (SCC) containing RCP generally exhibits greater drying shrinkage. Nevertheless, co-blending RCP with slag has been shown to mitigate this drawback and improve overall volumetric stability. Plate tests indicate that RCP enhances early-age crack resistance by delaying crack initiation and reducing total crack area, maximum crack width, and crack length (Liu et al., 2010). These improvements are primarily attributed to enhanced matrix cohesion and the internal curing effect of fine RCP particles.

RBP has also been reported to improve the volumetric stability of cementitious materials by mitigating autogenous shrinkage (Bektas and Wang, 2012; Turanli et al., 2003). For instance, SCC incorporating 5% RBP exhibited an approximate 30% reduction in autogenous shrinkage compared to control specimens (Irki et al., 2018). This improvement is mainly ascribed to the high water absorption and gradual water-release capacity of RBP, which helps maintain internal relative humidity during hydration and prevents self-desiccation. The slow release of absorbed water further contributes to pore refinement, thereby reducing evaporation-induced shrinkage and enhancing long-term dimensional stability (Zhu et al., 2016).

6. The role of RP in concrete

6.1. *Nucleation effect*

In certain instances, untreated RBP has been observed to exhibit a retarding effect on cement hydration. For example, the time to reach the peak hydration rate was reported to be delayed from 8 h to 9.2 h in pastes containing RBP (Bektas, 2007), indicating an inhibitory effect likely caused by the presence of clay minerals or unreactive phases. However, contrasting results have been reported by Wang and Wu (2025), who demonstrated that incorporating RCP and RBP-particularly at higher dosages-increased the initial hydration rate and shortened the time to peak heat release (Fig. 14a and b). This acceleration is primarily attributed to the high fineness of the powders, which enhances the availability of nucleation sites and improves particle packing (Zhou et al., 2025; Zhan et al., 2020, 2022a).

Despite this early-stage acceleration, the lower intrinsic reactivity of RCP and RBP compared with ordinary Portland cement (OPC) results in a marked reduction in cumulative heat evolution. For instance, replacing 45% of OPC with RCP reduced cumulative heat release by approximately 33%, with similar reductions observed for RBP-containing systems (Fig. 14c and d). Such reductions in heat evolution have important macroscopic implications: the limited formation of hydration products generally leads to lower long-term strength development and a more permeable microstructure. In particular, insufficient C-S-H generation at high RP dosages may reduce matrix densification, thereby compromising durability indicators such as chloride resistance, carbonation depth, and water permeability. These effects underscore the necessity of optimizing RP replacement levels or applying activation treatments when long-term mechanical and durability performance is required.

The nucleation-promoting potential of RP can be significantly enhanced through carbonation treatment. Kong et al. (2025) reported that carbonation increased the $CaCO_3$ content in RCP-referred to as carbonated recycled concrete powder (CRCP)-which effectively enhanced C-S-H nucleation and promoted hydration. Similar improvements were observed with carbonated RBP. The underlying mechanism, illustrated in Fig. 15, involves the formation of fine $CaCO_3$ particles that provide abundant nucleation sites for C-S-H gel and facilitate the precipitation of hydration products. Additional evidence from Ouyang et al. (2017) shows that $CaCO_3$ exhibits strong Ca^{2+} adsorption capability, increasing local supersaturation and stabilizing C-S-H precipitation (Zhan et al., 2024, 2025). Moreover, the amorphous SiO_2 and Al_2O_3 phases present in RBP can participate in secondary pozzolanic reactions, further contributing to C-S-H formation and partially mitigating the long-term strength loss caused by reduced heat evolution.

6.2. Filler effect

The filler effect of RP plays a significant role in enhancing the packing density and microstructural integrity of cementitious composites (Zhan et al., 2021, 2022b; He et al., 2019a). Due to their relatively small particle size—typically around 15.4 μm, compared to approximately 20 μm for OPC—these ultrafine particles can effectively occupy the interstitial voids between larger cement grains. This leads to an improved particle size distribution, reduced porosity, and enhanced compactness of the hardened matrix (Rabehi et al., 2013). As illustrated in Fig. 16 (Manan et al., 2024), increasing the content of RCP has been shown to refine the concrete microstructure. RCP not only fills pores and microcracks but also partially participates in hydration reactions, contributing to the formation of cementitious compounds. The resultant matrix exhibits increased density and strength (Fig. 16b and c). However, the beneficial filler effect is generally observed at moderate replacement levels, typically in the range of 5–10 wt% RP, beyond which negative effects may emerge. When the replacement level exceeds approximately 15 wt%, the matrix tends to exhibit increased total porosity (Fig. 16d) and reduced flowability, ultimately compromising the compactness and performance of the concrete. Similar observations have been reported regarding RBP. Due to its lower pozzolanic reactivity, concrete incorporating high dosages of RBP tends to exhibit reduced mechanical strength. Nevertheless, compaction casting techniques have been shown to mitigate these drawbacks by improving particle packing and reducing void content (Wang and Wu, 2025; Zhao et al., 2025). X-CT analysis (Fig. 17) further confirmed that increasing RBP dosage enhanced microstructural compactness (Huang et al., 2024). This improvement is largely attributed to the filler effect of RBP, which enables it to occupy voids within the ITZs, intra-layers, and inter-layers. For RBP, optimal replacement levels are typically slightly higher than those of RCP, commonly around 10–15 wt%, whereas excessive incorporation (>20 wt%) may promote weak ITZ formation and reduce mechanical stability. Such spatial filling not only improves matrix density but also expands the effective bonding interface between aggregate particles and optimizes pore structure (Zhan et al., 2023; Xu et al., 2023), thereby reducing total porosity and enhancing mechanical properties.

However, conflicting findings have also been reported in the

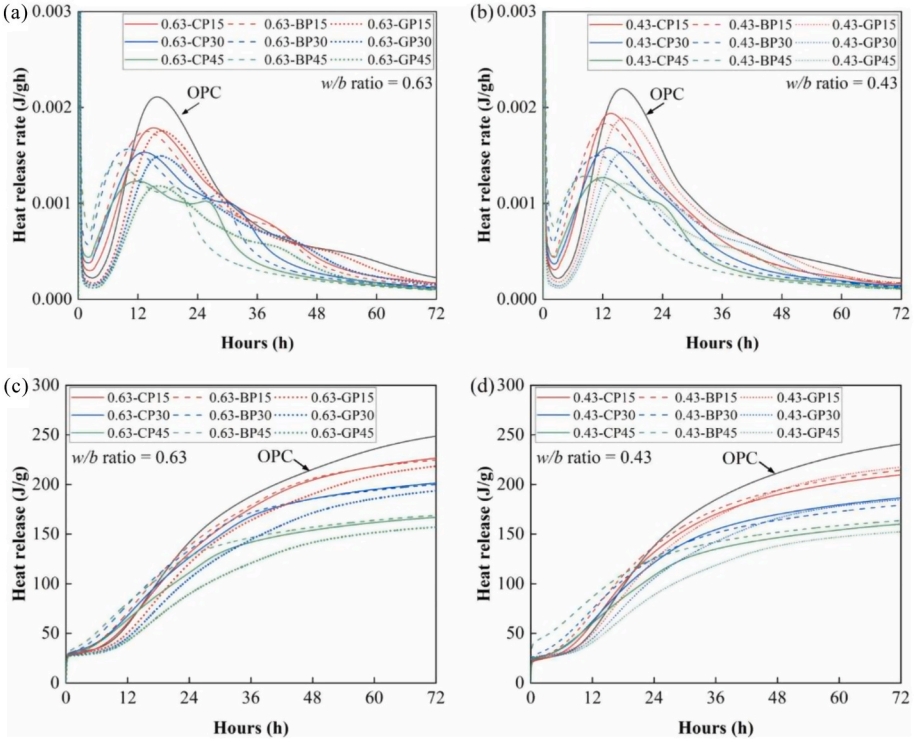

Fig. 14. Hydration heat curves of blended paste: (a) and (b) heat release rate; (c) and (d) heat release (Note: CP-recycled concrete powder; BP-recycled brick powder; GP-glass powder) (Wang and Wu, 2025).

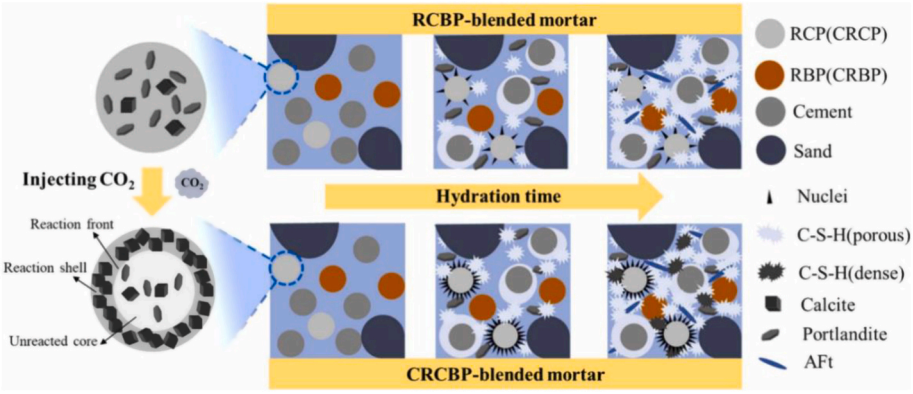

Fig. 15. Diagrammatic illustration of the impacts of carbonization treatment of RBP (Kong et al., 2025).

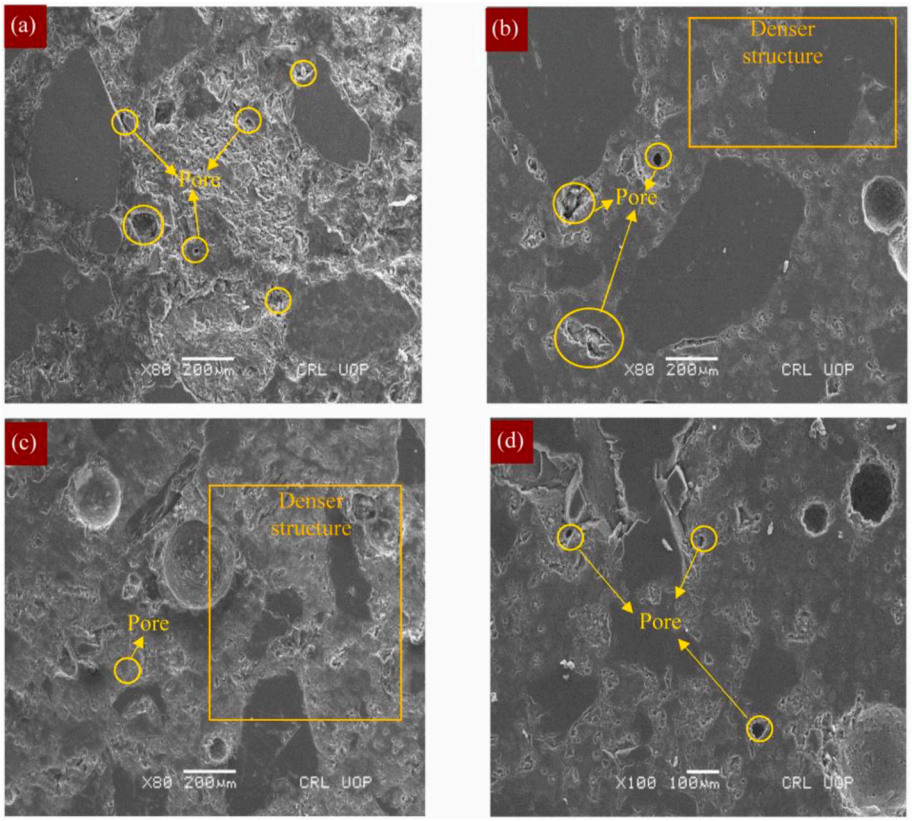

Fig. 16. SEM of concrete with different RCP content (a) Control (b) 5.0 % (c) 10 % and (d) 15 % RCP (Manan et al., 2024).

literature. Some researchers have observed that RP may negatively impact the uniformity and mechanical integrity of the hydrated cement paste (Lei et al., 2024). In particular, heterogeneous distribution of C-S-H gel, increased surface roughness, and a reduction in the content of high-stiffness C-S-H have been identified as potential concerns. Atomic force microscopy (AFM) analysis (Fig. 18) (Liu et al., 2014) revealed that regions containing both fine aggregate and RP (designated Region I) exhibited significant surface undulation, with height variations ranging from −2.2 μm to +2.2 μm and a root mean square (RMS) roughness of 595 nm. This value notably exceeds the RMS roughness (115–492 nm) previously reported for conventional mortar by Trtik et al. (2008). In contrast, Region II—devoid of RP and fine aggregate-exhibited a comparatively lower RMS roughness of 470 nm. AFM phase imaging further demonstrated that the homogeneity of C-S-H distribution in Region I followed the order: Region I-C > Region I-A > Region I-B. These findings suggest that the inclusion of RP significantly increases local surface roughness and disrupts the structural continuity of the C-S-H network.

To quantitatively assess the impact of RCP on the mechanical properties of C-S-H, nanoindentation testing based on the Hretz model was conducted. The results showed a pronounced reduction in the volume fraction of high-stiffness C-S-H in Region I—from 48% to 15%—accompanied by increases in the volume fractions of porous phases and low-stiffness C-S-H by approximately 20% and 12%, respectively. In a related study, Mondal (2008) reported that the elastic modulus of cement paste in Region II reached 32.7 GPa, while that in Region I was significantly lower at 25.6 GPa. This reduction was attributed to the presence of a poorly structured ITZ surrounding RP particles. Importantly, such reductions in nanoscale stiffness and increased heterogeneity have broader implications for durability-related properties. A higher proportion of low-stiffness C-S-H and porous phases typically leads to increased long-term deformation, including higher drying

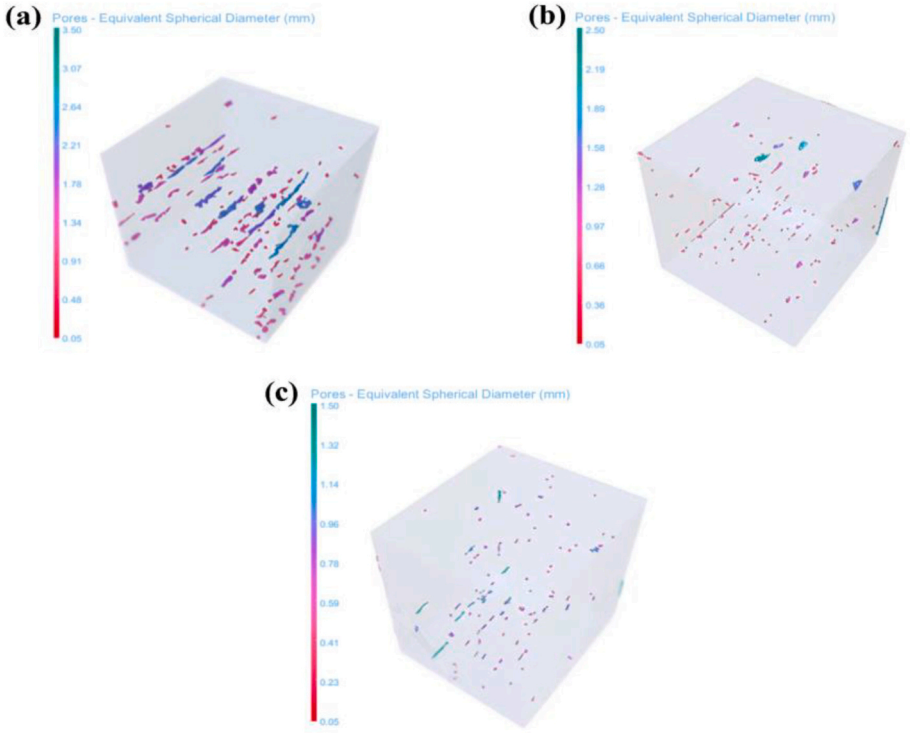

Fig. 17. Pore distribution for (a) 0-wt%, (b) 50-wt%, and (c) 100-wt% RCBP mixture (Huang et al., 2024).

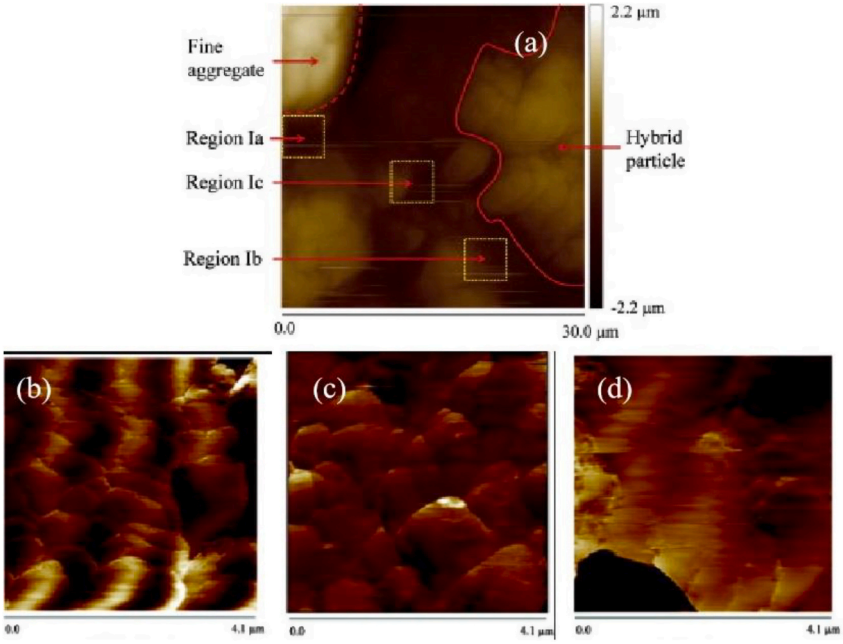

Fig. 18. AFM images of C-S-H gels in different regions (a) Region I, (b) Region I-A, (c) Region I-B and (d)Region I-C (Liu et al., 2014).

shrinkage and creep. Moreover, the weakened ITZ and discontinuous C-S-H network associated with excessive RP content may facilitate microcrack initiation and propagation under mechanical or environmental loading, thereby increasing cracking susceptibility and reducing the long-term structural stability of the composite. These findings suggest that the microstructural characteristics revealed by AFM and nanoindentation are closely linked to macroscopic durability outcomes.

Collectively, these results indicate that while moderate RP and RBP contents provide beneficial filler effects and improve microstructural densification, excessive replacement levels-generally beyond 15 wt% for RCP and 20 wt% for RBP-can disrupt C-S-H network continuity and degrade the mechanical integrity of the hardened matrix.

6.3. *Pozzolanic effect*

The pozzolanic activity of RP has been extensively documented in the literature. These materials contain reactive SiO_2 and Al_2O_3, which can chemically react with CH—a byproduct of cement hydration—to form additional C-S-H gel (Irki et al., 2018; Reig et al., 2013; Robayo et al., 2016). The formation of secondary C-S-H not only increases the

overall gel volume but also contributes to the refinement of the pore structure by reducing capillary pore connectivity and decreasing total porosity in cementitious matrices (Wang et al., 2001). TG-DSC analysis (Liu Dong et al., 2016) conducted on RCP-blended pastes further confirmed the occurrence of pozzolanic reactions. A broad endothermic peak between 150 °C and 550 °C was observed, corresponding to the loss of bound water from C-S-H gel and AFt, as well as partial decomposition of carbonates. At 550 °C, a mass loss of 4.53% was recorded, while an additional 6.4% mass loss between 550 °C and 750 °C was attributed to the continued dehydration of C-S-H and its decomposition into β-C_2S. Microstructural observations (Fig. 19) further corroborated the coexistence of RP and C-S-H gel within the hardened matrix (Xiao et al., 2018).

Compared to conventional concrete, RCP-enhanced cementitious composites exhibit a more robust microstructural framework due to the synergistic effects of primary hydration and pozzolanic reactions. The resulting matrix demonstrates improved bonding strength at the ITZ, increased matrix hardness, and enhanced resistance to flexural and tensile stresses. The reactive SiO_2 and Al_2O_3 in RCP react with CH to form a stable, cohesive network comprising hydrated silicates and aluminates, thereby improving matrix continuity and structural integrity (Taha and Alnahhal, 2025). MIP analysis (Kong et al., 2025) revealed that the incorporation of carbonated recycled concrete powder (CRCP) reduced total porosity from 23.82% to 17.92%. Concurrently, the proportion of harmless pores (<20 nm) increased from 13.6% to 17.2%, while the proportion of harmful pores (>200 nm) decreased from 49.64% to 33.1% (Fig. 20). These improvements are primarily attributed to the supplementary C-S-H formed through pozzolanic reactions, which effectively fill larger voids and refine the pore structure.

In addition to its pozzolanic contribution, RCP also improves the microstructure of the ITZ at both aggregate–mortar and sand–cement interfaces through its filler effect and secondary hydration. Experimental findings indicate that when the RCP replacement ratio is maintained below 30%, the flexural and splitting tensile strengths of the modified concrete surpass those of control specimens made with OPC (Xiao et al., 2018). Moreover, an increase in RCP content correlates with reduced failure displacement, suggesting enhanced structural compactness and improved load-bearing stability.

7. Environmental and economic effects

The utilization of RPs derived from C&D waste, including RCP and RBP, has been widely reported to offer notable environmental and economic advantages when applied as partial replacements for OPC. However, these benefits are strongly dependent on the defined system boundaries, functional units, and underlying assumptions adopted in LCA studies. Most available environmental assessments of RPs are conducted under cradle-to-gate system boundaries, typically encompassing raw material collection, crushing, grinding, and, in some cases, pretreatment processes, while excluding downstream construction, use, and end-of-life stages. Using a functional unit of 1 ton of binder material, several studies report that the energy demand for producing RPs is substantially lower than that of OPC. For example, LCA data indicate that producing 1 ton of RP material may require approximately 18 kWh, compared with about 105 kWh/t specified for OPC in the *Energy Consumption Standard of Unit Product of Portland Cement (GB 16780–2012)* (Xiao et al., 2018). Correspondingly, when upstream energy inputs and associated emission factors are considered, reported cradle-to-gate carbon footprints for recycled cementitious materials range around 48.8 kg CO_2/t, which is markedly lower than the commonly cited value of approximately 1095 kg CO_2/t for OPC (Xu et al., 2013; Chan et al., 2015). It should be noted, however, that such comparisons represent potential reductions under specific assumptions, rather than universally applicable values.

Within the broader category of RPs, laboratory-scale studies suggest that the grinding of RCP typically consumes around 0.182 kWh/kg, resulting in estimated carbon emissions of 0.19–0.25 kg CO_2/kg, which are lower than the approximately 0.82 kg CO_2-eq/kg reported for OPC production (Tan et al., 2020), Nevertheless, many of these estimates are derived by directly converting laboratory energy consumption into carbon emissions, without fully accounting for additional contributors such as transportation distances, pretreatment requirements, plant-scale efficiency, or regional electricity mix variability (He et al., 2019b; Turner and Collins, 2013). More comprehensive scenario-based LCA studies indicate that RCP produced via integrated thermo-mechanical processing could achieve carbon emission reductions of up to 94% relative to OPC under optimized conditions. Moreover, when RCP and recycled coarse aggregates are jointly incorporated at replacement ratios of 10% and 25%, respectively, reported reductions in the embodied carbon of concrete range from approximately 8.5%–20%, depending on mix design and system boundary definitions (Cantero et al., 2020b).

Carbonation treatment has been further proposed as a strategy to enhance the decarbonization potential of RPs by enabling direct CO_2 uptake. Under cradle-to-gate assumptions, some studies report that the carbon footprint of carbonated recycled brick powder (CRBP) can be as low as 9.72 kg CO_2/t, compared with reported OPC values ranging up to 700 kg CO_2/t (Kong et al., 2025; Mu et al., 2018). On this basis,

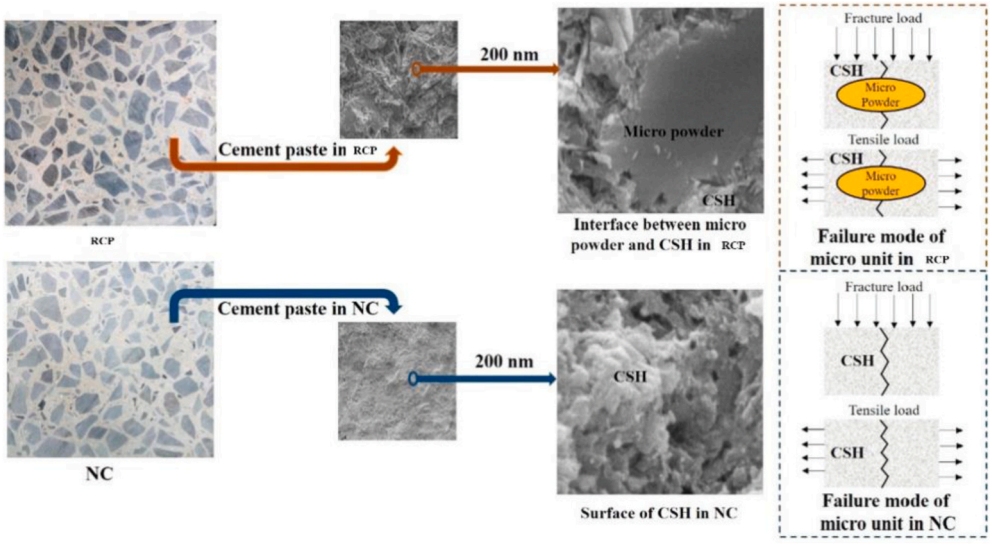

Fig. 19. Failure mechanism of RCP under bending and tensile splitting loading (Xiao et al., 2018).

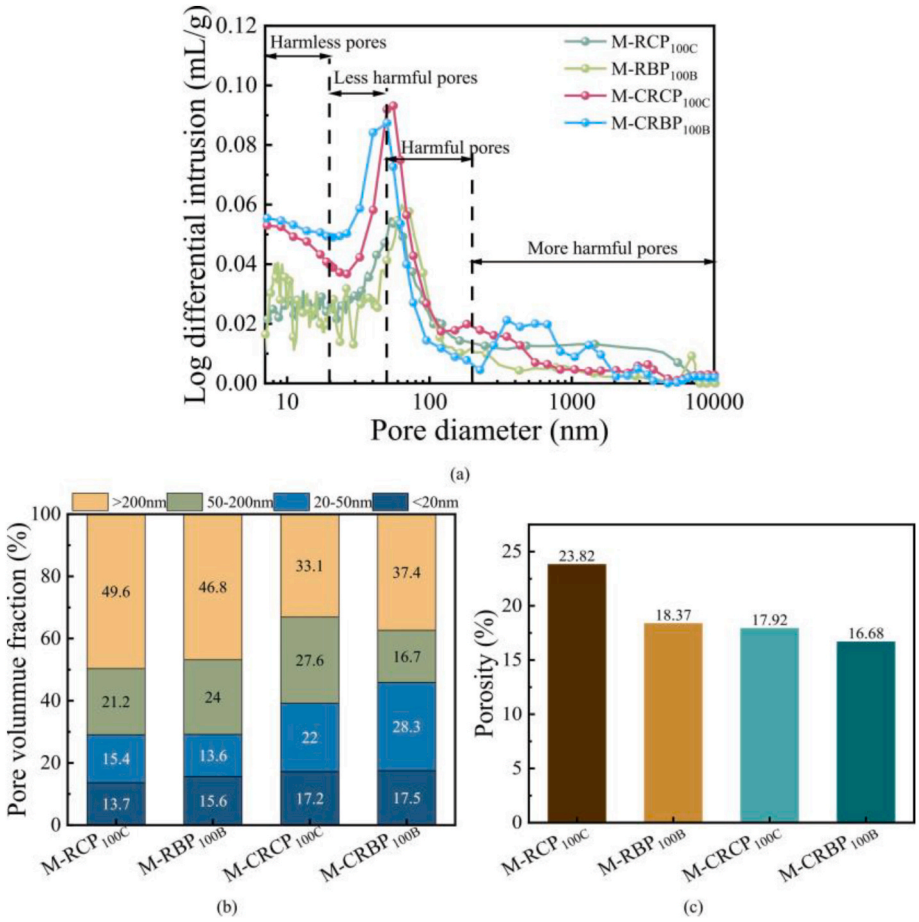

Fig. 20. The pore structure of composite mortar. (a) Cumulative intrusions; (b) Pore volume fraction; (c) Porosity (Kong et al., 2025).

substituting 20% of OPC with RBP in blended cementitious systems may result in an emission reduction of approximately 138 kg CO_2/t of binder. However, the actual CO_2 reduction is highly sensitive to carbonation protocols, curing efficiency, and the source of CO_2. Reported overall emission reductions associated with carbonated RBP therefore vary, typically ranging from 19.76% to 21.19% under controlled experimental conditions (Mahoutian and Shao, 2016). From an economic perspective, preliminary cost analyses-often based on localized assumptions and excluding large-scale logistics-suggest that the production cost of CRBP can be relatively low (e.g., approximately 1.16 USD/t), compared with around 100 USD/t for OPC. Even when accounting for the maximum reported additional cost of carbonation treatment (approximately 3.17 USD/t), partial substitution of OPC with 20% CRBP has been estimated to yield net cost reductions of roughly 19%. These figures should be interpreted as indicative estimates, as actual costs are strongly influenced by regional labor, energy prices, processing scale, and transportation distance.

Beyond quantified carbon and cost indicators, the utilization of recycled cementitious materials contributes to reduced landfill demand for C&D waste and mitigates the environmental impacts associated with virgin raw material extraction and transportation. Despite these promising trends, substantial variability remains in reported environmental and economic outcomes due to differences in RP composition, processing routes, carbonation efficiency, and end-of-life scenarios. To improve comparability and robustness, future studies should adopt standardized functional units, clearly defined system boundaries, and transparent assumptions in LCA analyses, particularly when extrapolating laboratory-scale results to industrial applications (Di Maria et al., 2018).

8. Conclusions and outlook

The incorporation of RCP into cementitious systems represents a promising strategy for the sustainable utilization of C&D waste. Numerous studies have confirmed that RCP can effectively enhance the hydration reactions of C_3S and C_3A, owing to its micro-filler effect and the presence of reactive components such as CaO, SiO_2, and Al_2O_3. These constituents promote the formation of C-S-H gel, which acts as nucleation sites, refines the pore structure, and improves both the mechanical performance and durability of cement-based materials. Under appropriate activation methods—thermal, mechanical, or chemical—the latent pozzolanic reactivity of RCP can be effectively stimulated, rendering it a viable and eco-friendly mineral admixture for partial cement replacement. In particular, carbonation treatment has been shown to enhance the physicochemical properties of RCP, increase its reactivity and structural compactness within cementitious matrices, and enable carbon sequestration through CO_2 mineralization. These features further underscore the potential of RCP in the development of low-carbon construction materials and the promotion of carbon-neutral building practices.

Despite these advancements, current research on RCP has predominantly focused on its effects on hydration kinetics, flowability, and early-age mechanical strength. However, studies on its long-term durability—such as volume stability, crack resistance, and its role within the ITZ—remain limited. Moreover, the mechanisms governing the morphology and spatial distribution of C-S-H gel in the presence of RCP—particularly under different activation regimes—are not yet fully understood. Future research should therefore utilize advanced characterization techniques, including nanoindentation, X-CT, and multiscale numerical modeling, to elucidate the microstructural evolution and

performance mechanisms of RCP-blended systems. In particular, multiscale numerical modeling should be leveraged to quantitatively link microstructural characteristics-such as C-S-H morphology, pore network connectivity, and ITZ heterogeneity-with macroscopic mechanical and durability performance, including stiffness development, creep and shrinkage behavior, permeability, and long-term degradation indices. Establishing these cross-scale correlations will greatly enhance the practical applicability of laboratory findings in structural design and service-life prediction. In addition, priority should be given to systematic durability assessments employing standardized tests such as freeze-thaw resistance, chloride ion diffusion, sulfate attack, and carbonation resistance, which are essential for evaluating long-term performance and ensuring field-scale implementation. Such investigations will be essential for bridging the gap between laboratory-scale findings and field-scale implementation.

In comparison, research on RBP remains in its early stages. Significant differences in composition, mineralogy, and reactivity have been observed between RBP and RCP. RBP, which is widely available, is primarily composed of SiO_2 and Al_2O_3, conferring it with latent pozzolanic activity. Under alkaline or chemical activation, the amorphous phases in RBP can participate in the formation of C–A–S–H gels, thereby contributing to matrix densification and strength development. Preliminary studies have also indicated that RBP possesses CO_2 uptake capacity, facilitating the formation of $CaCO_3$ and carbonate–aluminate compounds. These carbonation products can refine pore structure, reduce permeability, enhance microstructural uniformity, and improve nucleation efficiency for subsequent hydration reactions.

However, due to its inherently low reactivity, the beneficial effects of RBP are highly dependent on the activation strategy employed. Currently, systematic investigations into its multiscale hydration behavior, long-term durability, and interactions within the ITZ are lacking. To enable the practical application of RBP in cementitious composites, future research should focus on its hydration kinetics, the evolution of phase assemblages under various activation conditions, and its influence on dimensional stability, crack resistance, and environmental durability. Particular emphasis should be placed on durability evaluations involving freeze–thaw cycling, chloride penetration, sulfate exposure, and carbonation-induced deterioration, as these tests are critical for assessing RBP's performance in marine, coastal, and other aggressive service environments. Furthermore, the integration of multiscale numerical modeling is needed to map the evolution of RBP-modified microstructures onto macroscopic engineering properties-such as load-bearing capacity, transport resistance, and long-term reliability-which will support its broader adoption as a sustainable SCMs. These efforts will be critical in advancing the engineering application of RBP and realizing its potential as a sustainable supplementary cementitious material.

CRediT authorship contribution statement

Changshun Zhou: Conceptualization, Writing – original draft. **Dapeng Wang:** Resources. **Peimin Zhan:** Visualization. **Hongyu Tao:** Investigation, Methodology. **Mingyong Li:** Supervision. **Juan Wang:** Data curation, Funding acquisition, Writing – review & editing.

Declaration of competing interest

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

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Data availability

No data was used for the research described in the article.

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