ingegneria sismica
International Journal of Earthquake Engineering
Anno XLIII - Num. 3 - 2026

The influence mechanism of recycled micro powder on the workability and mechanical properties of concrete, as well as the control of micro pore structure

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SUMMARY: *In the context of global sustainable development, the contradiction between the massive generation of construction solid waste and the tightening of resource constraints is becoming increasingly prominent. As a key product of the resource utilization of construction solid waste, the application of recycled micro powder in concrete is of great significance for promoting green innovation of civil engineering materials and alleviating resource crises. This article systematically studies the physical and chemical properties and activity mechanism of recycled micro powder, analyzes its impact mechanism on the workability of concrete, explores its regulation path on the micro pore structure of concrete, and its role in improving durability. Research has shown that recycled micro powder can optimize the workability, mechanical properties, and microstructure of concrete through multidimensional effects such as filling effect and hydration reaction, providing theoretical support for its efficient application in concrete and assisting in the high-value utilization of construction solid waste.*

KEYWORDS: *Regenerated micro powder; Concrete workability; Mechanical properties of concrete; Microscopic pore structure regulation*

1 Introduction

At present, with the global concept of sustainable development deeply rooted in people's hearts, the field of civil engineering is facing a dual and severe challenge of resources and environment. With the rapid progress of urbanization, the construction industry is flourishing, accompanied by the generation of a huge amount of construction solid waste. If these construction solid wastes are not disposed of properly, they will not only occupy a large amount of valuable land resources, but also cause incalculable damage to the ecological environment.

In this context, as a key product of the resource utilization of construction solid waste, the application research of recycled micro powder in concrete plays a crucial role in promoting the green innovation of civil engineering materials and alleviating resource crises. As a key derivative of the construction solid waste resource utilization chain, recycled micro powder needs to be defined in the context of contemporary solid waste treatment technology evolution and material circular economy. From the perspective of materials science, it specifically refers to the powdery substances obtained from the crushing, screening, grinding and other series of processes of construction waste, with particle sizes ranging from sub micron to micron. Its composition mainly includes fine particles of building substrates such as waste concrete and bricks, and must meet specific harmful component limits and performance indicators before it

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https://doi.org/10.65102/is20261110
Published: 10 June, 2026

can be included in the scope of engineering applications.

At present, the huge amount of construction solid waste generated globally and the increasingly tight resource constraints have formed a sharp contradiction. Resource utilization has become the core path to solve this dilemma, and the development of recycled micro powders is a concrete practice of the development concept of "reduction, resource utilization, and high-value" of construction solid waste. Driven by the "dual carbon" strategy, the conversion of construction solid waste micro powder, which was originally considered waste, into recycled materials with engineering application value can not only effectively reduce the mining intensity of natural building materials, but also reconstruct the resource metabolism system of the construction industry. Its potential for resource utilization in the field of civil engineering materials is receiving high attention from academia and industry [6-8].

As shown in Figure 1, when searching authoritative paper index databases such as CNKI and Web of Science using keywords such as "recycled micro powder", "concrete workability", "mechanical properties of recycled micro powder", "micro pore structure", "recycled micro powder+interface transition zone", etc., and conducting statistics on related papers, it can be found that the number of related papers has shown an explosive growth.

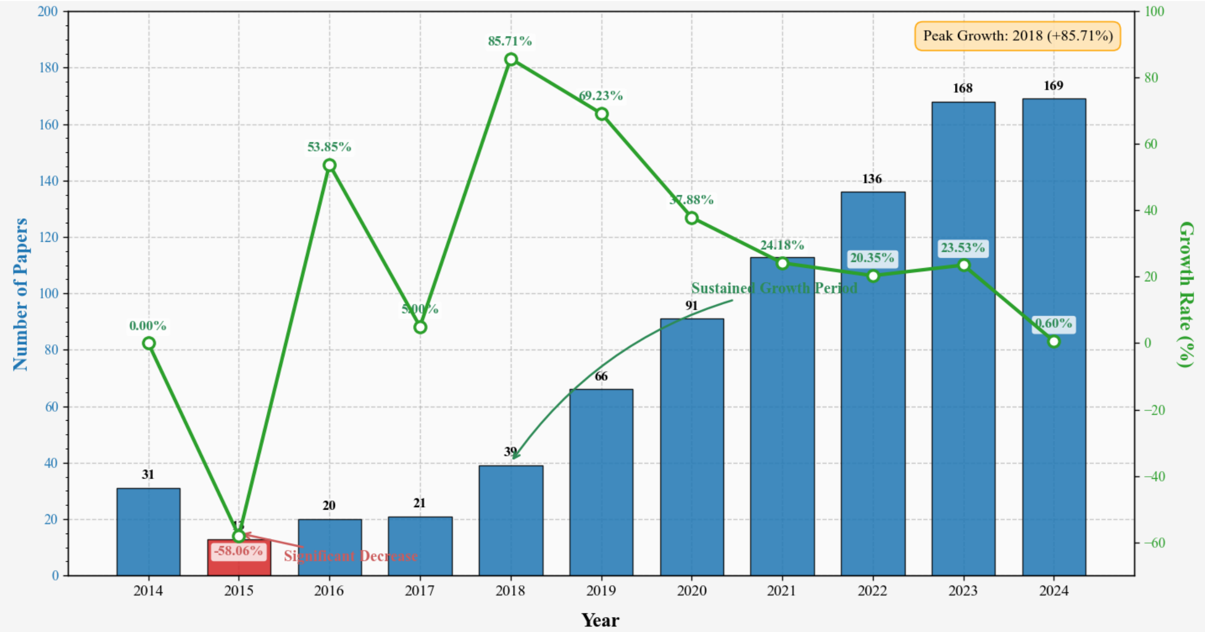

Figure 1: Growth Trend of Related Research Papers

The generation of construction solid waste micro powder runs through the entire life cycle of buildings, from the treatment of construction waste in new construction projects, to the crushing of materials during the demolition of existing buildings, and to the large-scale processing of construction waste resources by enterprises, all of which will produce a large amount of fine powder [9]. If these micro powders are not properly disposed of, their environmental hazards have multidimensional and cumulative characteristics [10]. In the atmospheric environment, fine particles are prone to form dust and participate in the secondary generation of atmospheric particulate matter, causing sustained impacts on regional air quality; In the soil and water environment system, heavy metal ions, soluble salts and other components carried by micro powders may enter the ecological medium through leaching, infiltration and other pathways, changing the physical and chemical properties of soil and the ecological balance of water bodies. Their long-term environmental risks have not been fully evaluated [11]. At present, traditional storage or landfill disposal methods are no longer able to meet the strict requirements of ecological environment protection. The environmental pollution problem of construction solid waste micro powder has become a prominent bottleneck restricting the overall resource utilization of construction solid waste. It is urgent to achieve the transformation from "pollutants" to "resources" through material utilization pathways.

In addition, the necessity of researching the application of recycled micro powder in concrete is also rooted in the dual drive of engineering practice needs and disciplinary theoretical development. Currently, the coordinated regulation of workability and mechanical properties of concrete has become a core demand for the development of high-performance concrete, and the introduction of recycled micro powders has made this regulation process more complex [12]. From the perspective of engineering practice, there is often a certain contradiction between improving the workability of concrete to meet the requirements of convenient construction and ensuring its mechanical properties to ensure structural safety. The high specific surface area of recycled micro powder may lead to a decrease in the fluidity of concrete, and increasing the water consumption or water reducing agent dosage to improve fluidity may have adverse effects on the mechanical properties [13]. The existing research has not yet established a balance regulation theory between the two, and lacks a collaborative optimization path based on material microstructure design, which greatly limits the dosage and application range of regenerated micro powders. In the context of the development of green buildings and new structures, higher performance requirements have been put forward for concrete materials. How to achieve the synergistic improvement of workability and mechanical properties through the scientific application of recycled micro powders has become an urgent engineering problem to be solved, and the theoretical gap of multi-scale regulation behind it needs to be filled urgently.

Based on this, this study focuses on the application of recycled micro powder in concrete, systematically exploring its impact mechanism on the workability and mechanical properties of concrete, as well as its regulatory effect on the micro pore structure. Firstly, the definition and sources of recycled micro powders were clarified, with a focus on analyzing the physical and chemical properties of recycled micro powders from waste concrete and waste clay bricks, including chemical composition, particle size distribution, specific surface area, as well as their activity mechanisms, such as secondary hydration reactions induced by volcanic ash effect and optimization of interfacial transition zones. On this basis, the influence of recycled micro powder on the rheological properties of fresh concrete was deeply studied, involving changes in parameters such as water demand, flowability, and setting time. At the same time, the influence mechanism of particle size distribution adjustment, water adsorption release, and bubble slurry interaction on the workability of concrete was analyzed at the micro level. In addition, the regulation path of recycled micro powder on the micro pore structure of concrete was explored, including the migration of pore size distribution curve and the blocking effect of pore connectivity. The improvement effect of these regulation effects on the durability of concrete, such as frost resistance, sulfate resistance, chloride ion permeability, etc., was analyzed. At the theoretical level, this article fills the gap in the multi-scale regulation theory of the application of recycled micro powder in concrete, deeply reveals the essential mechanism of its influence on the workability and mechanical properties of concrete, establishes the correlation between the dosage and activity excitation mode of recycled micro powder and the micro pore structure and macro properties of concrete, and provides a systematic theoretical framework for understanding the mechanism of action of recycled micro powder. At the practical level, it provides an effective path for the resource utilization and high-value utilization of construction solid waste. Through the scientific application of recycled micro powders, the synergistic improvement of concrete workability and mechanical properties can be achieved, expanding the dosage and application scope of recycled micro powders, helping to reduce the mining intensity of natural building materials, promoting the green and sustainable development of the construction industry, and providing new ideas for the research and application of high-performance concrete, meeting the higher performance requirements of green buildings for concrete materials.

2 Theoretical basis

The physical and chemical properties of regenerated micro powder are the core foundation for its material application, and its characteristics exhibit significant process sensitivity [14, 15]. In terms of physical properties, specific surface area is a key parameter that characterizes its surface effect and filling performance. Influenced by the properties of the original waste and the grinding process, it usually exhibits much higher specific surface area characteristics than ordinary Portland cement, which gives it strong interfacial potential. However, it may also cause problems such as increased water demand due to high surface energy [16]. Its particle morphology is mostly irregular, and the particle size distribution shows a wide distribution characteristic. The synergistic effect of these physical characteristics directly affects its packing density in the concrete system [17]. At the level of chemical properties, the composition of active components is the core element that determines their cementitious activity, mainly including unhydrated cement clinker minerals, silicon aluminum components with volcanic ash activity, and so on. The presence of these active components allows them to undergo hydration reactions or secondary hydration reactions in alkaline environments, but their activity levels are limited by factors such as mineral phase composition and crystal structure integrity, and often need to be enhanced through physical activation or chemical excitation [18, 19]. In recent years, research based on advanced characterization techniques has found that the functional groups and interfacial chemical properties present on the surface of recycled micro powders have an undeniable impact on their interaction with cement hydration products, providing a new research perspective for a deeper understanding of their performance contribution mechanisms.

The existing research on the application of recycled micro powder in concrete has established a preliminary cognitive framework, but as shown in Figure 2, there are still significant limitations in terms of systematicity, depth, and foresight. In the field of work performance research, current achievements mostly focus on the superficial description of macroscopic performance indicators, such as the variation law of concrete slump under a single dosage, but fail to delve into the essential mechanism of multi factor coupling [20]. The fractal characteristics of particle size distribution, micro heterogeneity of particle surface texture, and interface interactions with chemical additives such as water reducers of recycled micro powders constitute a complex system that affects the rheological properties of concrete. However, existing research lacks quantitative analysis of the synergistic effects of these factors, especially the evolution of rheological parameters of concrete mixtures during dynamic construction processes, such as viscosity response and thixotropic recovery characteristics under shear rate changes, which are still in their infancy and difficult to support precise control requirements under complex construction conditions. At the same time, there is insufficient research on the time-dependent performance of concrete after the introduction of recycled micro powder, and there is a lack of systematic explanation of its dynamic changes in water retention and cohesion during transportation and parking, resulting in a significant disconnect between laboratory research conclusions and engineering practical applications.

In terms of mechanical performance research, existing work mostly focuses on the static comparison of strength indicators, and the understanding of the mechanism of action of recycled micro powder in the internal mechanical behavior of concrete is relatively weak [21]. As a multiphase composite material, the mechanical properties of concrete depend on the synergistic effect of each phase component. As heterogeneous particles, the role of recycled micro powder in the stress transmission path, the matching of mechanical properties with the cement matrix interface transition zone, and the damage evolution mechanism under load have not been clearly explained [22]. For the mechanical response under complex stress states, such as the performance degradation law of recycled micro powder concrete under fatigue load and impact load, existing research mostly draws on the analysis framework of ordinary concrete and fails to establish a theoretical model that conforms to its material properties. In addition, the fluctuation of the quality of recycled micro powders is an unavoidable practical problem in engineering applications, and existing research on the performance adaptability of different quality recycled micro powders is insufficient. There is a lack of differentiated application technology system based on performance grading, which makes it difficult to effectively guarantee the stability and reliability of their engineering applications.

The research depth of micro pore structure, as a bridge connecting micro composition and macro performance, directly restricts the understanding of the mechanism of action of regenerated micro powder. Current research often uses traditional porosity testing or qualitative microscopic observation methods, which lack precise characterization of pore structure and fail to establish a clear correlation between the dosage of regenerated micro powder, the activation mode, and pore structure parameters [23]. More importantly, existing research mostly focuses on the final pore structure of concrete after hardening, and there is a lack of attention to the dynamic evolution of pore structure during the hydration process. In fact, the regulatory effect of recycled micro powder on cement hydration kinetics directly affects the formation and development path of early pores, and the characteristics of early pore structure have a "path dependent" effect on the later performance of concrete. The lack of research on this key link makes it difficult to fundamentally reveal the mechanism of the impact of recycled micro powder on concrete performance. Meanwhile, the research on the synergistic regulation mechanism of pore structure when recycled micro powder is mixed with other auxiliary cementitious materials is also relatively scattered, and a systematic theoretical understanding has not been formed.

The decisive role of micro pore structure in the durability of concrete has become a consensus in the fields of materials science and civil engineering, but there are still significant theoretical shortcomings in the study of the regulation mechanism of recycled micro powder on this key structure. The durability of concrete is essentially its ability to resist erosion from external environmental factors, and the pore structure, as the transmission channel and reaction site of the erosion medium, directly determines the rate and degree of the erosion process based on its characteristics. Fine and isolated pore structures can effectively delay the infiltration of corrosive media, while connected and coarse pores can accelerate material degradation. Although existing research has recognized that regenerated micro powders may improve pore structure through filling and activation effects, there is a lack of in-depth understanding of the quantitative laws and mechanisms of their regulation, such as how regenerated micro powders accurately regulate the spatial topology of pores and their differential impact mechanisms on durability under different erosion environments, which have not yet formed a systematic theoretical system [24, 25]. It is particularly important that current research on the relationship between pore structure and durability is mostly based on static correlation analysis, and has not established a pore structure durability evolution model that considers dynamic changes in the service environment. This makes it difficult for durability control based on recycled micro powders to meet the practical needs of long-term design of concrete structures, as it lacks scientific theoretical support.

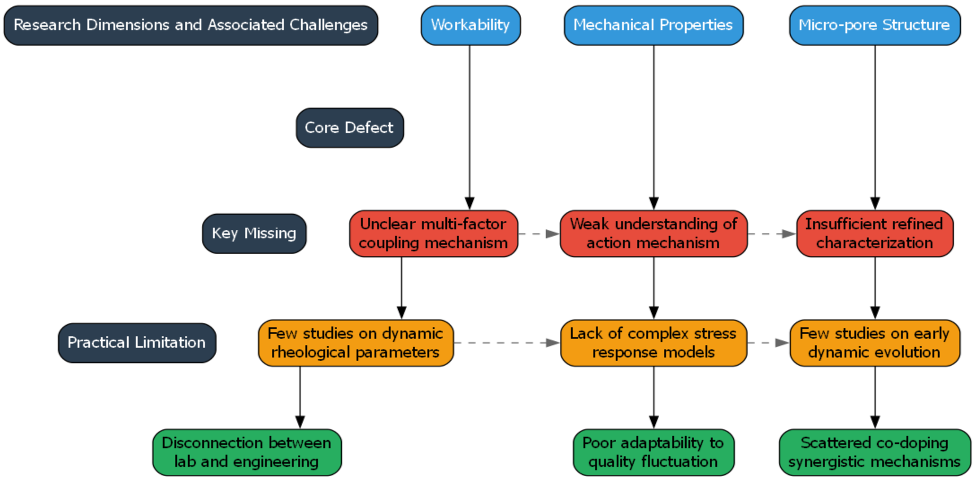

Figure 2: Schematic diagram of insufficient existing research

3 Characteristic analysis of regenerated micro powder

The effectiveness of recycled micro powder in concrete systems fundamentally depends on its own physicochemical properties and activity behavior, which together form the basis for its participation in the hydration process of concrete, its influence on microstructure and macroscopic properties. A systematic analysis of these characteristics and mechanisms of action is a prerequisite for achieving their efficient application in concrete.

1. Physical and chemical properties of regenerated micro powder

The physicochemical properties of recycled micro powder are the material basis for its interaction with various components of concrete. Its composition, particle size distribution, and specific surface area are key parameters that directly determine its functional performance in concrete and require in-depth analysis from multiple dimensions.

The recycled micro powders involved in this article include recycled micro powders of waste concrete (RCP) and recycled micro powders of waste clay bricks (RBP) [26]. As shown in Figure 3, the recycled micro powder samples of waste concrete were mainly taken from Beijing Urban Green Source Environmental Protection Technology Co., Ltd. The company collects waste concrete blocks from a large number of building demolition sites in the Beijing area. These waste concrete blocks come from a wide range of sources, including old residential buildings, concrete structural parts of commercial buildings demolished due to urban renewal and renovation, as well as waste concrete components replaced by infrastructure maintenance such as roads and bridges.

Its collection requires a complete industrial processing procedure. Firstly, there is raw material pretreatment. The waste concrete blocks collected from the demolition site of the building need to be sorted manually or mechanically to remove impurities such as steel bars and wooden blocks. Then, the surface dust and loose attachments are washed with a high-pressure water gun, and naturally dried or dried until the moisture content is below 5%. Next, it enters the crushing stage. The pre treated concrete blocks are first roughly crushed by a jaw crusher, with a feed gap of 100-150mm, and crushed into small pieces with a particle size of 50-100mm; Then send it to the impact crusher for crushing, adjust the gap between the plate and hammer to 20-30mm, and obtain particles with a diameter of 5-20mm; Finally, the impact sand making machine is used for fine crushing, and fine materials with a particle size of less than 5mm are obtained by controlling the impeller speed. Next is grinding and screening. The finely crushed material is sent to a ball mill, which is filled with steel balls with a diameter of

5-20mm and a set speed of 180-220r/min. After grinding for 2-3 hours, it is sieved through a 325 mesh vibrating screen. The coarse material on the screen is returned to the ball mill for secondary grinding, and the undersized material is recycled micro powder of waste concrete.

Most of the recycled micro powder samples of abandoned clay bricks come from the urban village demolition project in Zhengzhou City. In the process of urban construction, Zhengzhou has renovated a large number of old urban villages and demolished many houses mainly made of clay bricks as the main wall material. In addition, the construction waste treatment station in Huainan City is also an important source of waste clay bricks. The selected clay red bricks are crushed and screened to obtain recycled brick powder, which is a form of recycled micro powder for waste clay bricks.

Its acquisition also requires step-by-step processing. The raw materials are first sorted and discarded clay bricks are collected from the dismantled brick concrete structure walls. Cement slurry blocks, lime paste and other attachments are manually removed, and then metal impurities such as iron nails on the surface of the bricks are removed by magnetic separation equipment. Subsequently entering the crushing stage, the sorted clay bricks are first crushed by a hammer crusher, adjusting the gap between the hammer head and the sieve plate to 15-20mm, and crushed into fragments of 20-30mm; Then, the fragments are fed into the cage crusher and further refined through the relative rotation of the inner and outer cages, resulting in material blocks with a particle size of less than 10mm. Finally, the material block is ground and sent to the Raymond mill. The gap between the grinding roller and the grinding ring is set to 0.5-1mm. After grinding for 1-2 hours, it is screened by a 200 mesh analysis sieve. The coarse material that does not pass is re entered into the grinding chamber. The material that passes the screening is the recycled micro powder of waste clay bricks. If a higher specific surface area micro powder is needed, an air flow mill can be used instead. By adjusting the compressed air pressure, the same raw material can be ground for 1 hour to obtain a product that meets the requirements.

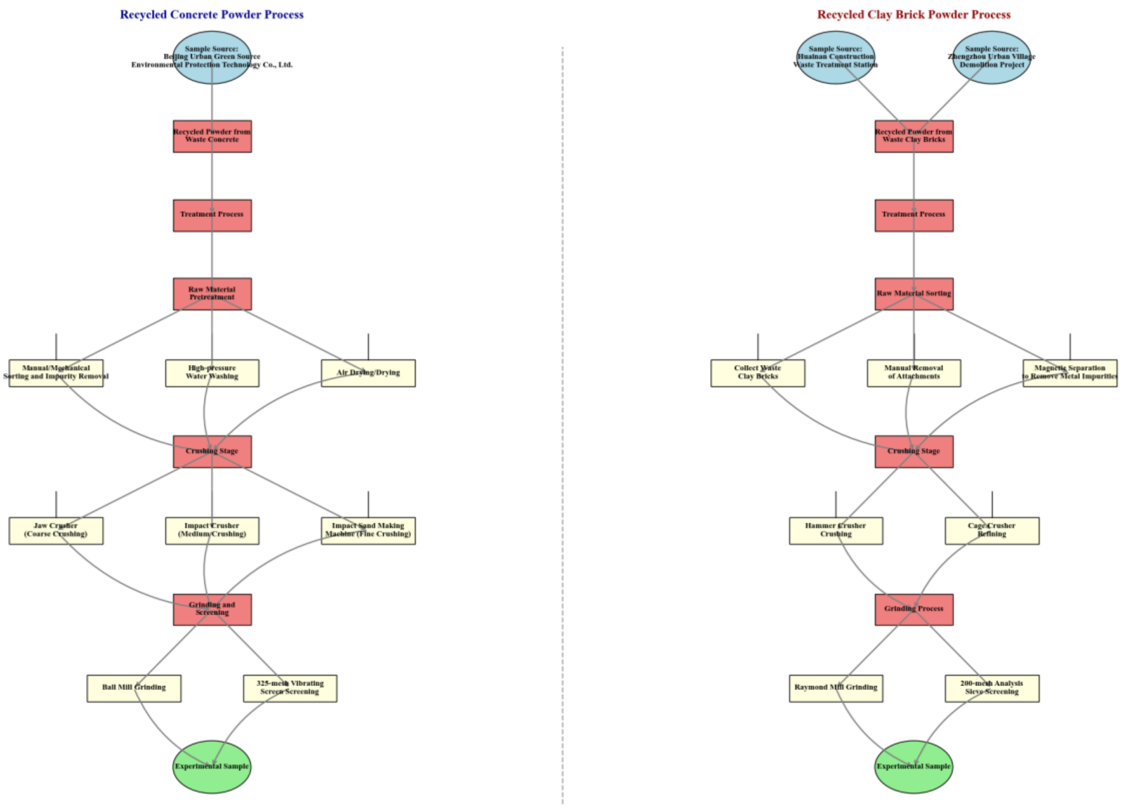

Figure 3: Schematic diagram of sample processing

The chemical composition analysis of the two is shown in Table 1. The chemical composition of recycled micro powder exhibits significant source dependence, with SiO_2 and CaO as the main components. The relative proportion of the two varies with the type of original building solid waste. If it comes from waste concrete, due to the high proportion of cement stone, the CaO content is usually higher, and it is often accompanied by a certain proportion of unhydrated cement particles [27]; If brick and tile solid waste is the main source, SiO_2 accounts for the highest proportion. The presence of unhydrated cement particles is an important characteristic that distinguishes recycled micro powder from ordinary mineral admixtures. Although its content is affected by the age of the original concrete and the grinding process, it can directly participate in the hydration reaction and become a direct contributor to its cementitious activity; The ratio of SiO_2 to CaO indirectly affects the potential of its volcanic ash activity, and the synergistic effect of the two provides material conditions for the reaction between regenerated micro powder and cement matrix.

Table 1: Chemical Composition Analysis

Chemical composition	RCP(%)	RBP(%)
SiO_2	20.0–25.0	50.0–65.0
Al_2O_3	4.0–8.0	12.0–20.0
Fe_2O_3	3.0–6.0	3.0–8.0
CaO	60.0–67.0	<10.0
K_2O	1.0–2.0	1.5–2.5
Na_2O	0.5–1.5	1.0–1.8
MgO	1.5–2.5	1.0–1.5
SO_3	≤3.5	≤1.5
Unhydrated cement particles	15.0–30.0	—
Loss on ignition	3.0–6.0	5.0–8.0

The particle size distribution and specific surface area are the core parameters that determine the physical effects of recycled micro powders, and they affect the performance of concrete through a dual mechanism of "filling effect" and "hydration competition". From the perspective of filling effect, when the particle size distribution of recycled micro powder is reasonable, its fine particles can fill the gaps between cement particles, optimize the packing density of the concrete system, and reduce porosity; The larger specific surface area provides more interfaces for it to come into contact with hydration products, which is conducive to the occurrence of physical adsorption and chemical reactions. However, it should be noted that excessively fine particle size and large specific surface area may also trigger "hydration competition", which can quickly adsorb a large amount of mixing water, resulting in insufficient water required for cement hydration. At the same time, high surface energy can accelerate the early hydration reaction rate, which may cause uneven distribution of hydration products and have adverse effects on concrete structures. Therefore, the regulation of particle size distribution and specific surface area needs to seek a balance between filling effect and hydration competition.

As shown in Figure 4, the particle size distribution of regenerated micro powder exhibits a significant bimodal characteristic, which evolves regularly with the change of micro powder type and grinding time. Both RCP and RBP exhibit two distinct peak ranges in particle size distribution at different grinding durations, namely the main peak and the secondary peak, which together constitute the main body of particle size distribution in micro powders. The main peak, as the dominant part of the particle size distribution, dominates the range and proportion of particles it covers, while the secondary peak corresponds to finer or finer particle size ranges. Although its proportion is relatively low, it plays an important complementary role in the integrity of the overall particle size distribution.

The extension of grinding time has a consistent effect on the bimodal characteristics of the two types of micro powders, mainly reflected in the shift of the main peak range towards smaller particle sizes, while the proportion of secondary peaks has increased. This indicates that as the grinding process continues, more larger particles are refined, not only narrowing the dominant particle size range, but also promoting the increase of fine particle components. In terms of span value and median particle size, both show a decreasing trend after prolonged grinding time, reflecting that the particle size distribution becomes more concentrated with prolonged grinding time and the overall refinement of particles improves.

Comparing the two types of micro powders, it can be seen that under the same grinding time, the main peak range of the waste clay brick micro powder is usually slightly larger than that of the waste concrete micro powder, and the proportion of the main peak is higher, while the span value is relatively smaller, indicating that the concentration of its initial particle size distribution is slightly better; As the grinding time prolongs, the difference in particle size distribution characteristics between the two gradually decreases, indicating that the grinding process has a universal regulatory effect on the particle size distribution of different types of micro powders. However, due to the different characteristics of the raw materials, there are still certain differences in the refinement rate and final distribution characteristics. The existence of this bimodal feature implies that recycled micro powder may simultaneously exert a synergistic effect of particles of different sizes in the concrete system. The particles corresponding to the main peak can participate in the dense accumulation of the system, while the fine particles of the secondary peak may fill the pores or participate in hydration reactions, thereby having a comprehensive impact on the performance of concrete.

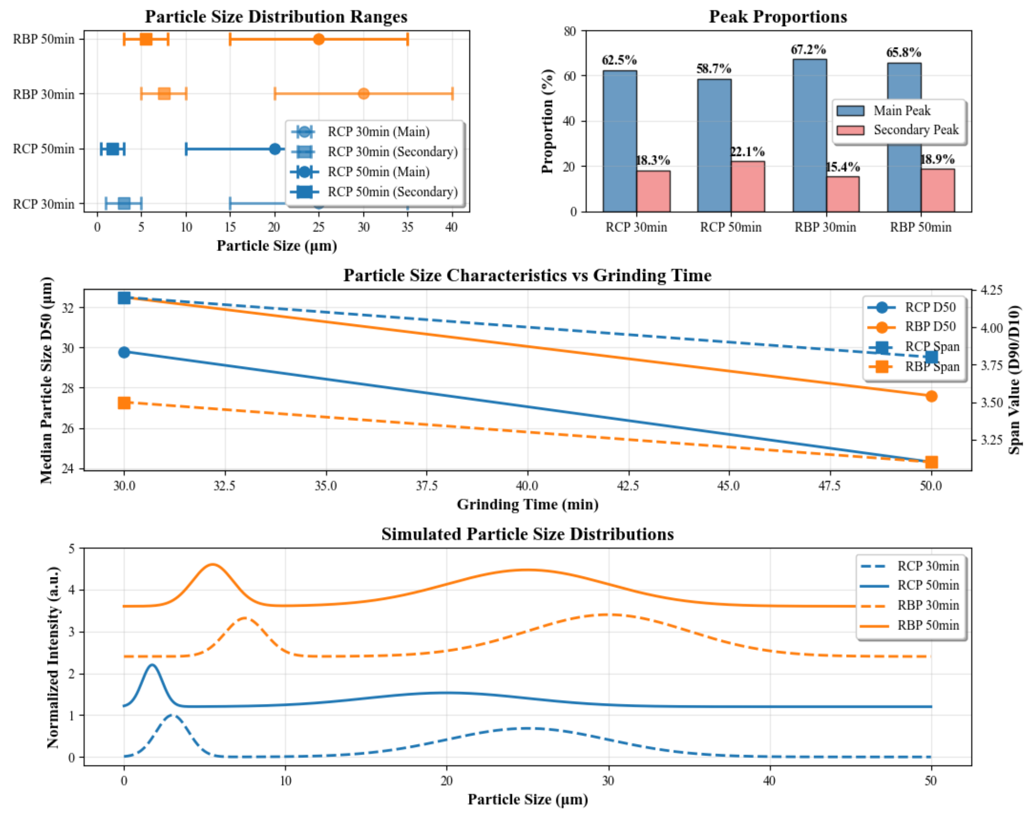

Figure 4: Particle size distribution of regenerated micro powder

As shown in Table 2, in terms of specific surface area, both RCP and RBP are within a considerable range of values, with RBP having a larger numerical span and overall higher than RCP. This difference may be due to the differences in the properties of the raw materials and the efficiency of the grinding process between the two.

In terms of characteristics, RCP exhibits multi angular particles and high porosity. These characteristics increase the water demand by 15-30% when mixed into concrete. Although its filling effect is significant and helps to compact the concrete matrix, its strong adsorption may affect the dispersion effect of chemical additives, thereby affecting the workability of concrete mixtures.

In contrast, the prominent feature of RBP is its high content of active substances. After grinding, its water demand ratio remains at a low level of 102-106%, indicating that it has better adaptability to concrete mixing systems in terms of water use. More importantly, its high volcanic ash activity potential means that in the alkaline environment of concrete, it can effectively participate in hydration reactions, generate additional hydration products to enhance the mechanical properties and durability of concrete, and show good application prospects in improving concrete performance.

Table 2: Specific surface area of regenerated micro powder

Type of Micro-powder	Specific Surface Area Range (m^2/kg)	Testing Method/Standard	Characteristic Description
RCP	350–450	"Method for Determination of Specific Surface Area of Cement - Blaine Method" (GB/T 8074-2008)	Particles are mostly angular with high porosity; water demand increases by 15–30%; filling effect is significant but adsorption is strong.
RBP	360–650	Same as RCP	High content of active substances; after grinding, water demand ratio is 102–106%; pozzolanic activity potential is high.

2. Activity mechanism of regenerated micro powder

The activity performance of recycled micro powder in concrete is the core driving force for its performance optimization, mainly reflected through the secondary hydration reaction induced by volcanic ash effect and the optimization of the microstructure of the interface transition zone, which together constitute the key connotation of its activity mechanism.

The volcanic ash effect of regenerated micro powder is an important manifestation of its activity, which refers to the slow secondary hydration reaction of its active components such as SiO_2 and Al_2O3 in the alkaline environment generated by cement hydration. This reaction path usually shows that the active component first dissolves and exchanges ions with $Ca(OH)_2$ to generate soluble silicate, aluminate and other intermediates, and then gradually coagulates and hardens, finally forming hydration products dominated by C-S-H gel. These new gel can fill the internal pores of concrete, especially refine the gross pore structure, thus improving the compactness and strength of concrete. Compared with the primary hydration of cement, the secondary hydration reaction rate is slower, but its continuous nature can continuously optimize the structure during the later service life of concrete, which is of great significance for the later strength development and durability improvement. The expression is as follows:

$$ceSiO2 + Ca(OH)2 + H2O -> C-S-H_{gel} \quad (1)$$

$$ceAl2O3 + Ca(OH)2 + H2O -> C-A-H_{gel} \quad (2)$$

The differentiation characteristics of the reaction pathway vary depending on the source of the micro powder. RCP contains unhydrated cement particles, and its C ∝ S and C_2S directly hydrate in alkaline environments, generating additional $Ca(OH)_2$ and further participating in the volcanic ash reaction, forming a "hydration volcanic ash" cascade effect. RBP is mainly composed of quartz and mullite crystal phases, which need to be mechanically ground to break down the crystal structure and release amorphous SiO_2 and Al_2O3. Its reactivity depends on the synergistic effect of fineness and alkali activator.

The interface transition zone (ITZ) is a weak area between aggregates and cement matrix in concrete, and its microstructural characteristics have a significant impact on the overall performance of concrete. The optimization of ITZ by recycled micro powder is another important aspect of its activity mechanism. When recycled micro powder is not added, ITZ often has many pores and cracks due to high water cement ratio and directional growth of $Ca(OH)_2$ crystals, resulting in poor mechanical properties. The addition of regenerated micro powder can optimize ITZ through multiple pathways: firstly, its fine particles can fill the initial pores in the ITZ area, improving the density of the area; Secondly, the secondary hydration reaction consumes excess $Ca(OH)_2$ near the ITZ, reducing the formation of coarse crystals and making the distribution of hydration products more uniform; Thirdly, the physical adsorption between regenerated micro powder and aggregate surface can enhance the interfacial adhesion. These effects collectively promote the transformation of the microstructure of ITZ from loose and porous to dense and uniform, thereby enhancing the interfacial strength and overall mechanical properties of concrete.

4 Influence mechanism

Regenerated micro powder intervenes in the concrete system, reshaping the workability from the rheological properties of the fresh mixing stage to the micro particle moisture interaction level.

1. Changes in rheological properties of fresh concrete

As shown in Table 3, the addition of regenerated micro powder disrupts the original material balance, triggering a chain reaction of changes in water demand, fluidity, and coagulation process. Due to its porous surface and irregular particle morphology, recycled micro powder has an adsorption effect on free water, which initially increases the water demand for standard consistency and squeezes the flowability space of concrete. But when the particle size distribution of micro powder is well adapted, fine particles can fill the gaps between coarse aggregates, and a "water reduction effect" can be formed within a certain dosage range, with a critical point where the water demand increases and decreases. This critical point is related to the specific surface area of micro powder, particle shape, and concrete mix proportion. Accurately capturing this point can achieve a dynamic balance between increasing water demand and ensuring fluidity, avoiding excessive sacrifice of workability or concrete dryness and segregation caused by uncontrolled water demand.

Table 3: Effect of Recycled Micro Powder on the Rheological Properties of Freshly Mixed Concrete

Characteristic Parameter	RCP	RBP
Dosage Critical Point	When dosage ≤ 20%, fluidity is improved; when dosage > 30%, water demand rises rapidly	When dosage ≤ 15%, fluidity is enhanced; when dosage > 25%, bleeding rate increases
Yield Stress (τ_0)	When dosage is 20%, the filling effect dominates	When dosage is 15%, particle angularity increases internal friction
Plastic Viscosity (η)	When dosage is 20%, high specific surface area increases viscosity	When dosage is 15%, low - active components reduce gel - bound water
Setting Time Regulation	Initial setting is prolonged by 15–30 min	Initial setting is shortened by 5–10 min
Bubble Stability	When dosage is 15%, unhydrated particles adsorb at the gas - liquid interface	When dosage > 20%, insufficient paste cohesiveness occurs

In addition, as shown in Figure 5, the active ingredients brought in by the regenerated micro powder interact with the cement hydration system, and some micro powders can delay the cement hydration process, causing a retarding phenomenon, especially in low-temperature environments or high dosage scenarios. By using a combination of retarders and regenerated micro powders, the setting time can be controlled in a targeted manner. The retarders adsorb onto the surface of cement particles, inhibiting early hydration. Combined with the blocking effect of micro powders on water and ion migration, the initial setting window can be extended to adapt to long-distance transportation and large-scale pouring; With the advancement of hydration in the later stage, the activity of micro powder is stimulated to participate in the reaction, and the effect of retarder is attenuated, ensuring the development rhythm of final setting strength and solving the problem of abnormal coagulation caused by micro powder.

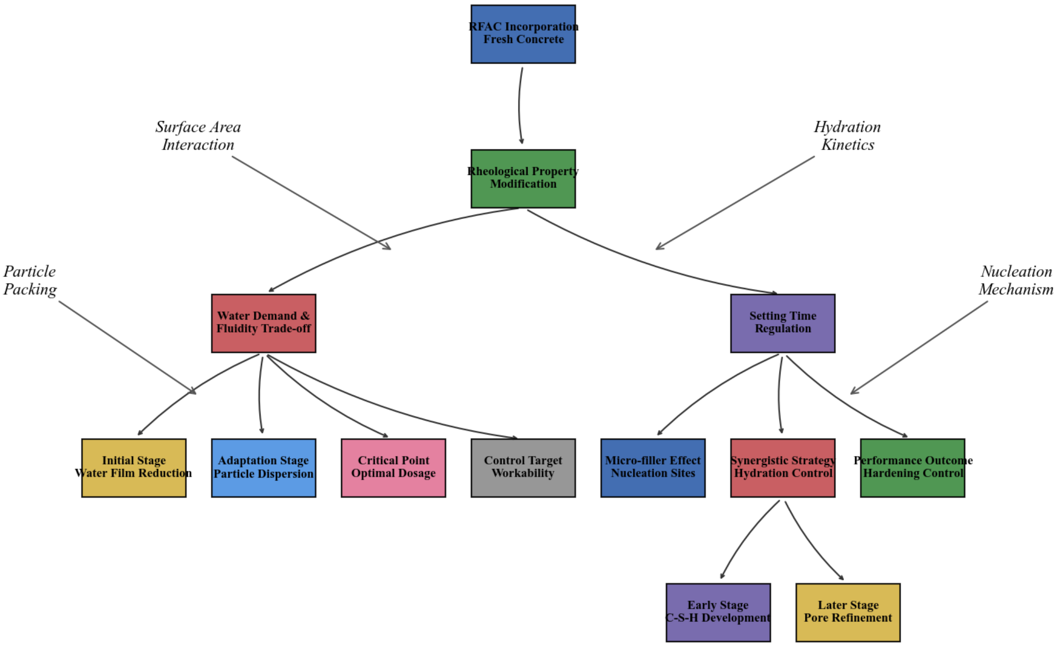

Figure 5: Schematic diagram of rheological property changes

2. Microscopic mechanism

As shown in Table 4, from a microscopic perspective, recycled micro powders reshape the relationship between water adsorption release and bubble slurry interaction within concrete, with particle size adjustment as the core.

Overall, the surface of regenerated micro powder is rich in pores, forming a "micro water storage unit". In the initial stage, it relies on surface energy to adsorb pore water, reducing the available amount of free water; With the advancement of cement hydration, the alkalinity of the system increases and the temperature rises. The water adsorbed by the micro powder is driven by chemical potential and thermal motion, gradually released to participate in the hydration reaction, forming a dynamic cycle of "adsorption release". This dynamic process affects the distribution rhythm of moisture in the slurry: the adsorption period constrains fluidity, the release period supplements hydration water sources, and this law can be used reasonably to regulate the loss of concrete slump over time and adapt to different construction time requirements.

In foam concrete, recycled micropowder plays a role by regulating the stability of bubble structure. Micro powder particles can adhere to the surface of the bubble liquid film, filling the pores of the film wall and enhancing the strength of the liquid film; On the other hand, relying on the friction between particles, it hinders the coalescence and bursting of bubbles. For example, for foam concrete containing recycled fine powder of waste clay bricks, the active component of the fine powder cooperates with the foaming agent to make the bubble size more uniform, reduce the bubble spacing coefficient, ensure the stability of the foam system before concrete setting, not only maintain the fluidity in the fresh mixing stage, but also lay a foundation for the lightweight and thermal insulation performance after hardening, showing the customized influence of recycled fine powder on the working performance of special function concrete.

Table 4: Comparison of Microscopic Mechanisms of the Influence of Recycled Micropowder on the Workability of Concrete

Action Scale	Action Mechanism	RCP Effect	RBP Effect
Particle Gradation Optimization	Filling Effect	Main peak particles fill the gaps between cement particles, reducing porosity; Spherical particles improve paste compactness	High proportion of coarse particles, prone to segregation; Needs to be compounded with ultra-fine slag to optimize gradation
	Hydration Competition	Secondary peak particles adsorb free water and compete for water-reducing agent molecules	Layered structure of clay minerals adsorbs water-reducing agents, increasing the adsorption capacity
Water Kinetics	Adsorption-Desorption Process	Mesopores adsorb water, which is desorbed during the hydration exothermic period	Micropores lock water, reducing the water release rate and exacerbating early self-shrinkage
	Bound Water Distribution	Optimizes the spatial distribution of hydration products, increasing the proportion of bound water	Low CaO content reduces C-S-H generation, increasing the proportion of free water
Bubble Structure Regulation	Interface Adsorption Mechanism	Unhydrated cement particles anchor at the gas-liquid interface, forming a mechanical barrier	Flaky clay minerals puncture the bubble film, resulting in weak bubble stabilization ability
	Rheological Support	Increased plastic viscosity inhibits bubble floating	Insufficient paste cohesiveness reduces bubble migration resistance

5 Microscopic pore structure regulation mechanism

The regulation of micro pore structure in concrete by recycled micro powder is one of the core paths to improve the macroscopic performance of concrete. This process is achieved through multi-dimensional optimization of pore characteristics and ultimately reflected in the improvement of concrete durability. The accurate characterization of pore characteristics needs to be carried out from two key dimensions: pore size distribution and connectivity, which together reflect the reshaping effect of recycled micro powder on the internal pore system of concrete.

1. Migration of aperture distribution curve

From the pore structure data presented in Table 5, it can be seen that the addition of recycled micro powder and different treatment methods have a systematic impact on the micro pore characteristics of cement slurry. This impact is not simply a parameter change, but gradually changes the compactness of the system through the coordinated adjustment of pore type proportion, pore size distribution and other dimensions.

Further analysis reveals that this optimization effect is related to the dosage and activation method. Taking unactivated RCP as an example, there is a suitable range for improving pores. Beyond this range, the proportion of harmful pores actually increases, indicating that excessive addition may weaken the control effect on pores due to uneven particle dispersion or hydration competition; However, thermal activated RBP and carbonized activated RCP have more significant pore optimization under similar dosage, especially carbonized activated RCP. Not only does the proportion of harmless pores increase significantly, but the most probable pore size also migrates to a smaller size. This is because activation treatment enhances the activity or filling capacity of micro powder, enabling it to participate in pore reconstruction more efficiently. Either more gel is generated through more sufficient hydration to refine pores, or the filling efficiency is improved through surface property optimization.

From a deeper perspective, the optimization of pore structure will directly affect the performance of the slurry. The specific surface area increases with the increase of harmless pores, indicating a change in the contact area between the internal and external media of the slurry, which may affect the hydration process or ion migration; The reduction of the most probable pore size will lower the permeation path of moisture and corrosive media in the slurry, laying the foundation for subsequent durability improvement. For example, the pore structure formed by the activated micro powder has fewer harmful pores and smaller pore sizes, which can more effectively hinder the invasion of external erosion factors. This also reflects the supporting role of micro pore regulation on macroscopic performance.

Table 5: Effects of Recycled Micropowder on the Pore Size Distribution of Concrete

Group	Dosage (%)	<20 nm (Harmless Pores) (%)	20–50 nm (Transition Pores) (%)	>50 nm (Harmful Pores) (%)	Most Probable Pore Diameter (nm)	Specific Surface Area (m^2/g)	Total Porosity (%)
Reference Cement Paste	0	20.3	31.5	48.2	53	1.28	18.7
RCP (Unactivated)	10	28.4	33.1	38.5	42	1.53	17.2
	20	34.8	35.7	29.5	26	1.86	15.9
	30	27.9	37.3	34.8	31	2.05	16.8
RBP (Thermally Activated, 600°C×2h)	15	36.1	36.9	27.0	29	1.97	14.3
	20	41.2	38.1	20.7	19	2.15	13.5
Carbonation-Activated RCP (CO_2-Treated)	20	38.6	37.5	23.9	17	2.32	14.1

As shown in Figure 6, intuitively, the migration of pore size distribution curve is the most intuitive characterization result. When the amount of recycled micropowder is in a reasonable range, the filling effect of its fine particles and the gel products generated by the secondary hydration reaction will shift the pore size distribution curve to the direction of small pore size, and the proportion of harmful pores that originally accounted for a high proportion will decrease, while the proportion of harmless pores will increase. This degree of migration is directly related to the particle size distribution and activity level of the micropowder. The micropowder with high activity can generate more hydration products, and has a more significant refining effect on large pore size.

Compared with the benchmark cement slurry without micro powder, both unactivated RCP, thermally activated RBP, and carbonized activated RCP can promote the development of pore structure towards a better direction at a reasonable dosage. The most obvious manifestation is the decrease in the proportion of harmful pores and the increase in the proportion of harmless pores. This means that the large pore size, which could have been a weak performance point, has decreased, while the small pore size, which has less impact on structural compactness, has increased. The overall pore system is becoming more refined. At the same time, the decrease of the total porosity also confirms the compaction effect of recycled micropowder on the slurry from a macro perspective. The gel products generated by particle filling or hydration reaction fill the original pores and make the system more compact.

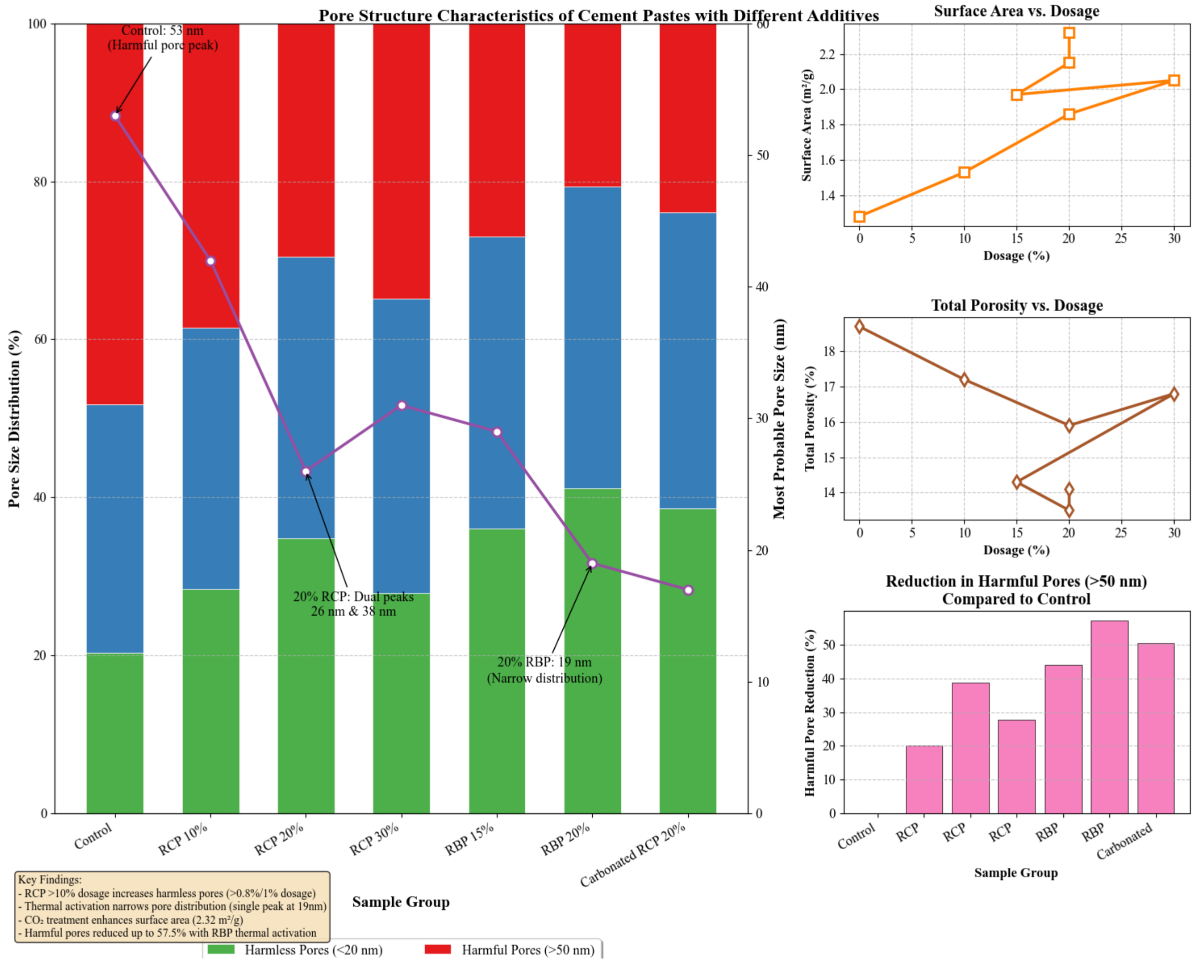

Figure 6: The influence of recycled micro powder on the pore size distribution of concrete

2. Blocking effect of pore connectivity

From the performance data presented in Table 6, it can be seen that the addition of recycled micro powder and different treatment methods have a clear regulatory effect on the anti permeability and anti diffusion performance of cement slurry. This effect echoes the changes in the micro pore structure and shows a certain regularity.

Intuitively speaking, compared with the benchmark cement slurry without micro powder, both unactivated RCP, thermally activated RBP, and carbonized activated RCP can improve the anti diffusion performance of the slurry after being added. The most direct manifestation is the decrease in permeability, which means that the difficulty of external media penetrating the slurry increases, and this is obviously related to the optimization of pore structure. The increase in pore tortuosity and the decrease in the proportion of effective diffusion channels make the permeation path of the medium longer and more complex, naturally reducing its permeation and diffusion efficiency.

Further observation reveals that this improvement effect is related to the dosage and activation method. Taking unactivated RCP as an example, with the increase of dosage, the overall optimization trend of relevant performance indicators is obvious, indicating that a reasonable increase in dosage can more fully exert its regulating effect on pores; However, it should be noted that this improvement is not infinite and needs to be combined with the actual dosage range to grasp the optimal effect. And the activated micro powder shows more outstanding performance, especially the activated RCP by carbonization. At the same dosage, the decrease in permeability is greater and the improvement in pore tortuosity is more significant. This is obviously because the activation treatment enhances the activity or filling ability of the micro powder, either by refining the pores through more thorough hydration reactions, or by further blocking the diffusion channels through optimization of surface properties, thereby more efficiently improving the anti permeability barrier effect of the slurry.

From a deeper perspective, these improvements in performance are essentially a macroscopic manifestation of micro pore structure optimization. The increase in pore tortuosity means that the connected paths of the internal pores of the slurry are further severed, and the decrease in the proportion of effective diffusion channels directly reduces the number of "effective paths" for medium permeability. Under the combined action of the two, the decrease in permeability becomes inevitable. This also means that by regulating the dosage and activation method of recycled micro powder, the anti-corrosion foundation of concrete can be optimized in a targeted manner, providing a feasible path for improving its durability in complex service environments.

Table 6: Blocking effect of pore connectivity

Group	Dosage (%)	Permeability ($\times 10^{-16}$ m²)	Chloride Ion Diffusion Coefficient ($\times 10^{-12}$ m²/s)	Pore Tortuosity (τ)	Proportion of Effective Diffusion Channels (%)
Reference Cement Paste	0	7.85	11.3	3.7	65.2
RCP (Unactivated)	10	5.21	7.9	4.6	47.8
	20	2.37	5.3	6.2	28.4
	30	1.82	4.6	7.1	22.7
RBP (Thermally Activated, 600°C×2h)	15	4.06	6.3	5.3	37.5
	20	1.15	4.2	8.0	15.3
Carbonation-Activated RCP (CO_2-Treated)	20	0.89	3.4	9.4	12.9

3. Pore control enhances durability

As shown in Table 7, the intervention of recycled micro powder is not simply a "supplement", but fundamentally reshapes the anti degradation ability of concrete, and this reshaping ability is deeply bound to the type and treatment method of micro powder.

Looking at the comparison with benchmark concrete alone, unactivated RCP can significantly improve various durability indicators. The core logic behind this is actually the optimization of the internal pore system of concrete by micro powder. Whether it is refining the pore size or blocking the connecting path, it reduces the invasion channels of external deteriorating media, which is equivalent to building a "physical barrier" for concrete. But what is more noteworthy is that heat activated RBP performs better in terms of freeze-thaw resistance, and carbonized activated RCP even achieves a strength retention rate of over 100% in resisting sulfate corrosion. This indicates that activation treatment is not a "simple enhancement", but triggers more complex interface reactions and material transformations.

For example, the extraordinary performance of activated RCP in resisting sulfate corrosion is likely due to the CO_2 treatment, which generates more stable carbonate products on the surface of the micro powder. These products not only fill the pores, but also preferentially react with sulfate ions when they invade, avoiding the erosion and decomposition of cement hydration products; At the same time, the high activity of the activated micro powder may promote the secondary hydration and generate more dense C-S-H gel, which instead makes the concrete "more dense" in the corrosive environment, and the strength increases instead of decreasing. The advantage of thermally activated RBP in terms of freeze-thaw resistance may be related to the structural transformation of clay minerals after treatment at 600 ℃. After removing bound water, particles are more easily dispersed and can fill pores more evenly, reducing the concentration of frost heave stress caused by large pores and making it more difficult for concrete to crack during repeated freeze-thaw cycles.

At a deeper level, these results actually reveal the key to turning recycled micro powders into treasures. Unactivated micro powders rely on "physical filling" to play a fundamental role, while activation treatment regulates the chemical activity or physical form of micro powders to give them "chemical defense" capabilities. It can actively block degradation pathways and generate stable substances through reactions in degraded environments. This means that recycled micro powder can not only reduce the carbon footprint of concrete, but also improve its service life in harsh environments such as cold and saline alkali.

Table 7: Improvement of Durability by Pore Control

Durability Type	Group	Key Performance Parameter
Frost Resistance	Reference Concrete	Failed at F150 grade
	20% RCP (Unactivated)	Met the standard at F250 grade
	20% Thermally Activated RBP (600℃×2h)	Met the standard at F350 grade
Sulfate Erosion Resistance	Reference Concrete	Strength retention rate of 68.3% after 180d immersion in 5% Na_2SO_4 solution
	20% RCP (Unactivated)	Strength retention rate of 92.7% after 180d immersion in 5% Na_2SO_4 solution
	20% Carbonation-Activated RCP (CO_2-Treated)	Strength retention rate of 123.1% after 180d immersion in 5% Na_2SO_4 solution
Chloride Ion Penetration Resistance	Reference Concrete	Chloride ion diffusion coefficient: 11.3×10^{-12} m²/s
	20% RCP (Unactivated)	Chloride ion diffusion coefficient: 5.3×10^{-12} m²/s
	20% Thermally Activated RBP	Chloride ion diffusion coefficient: 4.2×10^{-12} m²/s

6 Conclusion

This study systematically analyzed the influence and mechanism of recycled micro powder on the performance of concrete. The results showed that the physical and chemical properties of recycled micro powder have significant source dependence. RCP contains more unhydrated cement particles, CaO content is high, and the water demand increases significantly; RBP is mainly composed of SiO_2, which has high volcanic ash activity potential and better adaptability to water demand. Both have a bimodal particle size distribution, and reasonable grinding can optimize particle size distribution. In terms of its impact on the workability of concrete, the appropriate dosage can enhance fluidity through filling effect, while excessive dosage can reduce workability due to a surge in water demand. The "adsorption release" cycle of water can regulate the loss of slump over time. In terms of mechanical properties, recycled micropowder generates C-S-H gel and optimizes ITZ through pozzolanic effect, which significantly improves the strength of concrete, especially in the late stage. At the micro level, recycled micro powder can refine pore size, block pore connectivity, and effectively improve the durability of concrete, such as frost resistance and resistance to sulfate attack.

The research results indicate that the application of recycled micro powder in concrete fully reflects the ecological and economic value of high-value utilization of construction solid waste, providing an effective path for alleviating resource constraints and promoting green development. Its impact on the performance of concrete is the result of the synergistic effect of physical properties and chemical activity. A single indicator is difficult to comprehensively evaluate, and the mechanism needs to be analyzed at multiple scales from macro and micro perspectives. At the same time, the micro pore structure is the key to connecting the characteristics of recycled micro powder with the macroscopic properties of concrete. The core idea of research in this field is to achieve the synergistic improvement of workability and mechanical properties by regulating the pore characteristics.

Therefore, this article suggests that a classification and grading standard for recycled micro powders should be established as soon as possible, and applied according to indicators such as source, particle size, and activity to avoid quality fluctuations affecting the stability of concrete performance. Optimize pretreatment processes for different types of micro powders, such as thermal activation of RBP and carbonization activation of RCP, to enhance their activity and adaptability. Promote the construction of engineering application technology system, develop mix design guidelines, clarify parameters such as dosage and admixture compatibility, and shorten the gap between laboratory research and engineering practice. In addition, it is necessary to improve the environmental benefit assessment system, quantify its contributions in carbon emissions and solid waste disposal, and provide support for green building certification.

In the future, we can deepen the research on the co blending effect of recycled micro powder and other auxiliary cementitious materials, explore the synergistic regulation law of multiple components, and seek performance balance under higher solid waste content. Expand its application in special concrete, such as self-healing and lightweight insulation concrete, and explore its potential for functionalization. Introducing intelligent technology, utilizing machine learning to construct performance prediction models, and combining digital twin simulation of microstructure evolution to achieve precise design.

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