

The Utilization of Recycled Powder: A Critical Review

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Abstract

Recycled powder (RP), a by-product with a particle size smaller than 150 μm , is generated during the processing of construction and demolition waste (CDW) for recycled aggregate production. RP mainly consists of recycled concrete powder and recycled brick powder. Previous studies have demonstrated that RP can serve as a supplementary cementitious material (SCM) in concrete production. Due to the heterogeneity of parent materials with different ages, service environments, and compositions, the physicochemical properties and reactivity of RP vary significantly, which largely accounts for the inconsistent results reported in the literature. This paper presents a critical review of the application of RP as an SCM in construction. The preparation technologies, chemical and physical properties, microstructural characteristics, and activation methods of RP are systematically examined. Owing to its irregular and rough surface morphology, RP tends to reduce workability and increase water demand when incorporated as an SCM. Nevertheless, when the replacement level and median particle size are limited (typically below 30% and 20 μm , respectively), RP can contribute through micro-filling, nucleation, and limited pozzolanic effects, thereby mitigating adverse impacts on mechanical and durability properties. The mechanisms and effectiveness of mechanical grinding, thermal activation, chemical activation, and CO_2 treatment are comparatively evaluated. Moreover, the incorporation of RP in cement-based materials offers significant economic and environmental benefits.

Keywords: recycled powder; construction and demolition waste; chemical and physical properties; micro-structure; treatment



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1. Introduction

With the rapid development of urbanization, a substantial amount of construction and demolition waste has been generated worldwide and will continue to increase in the next decades [1–4]. CDW is predominantly disposed by landfilling and open stacking, which not only cause social and environmental problems but also results in a significant waste of resources [5,6]. The proportion of concrete and brick waste in CDW is more than 80%; RP accounts for more than 20–30% of concrete and brick waste [7]. Improving the reuse rate of concrete and brick waste is an effective way to reduce CDW and carbon emissions. Therefore, many scholars have studied the recycling of CDW and developed the recycling technology of CDW. The concrete and waste bricks in CDW are screened

out and broken into recycled aggregates to produce recycled aggregate concrete [8–10]. A number of investigations on the microscopic properties, mechanical properties, construction performance, and durability of recycled concrete have found that the use of recycled aggregate will reduce the performance of concrete, especially its durability and mechanical properties, which are very important to the service life of concrete [11–13].

In the process of crushing and producing recycled aggregate, RP with a particle size below 150 μm can be obtained through a dust collector. The RP obtained in this way generally has a larger particle size (more than 75 μm) and lower activity than cement and cannot be directly used as a supplementary cementitious material in concrete production like fly ash and mineral powder. It is generally only used as an inert filler to improve the particle size distribution of concrete [14,15]. The main components of the RP contain SiO_2 and Al_2O_3 , which is similar to the composition of fly ash and has a certain pozzolanic effect [16–18].

In recent years, beyond material-scale investigations, recycled powders derived from construction and demolition waste—such as recycled concrete powder, brick powder, glass powder, and ceramic waste powder—have attracted increasing attention as supplementary cementitious materials or precursors in cement-based systems. As a supplementary cementitious material, RP has a very low carbon emission of about 32 kg/t, which promotes efficient carbon reduction in the construction industry [19–22]. To enhance the reactivity and broaden the application potential of RP, various activation methods—including mechanical grinding, chemical activation, thermal treatment, and carbonation—have been proposed and investigated. While numerous studies have reported their effects on hydration behavior, strength development, and durability [23,24], the reported results remain highly scattered and, in some cases, contradictory. Similar replacement levels of recycled powder have been shown to both improve and deteriorate mechanical and durability performance, indicating that empirical dosage-based conclusions are insufficient to explain the observed variability [25–27].

Unlike existing review articles that primarily summarize preparation methods or report performance trends, the present review explicitly addresses the origin of these inconsistencies. The central premise of this work is that the performance of recycled powder cannot be evaluated solely based on replacement ratio or activation technique but must be interpreted through the coupled effects of source characteristics (parent material type, service age, and carbonation degree), particle-scale structure (size, morphology, and amorphization), and reaction environment. Accordingly, this review contributes beyond existing publications in three aspects: (i) it establishes a source–microstructure–reactivity–performance linkage to rationalize divergent experimental results; (ii) it critically compares mechanical, thermal, chemical, and CO_2 activation methods from a mechanism- and applicability-oriented perspective, rather than strength enhancement alone; and (iii) it extends the discussion from paste and mortar systems to engineering-oriented applications, including UHPC, SCC, and reinforced concrete elements. These contributions aim to provide mechanism-based performance envelopes to support the rational and reliable utilization of recycled powder in sustainable concrete construction.

2. Fundamental Properties of RP

2.1. Production Technology

CDW mainly consists of concrete, brick, glass, ceramic, steel, plastic and wood waste [28]. The reuse of waste concrete and bricks mainly includes the following four parts [14,29]: (1) Separating waste concrete and bricks from other substances. (2) The waste concrete and bricks are broken into 5–31.5 mm recycled coarse aggregate by a jaw crusher, (3) The recycled coarse aggregate is further crushed into recycled fine aggregate with a

particle size of 150 μm –5 mm by using a roll crusher. (4) A ball mill is used to produce RP, resulting in granulometry less than 150 μm [30,31]. Figure 1 shows the preparation process of RP. The RP directly obtained from the production of recycled aggregates from waste concrete and bricks has a large particle size and low activity and cannot be directly used as SCM in concrete [32].

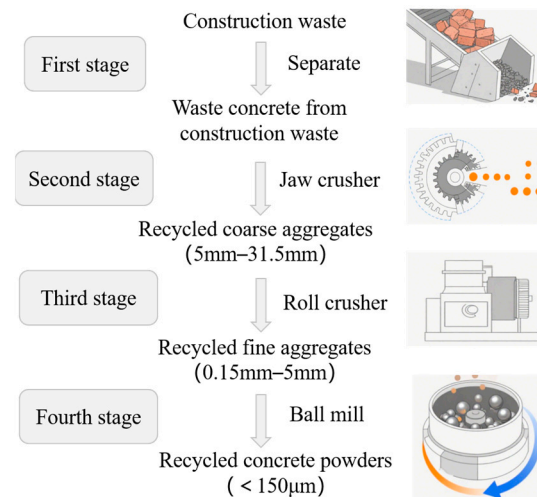


Figure 1. RCP production.

At present, the most commonly used RP preparation method is mechanical grinding. In general, a jaw crusher and roll crusher are used to produce aggregates with larger particle size, and a planetary ball mill is used to produce RP [33]. In addition, RP can also be treated by wet grinding [34,35] and jet grinding [36]. The micro-structure of RP produced by wet grinding and jet grinding is more regular than that produced by a ball mill, and the mechanical properties of concrete with wet-milled and jet-milled RP are better than those with ball-milled RP [36]. The same treatment method can lead to different effects on different raw materials. In general, raw materials dominated by calcium-bearing phases (e.g., calcite) tend to exhibit lower grinding resistance than those rich in silicon-bearing phases (e.g., quartz), due to differences in mineralogical composition and microstructural characteristics, and are therefore relatively easier to grind [37]. The grinding can increase the specific surface area and reduce the particle size of the RP. The specific surface area ranges from 170 to 860 m^2/kg , and the particle size ranges from 0.249 to 125 μm [32].

In addition to the type of raw materials, grinding time also affects the specific surface area and particle size distribution. Researchers found that as the grinding time increased, the specific surface area increased and the particle size decreased. However, with the extension of time, the grinding efficiency decreases [31,38]. Dun et al. [39] ground RP for 80 min, 100 min and 120 min, respectively. It was found that the particle size of 80 min changed greatly, and the particle size distribution of 100 min and 120 min was almost the same. Tang et al. [40] also investigated the relationship between grinding time and specific surface area. It was found that with the increase in grinding time, the specific surface area increased rapidly in the early stage, showing a linear growth, and tended to be gentle in the later stage. Therefore, RPs from different sources need to be tested many times to determine the best grinding method and time.

2.2. Physical and Chemical Properties of RP

The microstructure of RP affects its application in cement-based materials. Different from the smooth spherical structure of fly ash [41–43], RP exhibits irregular serrated morphology and a rough surface [34,44–46] (Figure 2). This irregular particle shape of RP

leads to poor fluidity and increased water demand [47–50]. On the other hand, Suwan et al. [51,52] found that the porous structure of the material can store water in advance. When the hydration water in the pores is insufficient, the stored water is released to further promote the secondary hydration of the slurry.

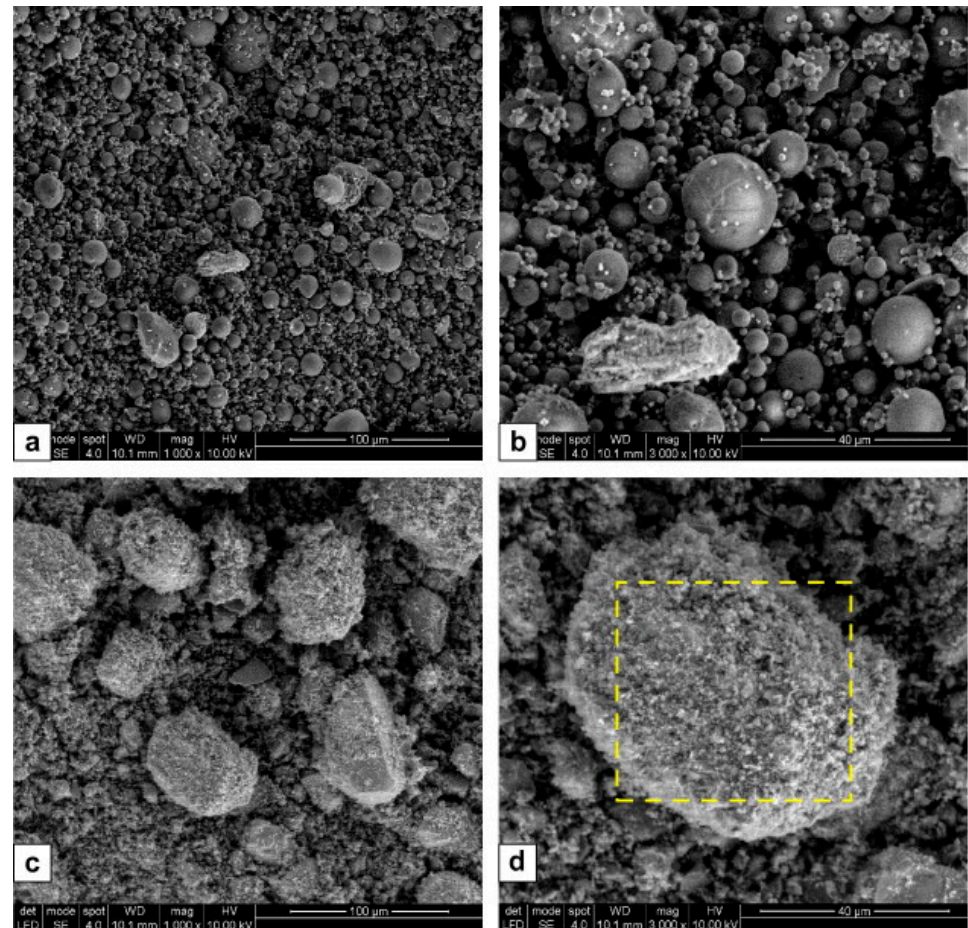


Figure 2. Low and high-magnification SEM micrographs of fly ash (a,b) and RP (c,d) [43].

RP is obtained from crushed waste concrete and bricks, and the curing age of the parent concrete significantly influences its physicochemical properties and reactivity. Concrete subjected to longer curing periods and service cycles typically exhibits higher cement hydration levels, resulting in reduced unhydrated clinker phases (C_3S and C_2S) and increased proportions of stable hydration products [53,54]. Consequently, recycled powder from aged concrete generally possesses lower inherent hydraulicity or pozzolanic activity, primarily contributing through microfilling and nucleation effects within cementitious systems [55]. Conversely, RP from fresh concrete or precast components with shorter curing periods retain more unhydrated cementitious minerals and metastable hydration products. CSH gel, unhydrated cement particles, SiO_2 particles, calcium aluminate hydrate (calcium aluminate), and calcium carbonate crystals can be observed in RP [39,56,57] (Figure 3). These materials can be reactivated in alkaline or strongly alkaline environments [54,58,59]. Studies indicate that the physicochemical properties of recycled aggregates—such as particle size distribution, specific surface area, and water absorption—vary with the curing time of the source concrete. When recycled aggregates are used in new mixtures, these properties influence their rheological behavior and hydration kinetics [60]. Furthermore, long-term environmental exposure—particularly carbonation—alters the Ca/Si ratio and structural order of hydration products, thereby influencing dissolution kinetics and reaction

pathways during recycled powder reuse. Studies on carbonated recycled cement paste powder have confirmed this phenomenon [61]. Therefore, differences in the curing age of source concrete and service conditions are critical factors determining the performance and applicability of recycled powders. SiO_2 primarily originates from fine aggregates and unreacted cement particles, while calcium carbonate crystals mainly stem from coarse aggregates and the carbonation of cementitious materials. The presence of these hydration products and crystals results in a complex surface structure and increased porosity of RP [62]. Mechanical grinding can make surfaces smoother and increase fluidity [63].

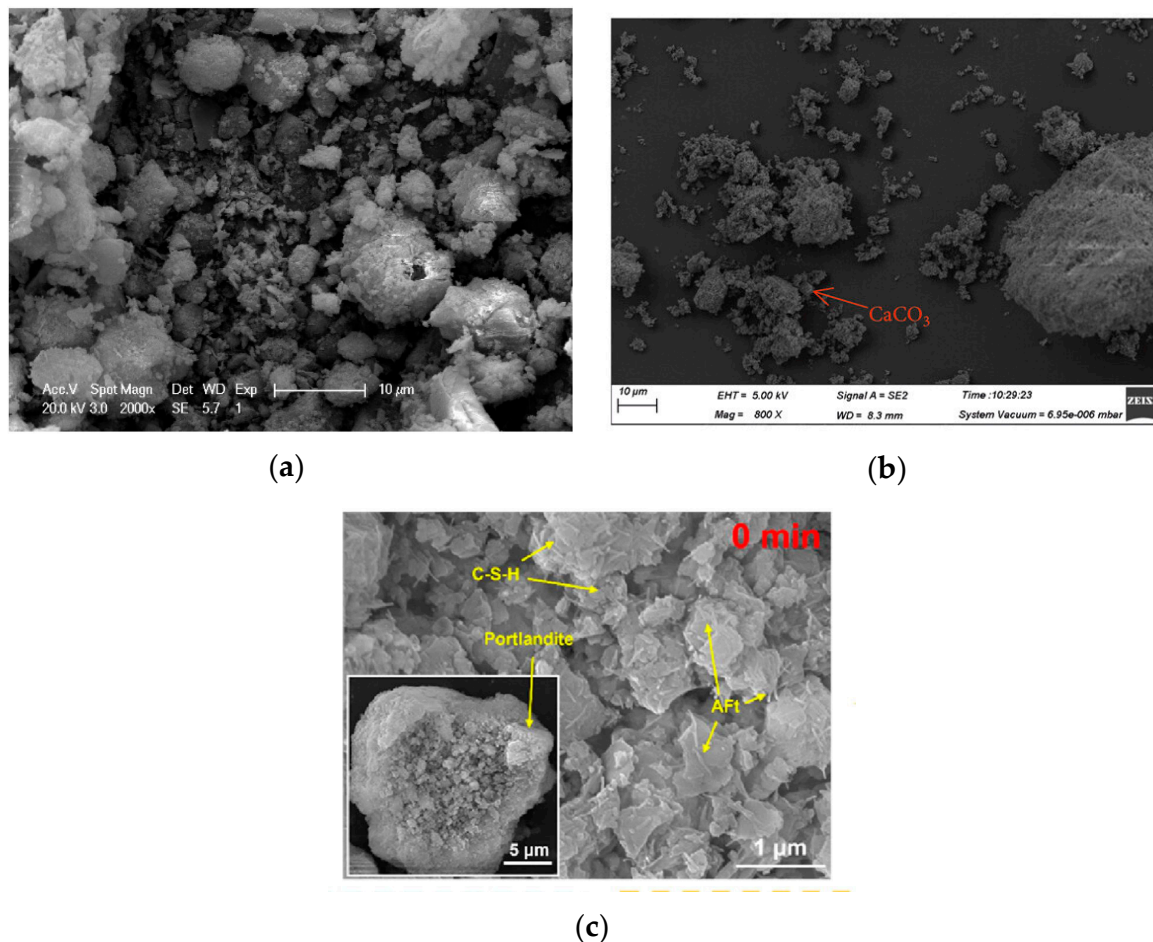


Figure 3. The microstructure of different RPs (a) [57] (b) [39] (c) [56].

Although RP has diverse sources, its primary constituent elements including Ca, Si, Al, O, with the main oxides being calcium oxide, silicon dioxide, and aluminum oxide, as shown in Table 1. Compared to cement, RP exhibits a higher silicon content and relatively lower calcium content, primarily due to the raw material sources used in RP production [64,65]. RP obtained from crushed waste concrete and bricks typically contains a high SiO_2 content, generally exceeding 30%. RP derived from crushed cement paste generally exhibits a high CaO content, typically exceeding 50%. The substantial Si and Al in RP, like supplementary cementitious materials such as fly ash, exhibit pozzolanic effects [14]. Since some of the SiO_2 in RP originates from aggregates, which are inert materials, they lack pozzolanic activity [32]. In summary, RP is a material with diverse sources, complex composition, rough surface, and high water absorption, which limits its application as a supplementary cementitious material in concrete. How to obtain RP with stable properties and high reactivity remains an ongoing research focus for scholars [66,67].

Table 1. Main chemical compositions of RCPs.

No.	Source	SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O	SO ₃
1	[68]	46.84	20.86	15.49	6.95	2.66	1.00	2.76	2.05
2	[47]	57.88	1.58	26.28	3.56	3.8	-	2.32	0.28
3	[25]	47.90	19.01	19.04	2.32	4.2	-	2.60	1.68
4	[17]	48.82	25.5	9.43	7.87	0.42	-	4.48	1.16
5	[26]	61.74	16.01	12.53	2.56	1.07	1.38	3.06	0.80
6	[69]	37.64	42.35	7.84	4.52	4.61	-	1.26	0.86
7	[70]	62.8	2.6	17.9	6.4	1.3	-	-	-
8	[71]	44.89	26.23	13.28	4.48	5.27	1.71	0.77	1.07
9	[72]	35.52	43.92	8.60	4.71	6.74	-	1.29	2.32
10	[42]	19.17	63.76	6.86	2.34	0.90	0.20	0.58	3.32
11	[73]	38.5	29.5	12.3	8.0	3.3	1.6	3.0	-
		19.5	65.9	5.44	3.38	1.43	0.15	0.30	-

2.3. Activity Index

The activity index is the most critical indicator for RP when used as a supplementary cementitious material. Currently, the most widely adopted standards are the GB/T 1596–2017 [74] and EN 450-1 [75]. The activity index is defined as the ratio of the compressive strength of mortar containing 30% cementitious material to that of mortar without cementitious material. A higher ratio indicates a greater proportion of active components within the cementitious material [74]. The RP activity index is closely related to the grinding equipment and time, source, and original strength of the waste concrete. Zhang et al. [34] found that by using wet grinding to prepare RP, the D₅₀ could be reduced to 249 nm, thereby enhancing the early strength and water resistance of the mortar. Yu et al. [36] found that RP ground using a jet mill exhibited a narrow particle size distribution, uniform particle shape, excellent filling effect, and activity as high as 70.2%, which was 7.4% higher than that achieved by vibratory ball milling. Grinding time primarily affects the particle size and specific surface area of RP. The activity index increases as the median particle size of RP decreases and the specific surface area increases [76,77]. It can be observed that as grinding time increases, the activity index of RP gradually rises, but a threshold exists. The optimal grinding time is approximately 60 min. Prolonged grinding beyond this duration leads to a diminishing marginal gain—or even a slight decline—in RP activity, as the system approaches a mechanical activation saturation state. Consequently, further energy input mainly results in agglomeration and energy dissipation rather than additional structural activation, causing unnecessary resource and energy consumption. The source of RP also affects the activity index. Li et al. [78] found that the activity index of RP gradually increased with the rising content of waste brick powder, primarily due to the higher concentration of active SiO₂ in the waste brick powder. Wu et al. [44] conducted comparative tests on waste concrete powder, mortar powder and pure slurry powder. They found that recycled mortar powder exhibited the highest reactivity, while recycled concrete powder and pure slurry powder demonstrated reduced reactivity due to their higher content of hydration products and inert substances. Chen et al. [79] compared the activity indices of waste concrete powder from different strength grades. They found that the activity index gradually increased with the rise in concrete's initial strength.

2.4. Critical Synthesis: Why RP Properties Reported in the Literature Are Highly Scattered

A critical comparison of published studies indicates that the wide scatter in reported RP activity indices, strength contributions, and durability performance cannot be attributed to experimental uncertainty alone. Instead, it originates from fundamental differences in RP source characteristics. RP derived from aged and highly carbonated concrete is

dominated by stable phases (calcite and low-Ca CSH) and therefore behaves primarily as an inert micro-filler. In contrast, RP obtained from younger concrete or precast waste may retain unhydrated clinker phases and metastable hydrates, enabling limited hydraulic or pozzolanic reactivity under alkaline conditions. Failure to explicitly report parent material age, exposure history, and carbonation degree explains why similar replacement ratios have led to contradictory conclusions in different studies. This observation highlights the necessity of moving from empirical replacement limits toward mechanism-based performance evaluation.

3. Micro-Properties of the Cementitious Materials with RP

3.1. Hydration Reaction

The hydration reaction of cementitious materials influences their microstructure and macroscopic properties. The addition of RP acts as a diluent, increasing the early heat release rate of cementitious materials and shortening the induction period [80–82]. Research has found [64,65,83,84] that RP also exerts a nucleating effect, primarily promoting early hydration within the first 30 min. As time progresses, the hydration reaction weakens, resulting in a decrease in the cumulative heat released. Of course, hydration is also closely related to the dosage of RP. Chen et al. [85] and Rahhal et al. [86] found that both the hydration heat release rate and cumulative hydration heat decreased with increasing RP content. Shao et al. [87] reached the same conclusion, reporting a 35.4% reduction in cumulative hydration heat after 3 days when RP content reached 40%.

Figure 4 shows the relationship between cumulative heat release during hydration and RP replacement ratio [64,87–89]. As the RP replacement ratio increases, the cumulative peak heat release decreases. Tang et al. [40] found that cumulative heat release not only decreased with increasing RP replacement ratio but also exhibited a linear relationship between the two. The linear relationship equation is shown in Equation (1). The primary reason for the reduced hydration heat is that the active substances in RP are lower than those in cement, resulting in a decrease in the hydratable components [90]; moreover, the addition of RP reduces the quantity of hydration products such as calcium hydroxide and CSH gel [14]. However, this linear assumption may no longer be valid when RP contains a significant nano-sized fraction. Nano-scale RP particles possess extremely high specific surface area and surface energy and can act as effective nucleation centers for hydration products, particularly CSH gel. This nucleation and acceleration effect enhances early-age hydration kinetics and may partially compensate for, or even locally outweigh, the dilution effect caused by cement replacement.

$$(H_R = 1 - 0.0064PP_{RP}) \quad (R^2 = 0.93) \quad (1)$$

where H_R is the hydration heat of the cementitious material and P_{RP} is the replacement rate of RP (%).

On the other hand, Hou et al. [91] found that the cumulative hydration heat over 12 h for mixtures containing 10% and 20% RP was higher than that of the control group. Deng et al. [64] achieved the same results by modifying RP through wet grinding. Reducing RP particle size to the nanoscale exposes more unhydrated particles, increasing the number of hydration reaction sites and causing the hydration heat to rise as RP content increases. Yang et al. [35] and Wang et al. [92] conducted experiments using ultrafine RP particles, demonstrating that RP nanoparticles accelerate the hydration rate, shorten the induction period, increase cumulative heat release, and promote hydration. Liu et al. [83] modified RP with nano-silica, which served as a growth nucleus for CSH and other hydration products, accelerated C_3S dissolution, enhanced hydration rate, and increased hydration

heat. Additionally, the amorphous silica in RP undergoes pozzolanic reactions with calcium hydroxide [93], while calcium carbonate reacts with calcium aluminate in cement to form monoaluminate, further promoting hydration reactions [66].

Further analysis of the hydration products of RP revealed that while the addition of RP altered the hydration process, the primary types of hydration products remained consistent, including calcium hydroxide, calcium carbonate, CSH and Aft [94]. Peng et al. [95] investigated the effect of RP on the hydration reaction of ultra-high-performance concrete and reached the same conclusion.

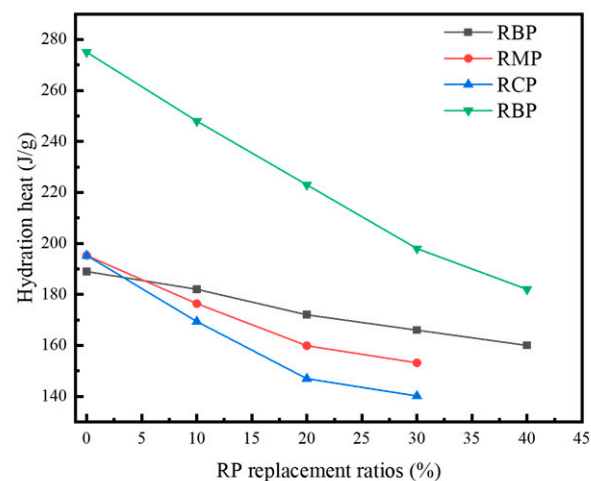


Figure 4. Relationship between cumulative heat release and RP replacement ratios [77–79].

3.2. Elemental and Compound Composition

Figure 5 shows SEM images of cementitious materials containing RP and those without RP. SEM images reveal that the microstructure of slurries containing RP is more porous than that of RP-free slurries, exhibiting a greater number of pores and cracks. This is attributed to the presence of RP reducing the quantity of hydration products [14]. At the same time, distinct RP particles can be observed, enveloped by hydration products such as CSH, which promote nucleation effects. The elemental analysis chart shows that the addition of RP reduces calcium content while increasing silicon content. This demonstrates that RP has a higher silicon content and lower calcium content than cement [96].

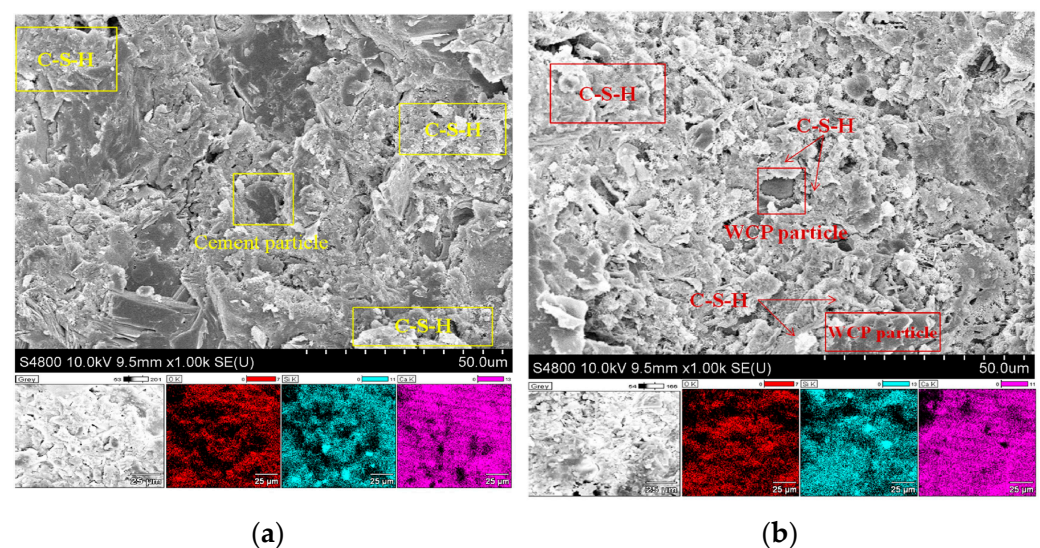


Figure 5. Micro-structure of paste including waste cementitious powder by SEM [97]. (a) Paste without waste powder. (b) Paste including 30% WCP.

As shown in Figure 6, XRD analysis of cementitious materials containing RP revealed that the primary mineral phases include calcium hydroxide, silica and calcium carbonate, along with Aft [98–100], unhydrated C_2S and C_3S [39,64,66], crystalline CSH gel [66,101,102], gypsum [39,97] and tobermorite [103]. Silica dioxide primarily originates from fine aggregates in RP. Part of the active SiO_2 promotes the hydration process of cementitious materials through the pozzolanic effect and microaggregate effect [44,104–106]; $Ca(OH)_2$, Aft and CSH gel originate from the hydration of cement [39,107]. Part of the $Ca(OH)_2$ originates from residual RP [107]. Calcium carbonate originates from the carbonation of calcium hydroxide, with some introduced during the crushing of aggregates [78,104,108]. As shown in Figure 6a, the calcium hydroxide diffraction peak diminishes with the addition of RP. In cement-based systems, CH primarily originates from the hydration of silicate minerals in a cement clinker. RP contains a certain amount of amorphous or low-crystallinity components such as active SiO_2 and Al_2O_3 . These active substances can undergo secondary reactions with CH generated during hydration, further consuming CH. Therefore, as RP content increases, the XRD diffraction peak of CH decreases [49,87,109].

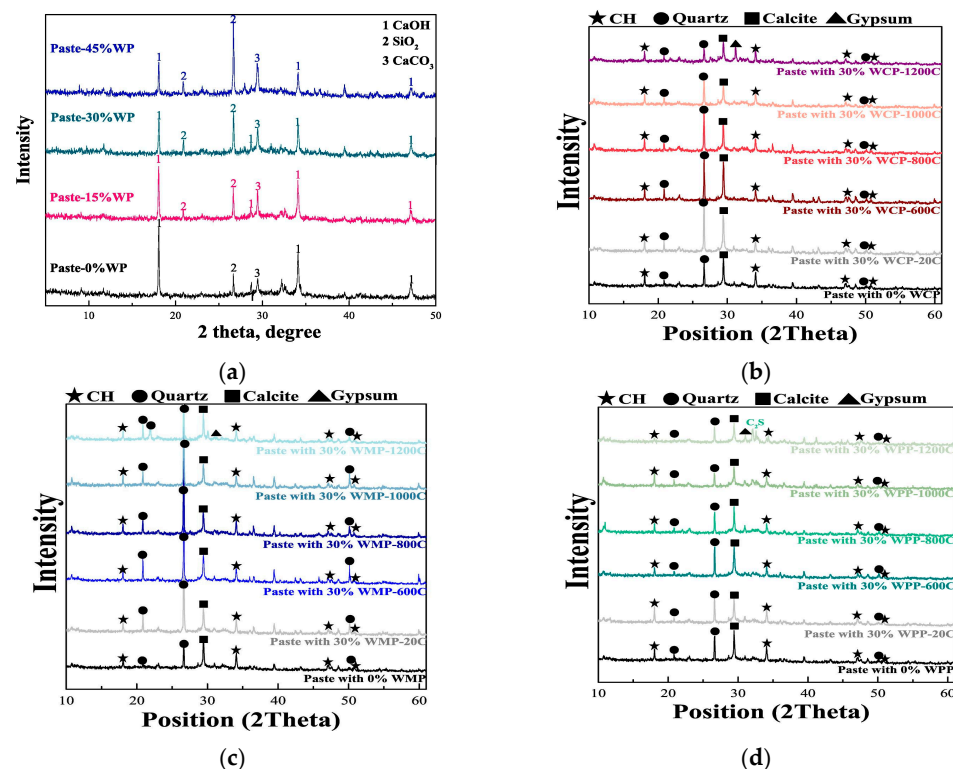


Figure 6. XRD pattern of paste including RP [96,97]. (a) Paste with different content WP. (b) Paste with WCP. (c) Paste with WMP. (d) Paste with WPP.

Overall, the addition of RP reduces the content of chemically bound water in cementitious materials, as incorporating RP decreases the amount of hydration products within the cementitious matrix [90]. Ma et al. [110] subjected RP to activation treatment at high temperatures and found no significant difference in mineral composition compared to untreated samples; Shen et al. [56] subjected RP to carbonation treatment, increasing the calcium carbonate content while reducing the levels of calcium hydroxide, C_2S and C_3S , thereby refining the porous structure within the cement matrix. Wang et al. [111] treated RP with TA and found no new characteristic peaks in the characterization of cement-based materials, indicating that TA also does not produce new compounds. Due to RP's low calcium content and high silicon content, increasing RP dosage reduces the Ca/Si and Ca/(Al + Si) ratios [95,112]. Additionally, the incorporation of RP promotes secondary

pozzolanic reactions with $\text{Ca}(\text{OH})_2$, leading to the consumption of Ca^{2+} and a gradual reduction in the Ca/Si ratio of the cementitious matrix. A lower Ca/Si ratio diminishes the supply of free calcium required for the conversion of Aft to AFm, thereby slowing the transformation of Aft into AFm.

3.3. Pore Structure

Pore structure and porosity are crucial to the durability and mechanical properties of cementitious materials [113,114]. Based on pore size and its effect on cement materials, pores can be classified as: harmless pores (<20 nm), pores with minor harm (20–50 nm), harmful pores (50–200 nm), and pores with significant harm (>200 nm) [115]. Researchers have found that as the RP content increases, the pore size and total pore volume of cementitious materials also increase [44,45,116–119], as shown in Figure 7. Chen et al. [85,120] found that at a RP content of 10%, the volume of harmless pores increased while that of harmful pores decreased. This indicates that the nucleation effect and microaggregate effect of RP promote more complete hydration reactions in cementitious materials, yielding greater quantities of hydration products. This process transforms harmful pores into harmless or less detrimental pores, resulting in a denser pore structure. When the RP content exceeds 40%, the harmful effects become significant as the pore volume increases substantially, as shown in Figure 8. He et al. [41] and Ma et al. [17] similarly observed that incorporating small amounts of RP resulted in a denser pore structure, with increased volumes of gel pores and interlayer pores smaller than 10 nm in diameter. Research has demonstrated [97,117,121,122] that when the RP content exceeds 30%, the volume of hydration products decreases while the volume of harmful pores (>50 nm) increases, leading to a decline in the mechanical properties and durability of cement paste.

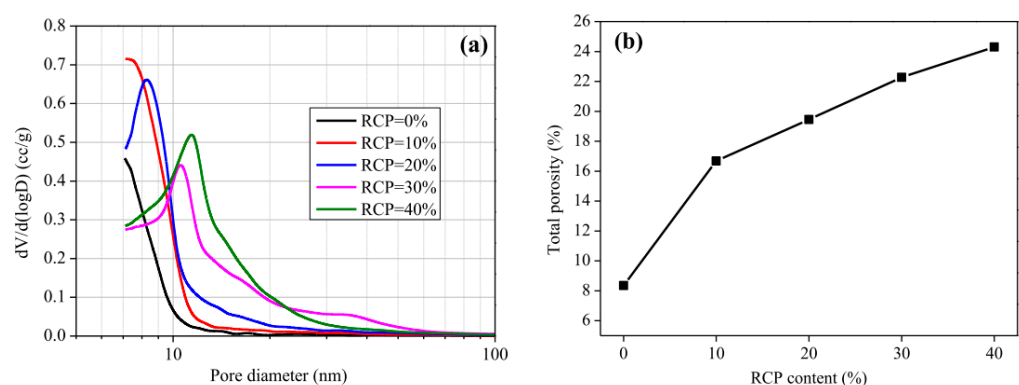


Figure 7. Pore structure of alkali-activated slag blended with different contents of RCP cured for 28 days. (a) Pore size distribution and (b) total porosity [45].

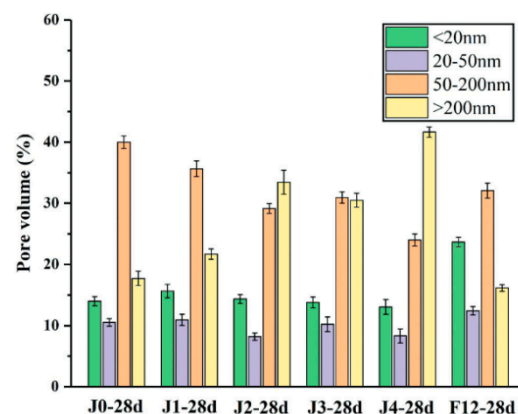


Figure 8. Pore volume distribution of paste [120].

Extending the curing time can mitigate the adverse effects of RP on increasing the porosity of cementitious materials. This is because prolonged curing promotes pozzolanic reactions, generating more CSH gel and resulting in a denser pore structure [122]. Zhao et al. [63] demonstrated through MIP and mechanical property tests on mortars with the same mix ratio at 28 d and 90 d that the total porosity after 90 d curing was reduced by about 5–20% compared to that after 28 d curing. Furthermore, pores smaller than 100 nm increased during the 90-day curing period, as shown in Figure 9. This is mainly due to the combined effect of cement hydraulic reaction and secondary hydraulic reaction of CBP leading to a decrease in total porosity and optimization of pore structure. Some researchers also propose that RP exists within the capillary pores of the matrix. As curing time increases, water permeates into these capillary pores and undergoes secondary hydration reactions with RP, thereby filling the pores [62,123].

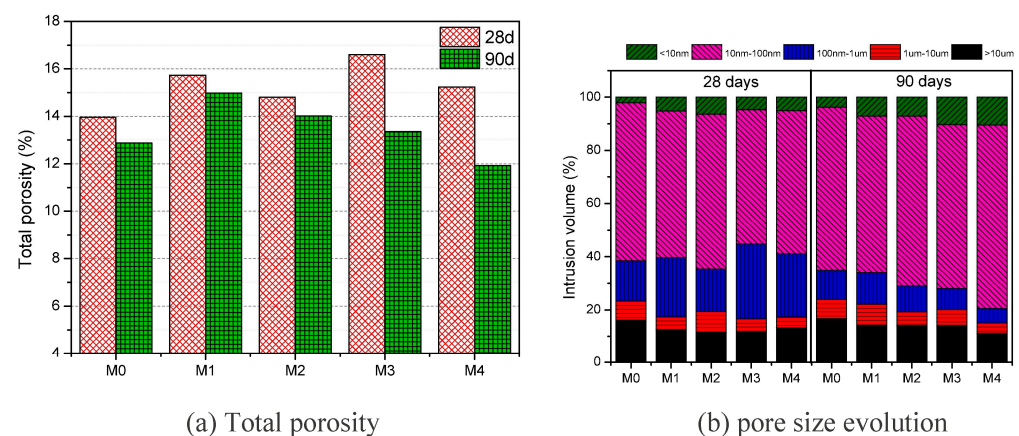


Figure 9. Total porosity and pore size evolution of mortars at 28 days and 90 days [63].

Additionally, increasing RP fineness can refine the pore structure, as finer RP particles exert nucleation and filling effects that promote hydration reactions [120]. When the D_{50} of RP is reduced below the threshold range of approximately 20–30 μm , a pronounced beneficial micro-filling effect occurs. At this particle size scale, the RP particles are sufficiently small to effectively fill interstitial spaces between cement grains and hydration products, leading to a denser particle packing structure. This physical filling effect significantly reduces the volume of larger capillary pores (>50 nm) and shifts the pore size distribution toward finer pores (<50 nm). From a micro- and nanostructural perspective, the refined pore structure directly influences the formation and morphology of the CSH gel. The presence of ultrafine particles provides abundant nucleation sites for CSH precipitation, promoting the more homogeneous and compact growth of CSH at the nanoscale. As a result, the CSH gel evolves from a loosely packed, fibrillar morphology toward a denser, foil-like or interlocked nanostructure with reduced gel pore connectivity. This transformation enhances the continuity of the solid phase and further constricts capillary channels. The combined effects of physical micro-filling and nanostructural densification of the CSH gel lead to a dominant pore population in the <50 nm range, which markedly decreases permeability and limits the transport pathways for aggressive agents (e.g., chloride ions and moisture). Consequently, durability-related properties are significantly improved.

Figure 10 shows that the cumulative pore volume of cementitious materials containing RP increases with increasing RP particle size. Wei et al. [122] found that increasing the fineness of RP compacted the pore structure of cementitious materials at both 3 d and 28 d, shifting pores from harmful and highly harmful ranges to less harmful and harmless regions, as shown in Figure 11. He et al. [103] demonstrated that when $D_{50} = 142$ μm , the addition of RP deteriorates the pore structure of the cement matrix, resulting in negative

effects, whereas when $D_{50} = 2.3 \mu\text{m}$, it optimizes the pore structure of the cementitious material. Generally, RP with particle sizes greater than 75 microns reduces the hydration reaction, while high-fineness RP can improve the pore structure of cementitious materials [124]. However, excessive addition of RP, regardless of fineness, will reduce the amount of hydration products and introduce harmful pores [44,85].

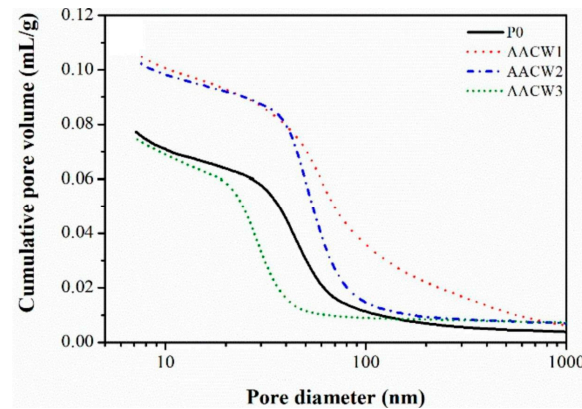


Figure 10. Pore size distribution of RP with different finenesses [103].

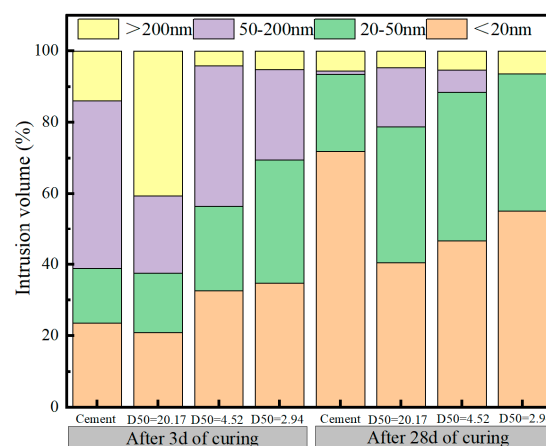


Figure 11. Effects of RP particle size on the micro-structure of a cement-based material [122].

Of course, other treatments can be applied to RP to improve pore structure. Heat-treated RP can exert a better diluting effect, promoting further hydration, thereby converting more pores into harmless ones while reducing harmful pores [122]. Researchers have found [38,97,110,125] that heat treatment within the temperature range of $600\text{ }^{\circ}\text{C}$ to $1000\text{ }^{\circ}\text{C}$ significantly refines the pore structure. Temperatures that are either too high or too low yield negligible effects on pore structure optimization. RP pretreated with carbonation contains more calcite, which can form carboaluminate during hydration, inhibiting the transformation from Aft to AFm. The cumulative pore volume of the cement matrix gradually decreases as curing time increases [66]. Additionally, scholars have employed TA and SMS to process RP, with both methods achieving denser pore structures and reduced pore diameters [126,127].

4. RCP Treatments

4.1. Mechanical Activation of RCPs

When using RP as an SCM, increasing its fineness is an effective method to enhance RP activity. Numerous studies have reported a positive correlation between RP activity index and grinding time [32,65,128]. From a physical perspective, prolonged grinding

increases the specific surface area of RP, thereby exposing a larger number of surface defects and nucleation sites, which can accelerate hydration reactions and contribute to matrix densification [64,129]. From a mechanochemical standpoint, mechanical activation forces induction of lattice distortion in the surface layer of particles; the crystal structure is transformed into an amorphous structure. This structural disorder reduces the activation energy required for dissolution and subsequent pozzolanic reactions [63,130].

XRD-based investigations provide direct evidence of this amorphization process. Gao et al. [25] observed that with increasing mechanical activation time, the characteristic diffraction peaks of albite and quartz gradually weakened, as shown in Figure 12, indicating a reduction in crystallinity. When the ball milling time was increased from 40 min to 80 min, the amorphization levels of Albite and SiO_2 rose from 35.14% and 5.34% to 41.75% and 25.48%, respectively. However, when the milling time was further extended from 80 min to 120 min, the amorphization levels decreased, suggesting that excessive grinding may promote particle agglomeration or structural reorganization, thereby offsetting the activation effect. Yu et al. [36] found that after ball milling, the peak intensity of SiO_2 significantly decreased, and SiO_2 transformed from stable $\alpha\text{-SiO}_2$ to amorphous SiO_2 . The amorphous phase contributes to enhancing the hydration activity of cementitious materials.

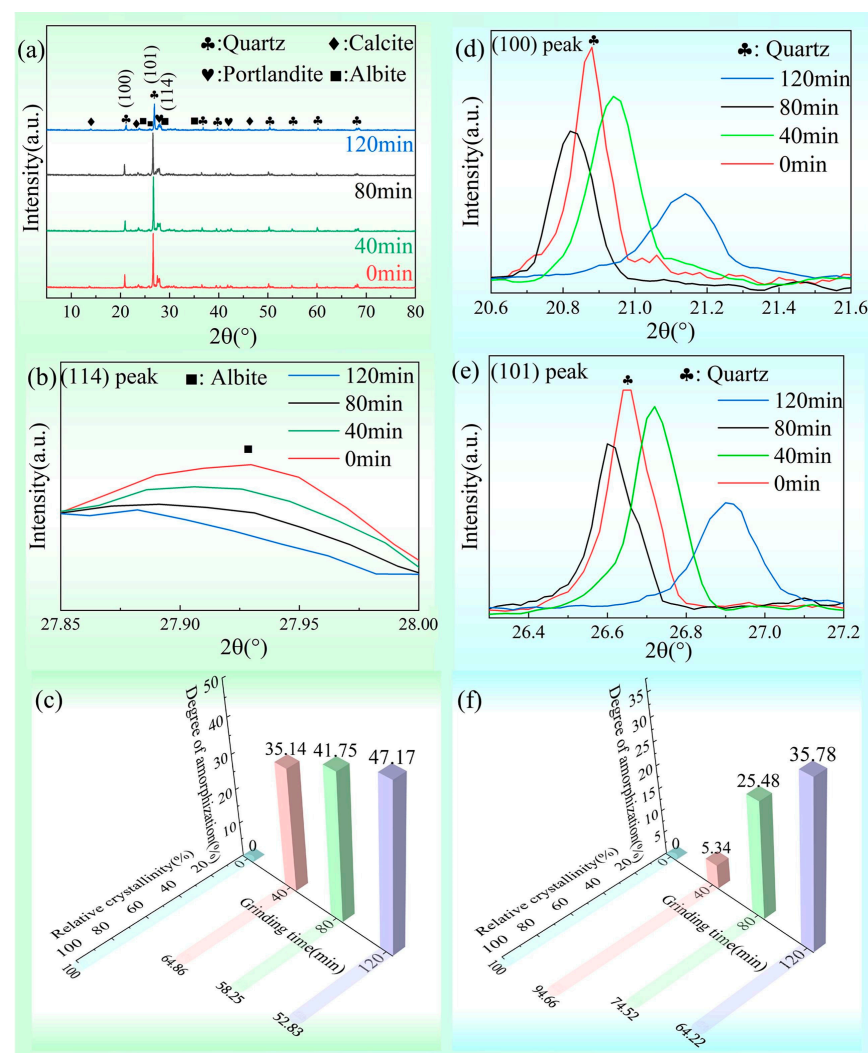


Figure 12. (a) XRD spectra of RCP with different mechanical activation time. (b) The locally enlarged diagram of the (114) peak. (c) Relative crystallinity and amorphous degree of albite phase. (d) The locally enlarged diagram of the (100) peak. (e) The locally enlarged diagram of the (101) peak. (f) Relative crystallinity and amorphous degree of quartz phase [25].

In addition to mechanical activation, mineralogical interactions between RP and cement phases also influence performance. Additionally, when RP is incorporated into cementitious materials, the calcite present in RP particles smaller than 75 μm reacts with C_3A in cement to form calcium aluminate carbonate. This inhibits the transformation of Aft to AFm, thereby enhancing the strength of cementitious materials. This phenomenon does not occur when particle sizes exceed 75 μm [124]. Moreover, as the grinding time of RP increases, the chemical energy required to break its Si-O and Al-O bonds decreases, further promoting the hydration process of the matrix [63,94].

Researchers investigated the mechanical properties of cementitious materials, incorporating RP of different types and grinding durations. Liu et al. [131] subjected RP to mechanical grinding for 20 min, 30 min, and 50 min, respectively. The activity index of RP increased by 67.5%, 75.0% and 77.0%. As shown in Figure 13 [77,132–136], the activity index generally increases with grinding time; however, the rate of improvement gradually diminishes, indicating the existence of an optimal fineness range rather than a linear relationship.

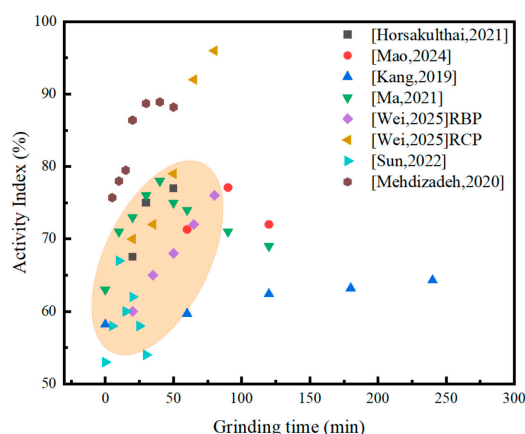


Figure 13. Activity versus grinding time [61,62,67,121–124].

Grinding time also significantly affects early-age performance and workability. As RP becomes finer, its specific surface area increases, leading to higher water demand due to enhanced water adsorption [137,138]. However, some scholars have found that mechanical grinding reduces particle size and rounds irregular particles, thereby decreasing internal friction within the pulp and lowering water demand [63,139]. These seemingly contradictory observations highlight the competing effects of particle refinement and surface energy. While RP addition generally reduces fluidity because of its high water absorption capacity [95,140], Che [136] observed that flowability increased with grinding time and stabilized at approximately 20 min. Gao [135] found that mechanical grinding reduced RP particle size, filling inter-particle voids and increasing flowability. However, as grinding time increased, the specific surface area expanded and surface energy rose, causing electrostatic forces to aggregate powder particles and decrease flowability. The optimal grinding time was determined to be 15 min.

4.2. Heat Treatment on RP

Heat treatment is another effective method for enhancing the reactivity of RP by modifying its physical and chemical characteristics. [50,118,122,129]. At elevated temperatures, hydration products and carbonate phases undergo thermal decomposition, generating highly reactive phases that can participate in subsequent hydration reactions [141,142].

The decomposition process proceeds as follows: When the temperature reaches 300 °C to 400 °C, the hydration products Aft and CSH begin to decompose [129]. At temperatures

between 400 °C and 650 °C, calcium hydroxide decomposes and partial decarbonation of calcium carbonate begins; around 800 °C, calcium carbonate decomposes. The particles generated by these thermal decomposition processes become new active fillers [43,143]. Therefore, peaks of Ca_3SiO_5 and Ca_2SiO_4 were detected between 400 °C and 800 °C [141], while peaks of CaO , C_2S , and C_3S were observed between 800 °C and 1000 °C. Anhydrous gypsum and amorphous SiO_2 were observed at 1200 °C [97,110,121]. Figure 14 shows the SEM-EDS and XRD patterns of RP under different temperature treatments [141,144]. After heat treatment, the decomposition of compounds reduces RP particle size, resulting in a denser microstructure. As temperature increases, some particles transform into an amorphous state, diminishing the nucleation effect of RP particles [145]. High temperatures alter the mineral phases of RP, but the primary elements remain unchanged. Therefore, heat treatment is an effective method for improving RP properties.

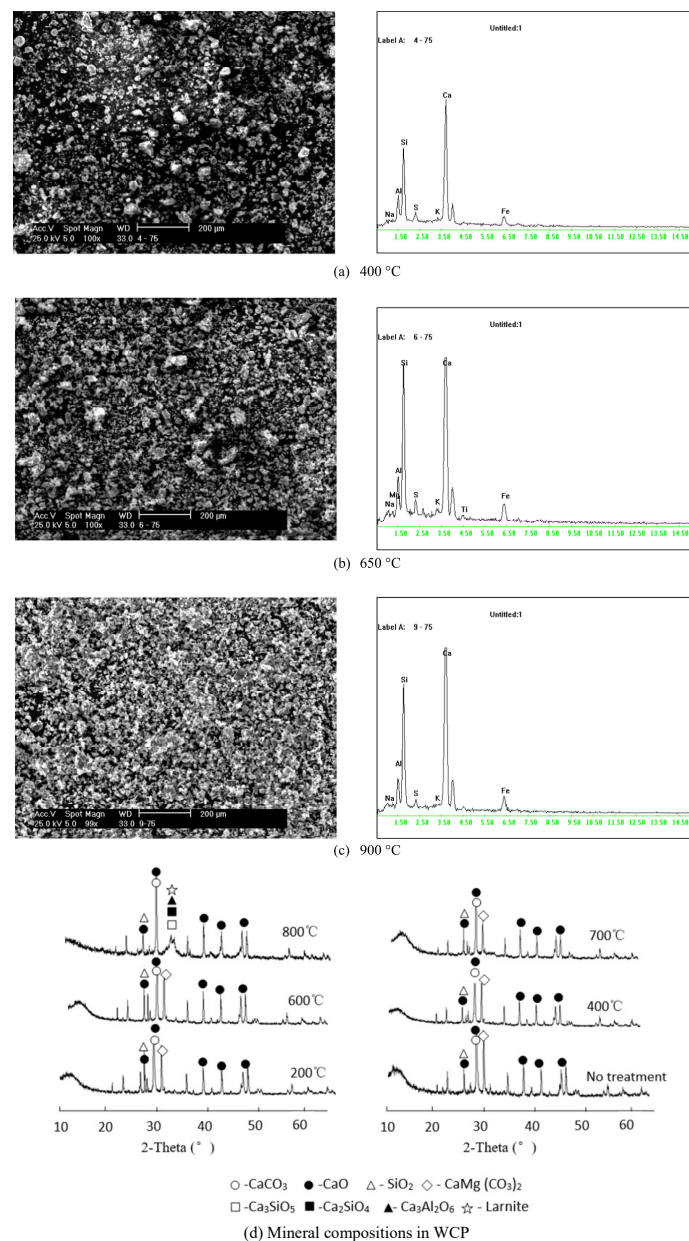


Figure 14. SEM-EDS images and XRD of the RCP after various heat treatment temperatures.

Kang et al. [146] compared different activation methods for RP and found that mortar prepared using RP treated at 800 °C exhibited higher 28-day strength than that prepared

using chemically or mechanically activated RP. Kim et al. [50] subjected RP to treatment at 600 °C and 800 °C. This increased the compressive strength of the mortar by 19% and 16%, respectively, and improved its shrinkage resistance. Yang et al. [147] and Ma et al. [110] also found that RP treated at temperatures between 600 °C and 800 °C exhibited mortar compressive strengths 16% to 27% higher than untreated RP. However, there exists a threshold for heat treatment temperatures. Figure 15 summarizes the changes in the activity index of RP across different treatment temperature ranges. The optimal heat treatment temperature for RP is 600 °C to 800 °C. Within this temperature range, first, $\text{Ca}(\text{OH})_2$ is fully decomposed, maximizing the availability of reactive CaO . Second, CaCO_3 begins to partially decompose, which increases lattice distortion and promotes the formation of additional reactive calcium species without causing excessive sintering. Third, thermally unstable crystalline Ca–Si phases undergo partial breakdown into transient amorphous Ca–Si structures. These amorphous or poorly ordered phases exhibit higher Gibbs free energy and enhanced solubility under alkaline conditions, thereby significantly improving their reactivity during subsequent hydration or alkali activation. RP’s activity index significantly increases. When the temperature exceeds ~800 °C, recrystallization and solid-state reactions become dominant. This recrystallization reduces defect density, decreases specific surface area, and lowers the chemical potential driving dissolution, ultimately diminishing reactivity. Additionally, higher temperatures require greater energy consumption.

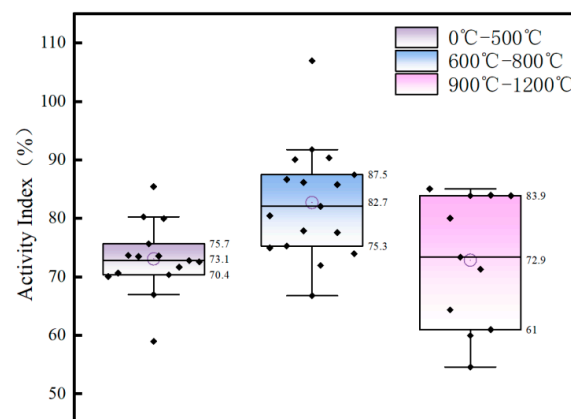


Figure 15. Activity index versus temperature [46,81,97,110,117,121].

4.3. Chemical Activation Methods of RP

Enhancing the hydration capacity of RP through the use of reagents is also a commonly employed activation treatment method, primarily including alkali activation, salt activation, and other activation techniques. The corresponding reaction equations are shown in Table 2. As shown in Figure 16, SEM images of RP paste after excitation by different reagents are presented. More hydration products and a denser microstructure can be observed [148,149].

Table 2. Different kinds of reagents used to activate RCPs and reaction equations [135].

Reagents	Reaction
CaO , $\text{Ca}(\text{OH})_2$	$\text{CaO} + \text{H}_2\text{O} = \text{Ca}(\text{OH})_2 \downarrow$ $m\text{Ca}(\text{OH})_2 + \text{SiO}_2 + n\text{H}_2\text{O} = m\text{CaO} \cdot \text{SiO}_2 \cdot \text{H}_2\text{O}$ $m\text{Ca}(\text{OH})_2 + \text{Al}_2\text{O}_3 + n\text{H}_2\text{O} = m\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot n\text{H}_2\text{O}$
$\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$	$\text{SiO}_3^{2-} + \text{Ca}^{2+} + \text{H}_2\text{O} = \text{CaO} \cdot \text{SiO}_2 \cdot \text{H}_2\text{O}$
NaOH	$2\text{OH}^- + \text{Ca}^{2+} = \text{Ca}(\text{OH})_2 \downarrow$ $m\text{Ca}^{2+} + \text{SiO}_4^{2-} + n\text{H}_2\text{O} \rightarrow m\text{CaO} \cdot \text{SiO}_2 \cdot n\text{H}_2\text{O}$
SO_4^{2-} salt	$\text{AlO}_2^- + \text{Ca}^{2+} + \text{OH}^- + \text{SO}_4^{2-} \rightarrow 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 32\text{H}_2\text{O}$
Cl^- salt	$\text{Ca}^{2+} + \text{Al}_2\text{O}_3 + \text{Cl}^- + \text{OH}^- \rightarrow 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCl}_2 \cdot 10\text{H}_2\text{O}$

4.3.1. Alkali Activation

The incorporation of RP into concrete reduces its alkalinity and strength. Researchers have discovered that adding alkali activators can enhance its activity [27,146,150]. Common alkali activators include CaO, $\text{Ca}(\text{OH})_2$, $\text{Na}(\text{OH})_2$ and sodium silicate. The OH^- ions in alkaline additives accelerate the breaking of Si-O and Al-O bonds, reducing the polymerization degree of the RP surface network polymer. This promotes the reaction between RP and cement hydration products in mortar, generating new cementitious products that densify the cement matrix structure [148]. CaO and $\text{Ca}(\text{OH})_2$ can also supply Ca^{2+} for hydration, thereby promoting the formation of CSH gel, CASH gel and Aft [151]. The Na^+ ions produced by NaOH ionization promote the depolymerization of the silicate network, releasing Ca^{2+} and SiO_2 which react with OH^- to form CSH gel [152]. As an alkali activator, sodium metasilicate not only provides an alkaline environment to promote the decomposition of silica and alumina components but also reacts with Ca^{2+} and Al^{3+} to form CSH or CASH gel, thereby enhancing strength [153]. Kang et al. [146] found that adding calcium hydroxide increased the compressive strength of RP mortar by 18.5% compared to non-activated mortar. Zhao et al. [154] activated RP with calcium hydroxide and $\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$, resulting in concrete strength increases of 3.5% and 4.5%, respectively. When Liu et al. [151] modified RP with 10% CaO, the 28-day activity index increased by 30% compared to the unmodified material. Zhang et al. [155] found that calcium hydroxide exhibited superior activation effects on RP compared to $\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$ at the same dosage, with an optimal $\text{Ca}(\text{OH})_2$ content of 3.5%. At moderate $\text{Ca}(\text{OH})_2$ additions, the released Ca^{2+} ions participate effectively in the dissolution–precipitation reactions, promoting the formation of C–S–H gel and improving matrix densification. However, when the $\text{Ca}(\text{OH})_2$ dosage exceeds an optimal threshold, excessive Ca^{2+} ions accumulate in the pore solution, disturbing the local ionic equilibrium. Concurrently, non-uniform Ca^{2+} diffusion promotes localized recrystallization and growth of coarse $\text{Ca}(\text{OH})_2$ crystals, which are poorly bonded to the surrounding gel, leading to decreased strength [152,154].

4.3.2. Salt Activation

The addition of sulfates promotes the formation of calcium aluminate hydrates. Kang et al. [146] demonstrated that adding sodium sulfate increased the compressive strength of RP mortar by 14.4% compared to non-activated mortar. Liu et al. [137] found that when RP was modified with 1% gypsum, the 28-day activity index increased by 30% compared to the unmodified material. Cl^- can react with activated Al_2O_3 to form calcium aluminate hydrochloride, which participates in hydration and alters osmotic pressure, thereby improving mortar properties [152]. When CaCl_2 is used as an activator, the optimal dosage is 3.5%. Strength increases initially and then decreases as the CaCl_2 dosage increases [156]. The hydrolysis of Na_2CO_3 and NaHCO_3 produces a weakly alkaline solution that promotes the formation of cementitious materials and enhances reaction activity. Xu et al. [152] found that the strength of cement paste initially increases and then decreases with increasing Na_2CO_3 content, with the optimum content being 3%. Dong et al. [157] achieved a maximum specimen strength of 22 MPa at a Na_2CO_2 content of 10%.

4.3.3. Other Activators

Wang et al. [111] employed tannic acid (TA) for RP modification. Calcium hydroxide diffraction peaks from RP treated with varying concentrations of TA diminished, yielding submicroscopic particles without generating new phases. These particles not only filled pores but also provided nucleation sites for cement hydration. Qu [158] treated RP with triethanolamine and found the optimal incorporation level to be 0.01%. Compared to the unexcited sample, the 3 d and 28 d intensities increased by 79% and 46%, respectively.

Triethanolamine exhibits strong alkalinity, promoting the depolymerization of Si-O and Al-O bonds. By providing excess electron pairs to form covalent bonds with cations in the RP, it generates gel substances [159]. Additionally, it can promote surface dissolution of RP particles, thereby accelerating the hydration reaction process. Many researchers have also explored synergistic treatment of RP using alkali and salt composites, which can simultaneously leverage the advantages of alkali activation and salt activation to promote hydration and form a dense microstructure [25,26,42,43,46,160,161]. Zhang et al. [46] achieved the optimal activity index by blending $\text{Ca}(\text{OH})_2$ and CaSO_4 in a 1:1 ratio. On one hand, OH^- stimulated the pozzolanic activity of RP, forming a dense CSH gel. On the other hand, Ca^{2+} , SO_4^{2-} and OH^- promoted the formation of AFt, filling the pores. Dong [157] investigated the composite treatment of RP using NaOH combined with $\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$, Na_2CO_3 , and $\text{Ca}(\text{OH})_2$, observing its strength and microstructure. The results demonstrated that composite activation yielded superior effects compared to single-component addition. Among these, the composite activation of NaOH and $\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$ achieved the highest specimen strength (39 MPa). Through composite excitation treatment, part of the crystalline SiO_2 in RP dissolves under high alkalinity, generating more highly polymerized geopolymers, CSH and CASH. The particles on the specimen surface become smaller, and the structure becomes more compact.

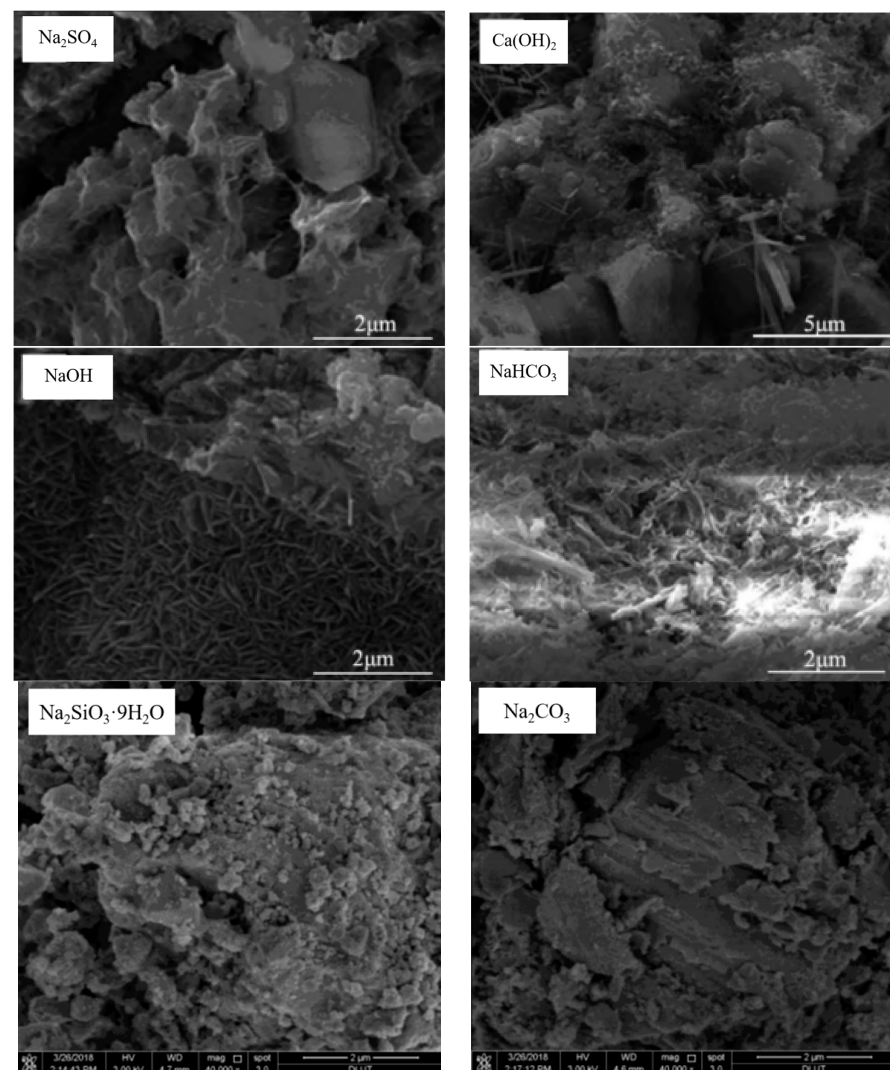
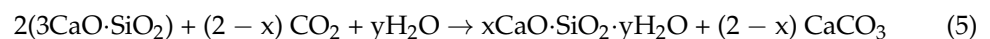
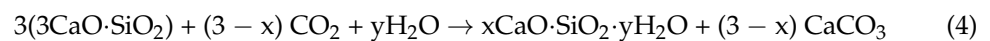
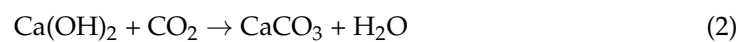


Figure 16. SEM images of RP paste with different activators [148,157].

4.4. CO₂-Curing Treatment

Cementitious materials contain substantial amounts of calcium, which can improve their microstructure and mechanical properties through carbonation. This process also serves as an effective means for CO₂ sequestration [66,162–164]. In recent years, the technology of using CO₂ to cure recycled aggregates has been widely adopted. Results demonstrate that concrete made with CO₂-treated recycled aggregates exhibits superior workability and durability compared to untreated concrete [165,166]. Since the surface composition of recycled aggregates is similar to that of RP, researchers have recently employed CO₂ to treat RP and enhance its properties [167–169]. The degree of carbonation in RP is primarily influenced by factors such as CO₂ pressure, concentration, temperature, humidity, and carbonation time [26]. The optimal carbonation conditions established through a series of studies were set at 0.1 MPa [124,170], 20% [171], 20 °C [172,173], and 70% [174]. Equations (2)–(5) show the chemical reaction equations during the carbonization process [124,175].



As shown in Equation (2), calcium hydroxide in cementitious materials reacts with CO₂ to form CaCO₃. Other reactions primarily involve calcium silicate reacting with CO₂ to produce calcium carbonate. Therefore, in XRD analysis, the carbonized RP primarily exhibits peaks corresponding to CaCO₃, followed by aragonite and dolomite [66,84,176]. TG results also indicate that RP treated with carbonization exhibits higher mass loss between 500 °C and 900 °C due to calcium carbonate decomposition [177,178]. When carbonated RP is incorporated into cementitious materials, the CaCO₃ within it reacts with aluminates to form structurally denser calcium aluminate semi-carbonate and calcium aluminate monocarbonate. This stabilizes the formation of Aft, thereby enhancing the performance of cementitious materials [49]. On the other hand, compared to untreated RP, carbonized RP exhibits a denser microstructure due to the formation of CaCO₃ and silica gel, resulting in reduced porosity and an optimized pore size distribution [49,176]. The generated CaCO₃ particles exert a nucleation effect, promoting the rate of cement hydration and the production of hydration products [179]. Additionally, Wu et al. [49] and Kaliyavaradhan et al. [176] noted that carbonization treatment increases particle size, primarily due to the formation of CaCO₃ particles with silica gel. In contrast, Mehdizadeh et al. [180] concluded that carbonization treatment does not significantly alter the particle size distribution of RP.

The mechanical properties of RP after carbonization treatment have also been enhanced. Lu et al. [66] found that the 28-day strength of mortar specimens containing 10% and 20% RP increased by 3.3 MPa and 14.2 MPa, respectively, after carbonation treatment. Kaliyavaradhan et al. [176] replaced cement with 20% carbonized RP, achieving a 28-day activity index exceeding 75%. The interaction between C₃A and CaCO₃ to form calcium aluminate carbonate was a key factor in the increase in early strength. Zhu et al. [26] found that the strength of RP mortar first increases and then decreases with increasing carbonation time, with an optimal treatment time of 10 h. Calcium carbonate particles formed during early carbonation exert a nucleation effect, while deep carbonation causes CSH depolymerization and weakens the reactivity between carbonation products and the cement paste. Wu et al. [181] found that temperature also affects the activity of carbonized RP. At higher carbonization temperatures, vaterite transforms into calcite, resulting in larger

particle sizes and greater thermodynamic stability, which enhances strength. Beyond calcite formation, the amorphous silica gel in carbonized RP can react with calcium hydroxide in the cement paste to form CSH gel, further improving strength [84].

5. Applications of RP

5.1. SCM and Geopolymers with RP

RP exhibits pozzolanic activity and can be used as an SCM or precursor for producing geopolymers. When activated with an alkali activator, a zeolite structure can also be observed [182,183]. Ren et al. [102] utilized the pozzolanic activity of RP to produce concrete blocks, substituting 20% RP for alkaline slag. Since RP exhibits lower pozzolanic activity than alkaline slag, this substitution reduces the strength of the concrete blocks. Liu et al. [184] prepared mortar using RP from different sources as a replacement for fly ash, resulting in reduced workability and strength of the mortar. Liang et al. [185] directly blended RP into alkali-activated fly ash and slag, observing reduced shrinkage and increased strength. Huo et al. [186] and Wang et al. [187] prepared geopolymers using RP and alkali activators. Bayer et al. [188] conducted microstructural analysis on the prepared geopolymers, finding that increasing Si/Al ratios resulted in enhanced geopolymer strength. As the Si/Al ratio increases, the aluminosilicate framework of N–A–S–H gel transforms from short chains or low-connectivity units (Q^1 – Q^2) to long chains and highly polymerized Q^3 – Q^4 units, resulting in a more compact and continuous microstructure. Although RP has been demonstrated to improve chloride ion erosion resistance when used as a precursor for geopolymer preparation, durability remains a concern [185,189].

5.2. High Performance Concrete with RP

RP can be used as an inert filler in high-performance concrete. He et al. [41] found that incorporating 30% RP into UHPC improved the bulk density between particles, with strength decreasing by only 3.9%. Peng et al. [95] used RP to replace cement, and the compressive strength of UHPC decreased with increasing RP content. However, at a 50% replacement rate, the 28-day strength was comparable to that of the control group. The incorporation of RP improves the particle size distribution across multiple scales, enabling a denser particle arrangement and reducing initial inter-particle voids. In this context, fine powder functions predominantly as a physical filler rather than a chemically reactive component. Furthermore, results indicated that UHPC with RP exhibited excellent water resistance and significantly reduced early self-shrinkage. Qian et al. [190] and Yao et al. [100] further investigated that when the RP content is below 30%, the compressive strength of UHPC exhibits minimal variation while also improving microstructure and durability. This composition can be used to produce UHPC with excellent performance. When using RP to produce UHPC, it can serve as a diluent, improving cement utilization and reducing environmental impact. However, current research on RP-based UHPC primarily focuses on mechanical properties, and its effects on durability still require further validation.

5.3. Self-Compacting Concrete with RP

Researchers have discovered that RP can be used to prepare self-compacting concrete (SCC). However, due to RP's high water absorption, admixtures must be added to adjust the mixture and achieve good workability [191]. Kim et al. [192] produced SCC by substituting cement with RP at 0%, 15%, 30% and 45% by weight. At 15% RP content, the 28-day compressive strength reached 30 Mpa. Blending RP with slag effectively improved the dry shrinkage rate and carbonation resistance of SCC. Duan et al. [130] investigated the properties of SCC prepared by mixing RP with recycled aggregates at varying ratios. The study found that fully replacing fly ash with RP had no significant effect on workability, but

compressive strength and splitting tensile strength decreased. X-ray CT results indicated that high RP content caused particle agglomeration, leading to higher porosity in the SCC and reduced durability.

5.4. Fiber-Reinforced Cementitious Composite Material with RP

Researchers incorporated RP into fiber-reinforced cementitious composites to evaluate its effects. Mao et al. [193] investigated the performance of RP mixtures at different ratios and found that at a w/b ratio of 0.16, with RP replacement of 30%, silica fume content of 15%, and steel fiber content of 2%, the concrete's workability showed no significant change. Furthermore, the addition of steel fibers enhanced both the strength and toughness of the concrete. Hlůžek et al. [194] enhanced the RP concrete fiber–matrix interface by subjecting polymer fibers to plasma treatment, thereby improving the adhesion between synthetic fibers and the cement matrix. Liang et al. [195] investigated the feasibility of using RP to prepare fiber-reinforced cementitious composites. The addition of RP reduced the quantity of hydration products and strength but increased the toughness index by 4.2–14.1%. By reducing the RP particle size and optimizing the microstructure, the strain-hardening properties of fiber-reinforced cementitious materials can be improved. Yu et al. [196,197] prepared ultra-ductile cementitious composites using RP as a substitute for fly ash, achieving stable strain hardening and fracture toughness while enhancing fiber bridging capacity. Li et al. [198] enhanced the load-bearing capacity and crack resistance of cementitious materials using RP and PVA fibers. Yu et al. [68] achieved maximum compressive and tensile strengths when substituting 25% RP for cement in fiber-reinforced cementitious composites.

5.5. Foam Concrete

Foam concrete has found widespread application in construction due to its low self-weight, high fluidity and excellent thermal insulation properties [199,200]. Research has demonstrated that the use of RP as an SCM for preparing foam concrete is feasible [201–203]. Jin [203] analyzed SEM images using the PCA system and found that as RP content increased, the total pore volume of foam concrete decreased and connectivity declined. This reduced water absorption and thermal conductivity while enhancing strength, as shown in Figure 17. Zhang et al. [204] prepared foam concrete by substituting cement with recycled powder produced using a jet mill. The addition of RP adjusted the particle size distribution of the system, optimizing the foam concrete's skeletal structure. The 28-day compressive strength of the foam concrete reached 3.09 Mpa, representing an 11.6% increase compared to the control group. Li [205] prepared foam concrete by substituting RP for cement. The RP foam concrete achieved the highest 28-day compressive strength at a 5% RP content. Liu et al. [206] optimized the mix design of RP foam concrete through orthogonal experiments. When $m(\text{cement}):m(\text{RP}):m(\text{fly ash}) = 70:15:15$, both compressive strength and water absorption met the requirements. Chemical agents such as lime and sodium hydroxide can be employed to enhance the performance of RP foam concrete. While sodium hydroxide accelerates the setting time of foam concrete, its standalone use is not recommended.

5.6. Structural Applications

In recent years, increasing attention has been paid to the structural performance of reinforced concrete beams produced with recycled concrete incorporating RP. Existing research indicates that when appropriate replacement ratios and mix designs are employed, recycled powder-modified recycled concrete beams exhibit minimal differences compared to conventional concrete beams in terms of flexural capacity, stiffness development, and crack propagation behavior [24,207]. During flexural loading, RP contributes to matrix densification through micro-filling effects and potential pozzolanic reactions, which enhance

the quality of the interfacial transition zone (ITZ) and delay the initiation and propagation of flexural cracks, thereby improving post-cracking load-carrying capacity [208]. T.S. Mustafa et al. [20] replaced cement and fine aggregate with waste glass powder to test the flexural properties of reinforced concrete beams. The results showed that beams containing 10% WG showed an increase in the cracking and ultimate loads, respectively, by 29.0% and 6.9% and beams containing 20% WG showed insignificant reductions in the cracking and ultimate loads. Gülden et al. [21] activated waste ceramic powder with an alkali activator and substituted it for cement, finding that this resulted in only a 4.57% reduction in compressive strength with no loss in flexural load-carrying capacity. Furthermore, beams containing ceramic waste exhibited delayed crack initiation, narrower crack widths, and improved stiffness retention after the first cracking stage, resulting in stable load transfer.

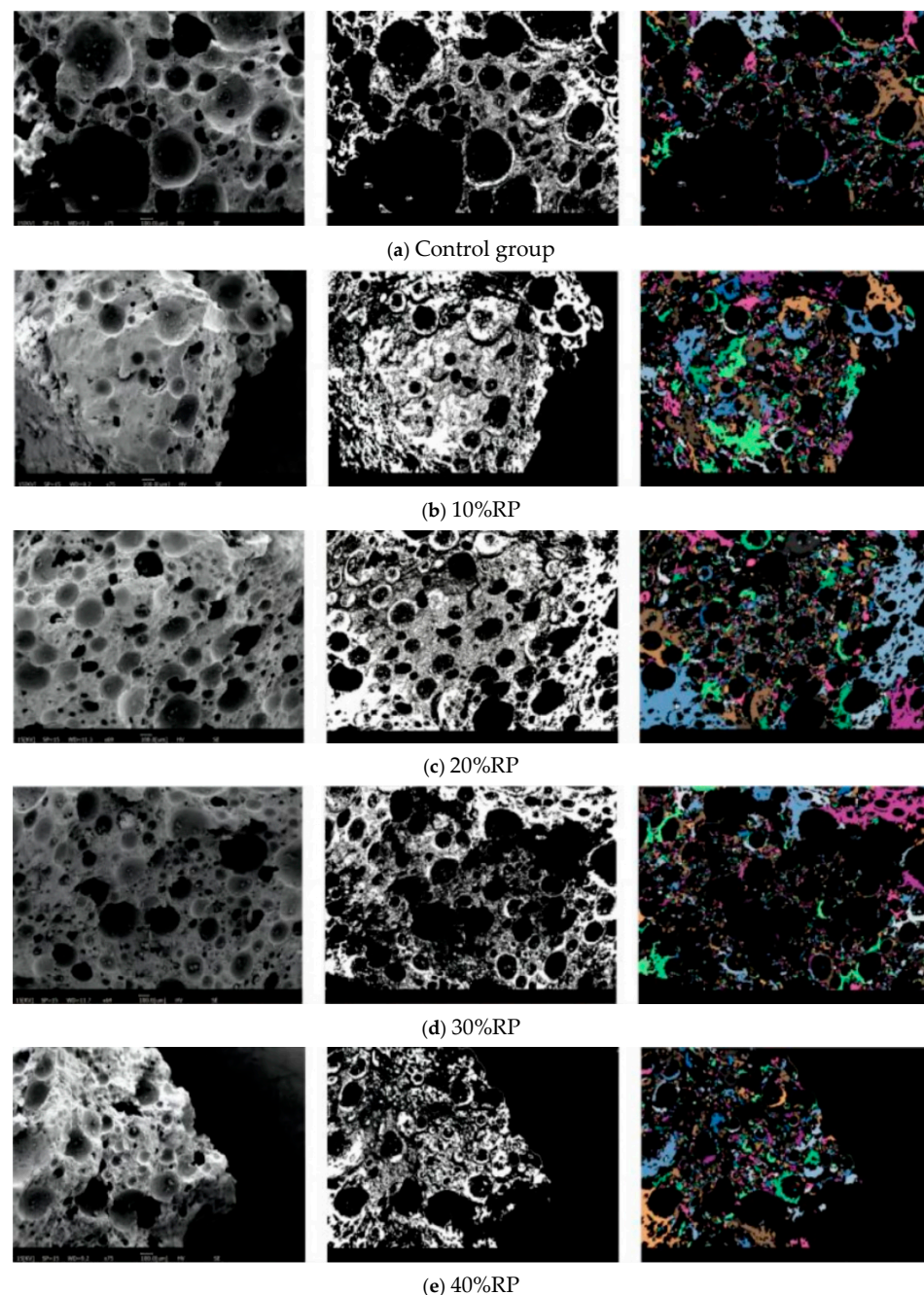


Figure 17. SEM images at different RP concentrations and images after PCA processing [203].

5.7. Other Applications

Qian et al. [209] prepared 3D-printed mortar using RP. Incorporating 10% RP increased the yield stress from 1423 Pa to 1573 Pa while maintaining the material's viscosity. Hou et al. [81] investigated the flowability, setting time, mechanical properties and hydration heat of 3D-printed mortar with varying RP replacement rates, demonstrating that 3D-printed mortar containing 10–30% RP exhibits excellent extrusion and constructability. Jiang et al. [210] and Deng et al. [211] employed RP to fabricate artificial aggregates. Although both drying shrinkage and mechanical properties were significantly lower than those of natural aggregates, the feasibility of this approach was demonstrated. Further research is needed on the interfacial transition zone between RP-prepared recycled aggregates and cementitious matrices. RP can also be converted into active fillers rich in calcium carbonate and silica gel, as well as amorphous NS, through processes such as carbonization or treatment with sodium carbonate solution, thereby enhancing the utilization value of RP [73,212–214]. Wang et al. [215] incorporated RP into road support mortar, with results indicating that adding 10% RP enhanced both the compressive strength and toughness of the mortar. Kanda [216] prepared ceramic tiles with high flexural strength using spark plasma sintering. Other researchers have employed RP as an adsorbent for phosphorus removal, SO₂ absorption, or CO₂ capture [177,217,218]. Although these approaches represent novel applications for RP utilization, further research is still needed on their costs, industrial scalability and environmental impacts.

6. Impact on the Environment and Economy

Environmental and economic impacts are important factors in evaluating RP as a substitute for cement or as a supplementary cementitious material. Research indicates that RP is more effective in reducing CO₂ emissions and energy consumption [103,219–221]. Prasath Kalyanasundaram et al. [222] significantly improved the carbon fixation capacity of RP by using thermomechanical treatment, with a carbon dioxide absorption rate of 9.83% and a carbonization degree of 45.62% in 24 h. Ismail Oguz Akgun et al. [223] used waste volcanic tuff and recycled concrete powder to prepare concrete that reduced carbon emissions by 34–36% compared to conventional concrete. Zhao et al. [63] indicated that replacing cement with 30% RP reduces CO₂ emissions by 179–271 kg per ton and lowers costs by 51–141 CNY. He et al. [103] replaced cement with 20% RP, reducing CO₂ emissions by 162.4–186 kg per ton and lowering costs by 90–120 CNY. Qian et al. [190] produced UHPC using RP at different dosages. CO₂ emissions decreased with increasing RP dosage, with the CO₂ emissions-to-strength ratios being 3.5, 3.3, 2.9, 2.7 and 2.5, respectively. The primary CO₂ emissions and energy consumption of RP depend on its activation process. Sun et al. [224] found that extending the grinding time of RP from 25 min to 75 min increased CO₂ emissions from 236.25 kg to 673.75 kg. However, as grinding time increased, the specific surface area of RP also increased, creating additional CO₂ absorption sites that partially offset the emissions. Researchers compared the cost–benefit evolution of cement production versus RP activation, revealing that RP activation incurs lower costs and CO₂ emissions than cement. Cement calcination generally requires temperatures reaching 1400 °C, whereas RP's optimal activation temperature range is 600–800 °C [14,63,103].

Most existing studies assess the environmental benefits of RP utilization using region-specific assumptions. While RP generally exhibits lower embodied carbon than Portland cement, its net environmental benefit strongly depends on system boundaries, transportation distance, activation energy demand, and achievable cement replacement levels. From an economic perspective, RP is often regarded as a low-cost material; however, additional processing steps such as fine grinding, thermal treatment, or chemical activation may offset

these advantages. Therefore, cost–benefit analyses should be conducted on a case-by-case basis, considering local energy prices, waste availability, and performance requirements.

7. Discussion

To rationalize the widely scattered and sometimes contradictory results reported in the literature, it is essential to move beyond a purely descriptive comparison of replacement ratios or activation methods. Existing review articles on recycled powder have provided comprehensive summaries of preparation techniques and macroscopic performance trends. However, most of them implicitly assume that RP behaves as a homogeneous supplementary cementitious material, which leads to empirical conclusions that are difficult to generalize across different studies. As a result, similar replacement levels or activation treatments have been reported to either improve or deteriorate mechanical and durability performance, without a clear explanation of the underlying causes.

Based on a critical synthesis of experimental evidence, a zone-based conceptual framework is proposed to interpret the performance variability of RP in cementitious systems (Figure 18). Rather than classifying RP solely by source or activation technique, this framework emphasizes the coupled effects of parent material characteristics, particle-scale structure, and reaction environment. In Zone I, RP functions predominantly as an inert filler, which is typically associated with highly carbonated parent concrete, coarse particle size, and limited amorphization. In this case, dilution effects dominate, and strength reduction is often observed at moderate to high replacement levels. In Zone II, partial activation and size reduction enable RP to contribute through micro-filling and nucleation effects, refining pore structure and accelerating early hydration without relying on strong intrinsic pozzolanic reactivity. In Zone III, intensive activation methods—such as fine grinding, thermal treatment, or coupled chemical–carbonation activation—can induce amorphization and secondary reactions, allowing RP to participate more actively in hydration or alkali-activated systems.

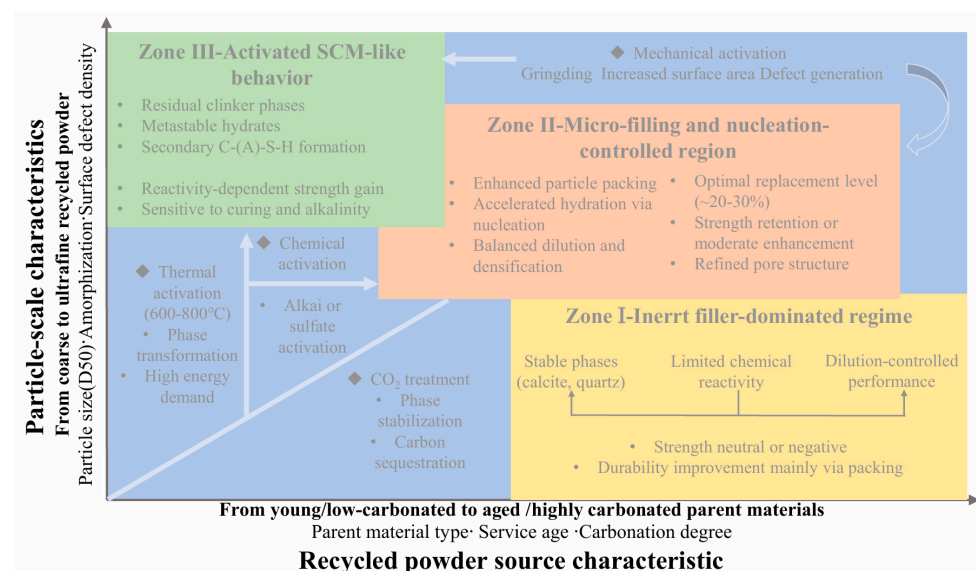


Figure 18. Mechanism-based decision framework for the utilization of recycled powder in cementitious materials.

Importantly, this framework is not limited to region-specific observations but is consistent with findings reported in international studies on recycled cementitious fines and emerging supplementary cementitious materials. Previous research has shown that, similar to low-reactivity SCMs, the primary contribution of RP in most practical applications arises

from dilution control, particle packing optimization, and microstructural densification, rather than from high pozzolanic reactivity. This explains why performance improvements are frequently reported in terms of durability and early-age hydration, while long-term strength enhancement remains limited unless intensive activation is applied. By explicitly linking these mechanisms to RP source characteristics and processing history, the present review provides a unifying explanation for the apparent inconsistencies across studies conducted in different regions and under different experimental conditions.

8. Conclusions and Engineering Implications

This review critically synthesizes recent research on recycled powder derived from construction and demolition waste and evaluates its role in cementitious materials from a mechanism-based perspective. Based on the analyzed literature, the following conclusions can be drawn:

(1) Recycled powder is not a single material but a spectrum of materials with fundamentally different reactivity. The chemical composition, mineralogical assemblage, and intrinsic reactivity of recycled powder are primarily governed by the parent material type, service age, and degree of carbonation. RP originating from aged and highly carbonated concrete or masonry is dominated by thermodynamically stable phases and therefore behaves mainly as an inert micro-filler, whereas RP derived from younger or less carbonated sources may retain unhydrated clinker minerals and metastable hydrates, enabling limited hydraulic or pozzolanic reactivity under suitable conditions.

(2) RP performance is controlled by coupled parameters rather than replacement ratio alone. Across different cementitious systems, threshold-type behavior is consistently observed. When the median particle size (D_{50}) is reduced below approximately 20–30 μm and the replacement level is maintained below about 30%, dilution effects can be largely compensated by micro-filling and heterogeneous nucleation. Within this envelope, acceptable mechanical performance and pore structure refinement can be achieved. Beyond this range, performance degradation becomes dominant regardless of further activation, explaining many contradictory conclusions reported in the literature.

(3) Activation methods enhance RP reactivity through distinct mechanisms with clear applicability limits. Mechanical grinding increases surface area and defect density; thermal activation (typically 600–800 $^{\circ}\text{C}$) generates highly reactive calcium-bearing phases; chemical activation promotes depolymerization and secondary gel formation; and CO_2 treatment modifies phase assemblage while enabling carbon sequestration. No single activation route is universally optimal. The effectiveness of each method depends on RP source characteristics, targeted performance, and energy or environmental constraints.

(4) Microstructural regulation provides a unified explanation for macroscopic performance variability. Differences in strength development, hydration kinetics, and durability reported in the literature can be consistently interpreted by considering the balance between dilution, nucleation, micro-filling, and secondary reactions. Improvements in durability are primarily associated with pore structure refinement and densification of the CSH network, rather than with high intrinsic pozzolanic reactivity of RP.

(5) The environmental and economic advantages of RP are conditional rather than absolute. Although recycled powder generally exhibits lower embodied carbon and material cost than Portland cement, its net sustainability benefit is highly sensitive to system boundaries, transportation distance, and the energy demand of activation processes. Therefore, generalized claims of environmental superiority are not justified without application-specific life-cycle assessment. Overall, this review demonstrates that the utilization of recycled powder should be guided by mechanism-based performance envelopes rather than empirical replacement limits. Future research should focus on standardized source

characterization, multi-scale structure–property relationships, and application-oriented mix design strategies to enable reliable, large-scale, and high-value use of recycled powder in sustainable cementitious materials.

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