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Enhancement of Concrete Durability with Waterborne Acrylic Resin: A Comprehensive Review

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KEYWORDS

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ABSTRACT

As an environmentally friendly polymer material, water-based acrylic resin has shown significant application advantages in the fields of construction, coatings, and concrete in recent years due to its molecular properties of using water as a solvent Compared with traditional solvent based resins, water-based acrylic resins use water as the solvent and have a lower content of volatile organic compounds, effectively alleviating construction pollution problems and in line with the development trend of green building materials Based on the analysis of the current development status and trends of the construction industry, this article mainly summarizes the development process and synthesis technology of water-based acrylic resin, and focuses on explaining its dual path application mechanism of external coating protection and internal mixing modification in concrete engineering By forming a hydrogen bond cross-linking network and interface strengthening effect, water-based acrylic resin can significantly improve the compressive strength, impermeability grade, and shrinkage cracking resistance of concrete matrix, achieving synergistic optimization of mechanical properties and durability Finally, future research directions were discussed.

INTRODUCTION

Amid the global consensus on environmental protection and the steady implementation of sustainable development strategies, the growth of traditional solvent-based coatings has become increasingly constrained due to their high safety risks and environmental pollution. Against this backdrop, the vigorous development of low-toxicity, eco-friendly coating products has emerged as an inevitable trend and urgent demand for the industry. As a key component of water-based coatings, waterborne acrylic resins have gained extensive application in numerous traditional fields, such as coatings, adhesives, and papermaking, owing to their non-toxic, harmless, and environmentally friendly properties. In recent years, their applications have further expanded into emerging domains, including concrete and construction, demonstrating remarkable prospects and potential. These resins are poised to become a driving force in the green transformation of related industries in the future.

As one of the most essential construction materials, the durability, impermeability, and aesthetic properties of concrete critically determine the service life and visual quality of buildings [1-2]. However, inherent limitations such as high porosity, proneness to carbonation, and susceptibility to cracking render concrete vulnerable to environmental degradation, leading to performance deterioration and increasingly prominent durability issues.

In this context, modified cement-based materials characterized by synergistic performance enhancement have emerged as a research focus. Among these, acrylic resins have drawn considerable attention due to their exceptional adhesive properties, weather resistance, and chemical stability. Recent years have witnessed extensive studies by domestic and international scholars on the application of

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waterborne acrylic resins in concrete and construction domains, yielding significant progress. Nevertheless, challenges persist in this field. This paper systematically examines the research advancements in waterborne acrylic resin applications, encompassing surface coatings and internal admixtures for concrete, starting from their synthesis processes. Furthermore, it analyzes future development trends to provide theoretical foundations and technical references for further research and practical implementation of waterborne acrylic resins in concrete-related applications.

1.Synthesis of Waterborne Acrylic Resins

Waterborne acrylic resins are typically synthesized through copolymerization of acrylic acid, methacrylic acid, their esters, or other derivatives. The structural diagram of their fundamental components[3] is illustrated in Figure 1 , while Figure 2 outlines the synthesis methodologies, which primarily include emulsion polymerization, solution polymerization, bulk polymerization, and soap-free emulsion polymerization.

1.1.Emulsion Polymerization

Emulsion polymerization[4] stands as one of the most prevalent methods for synthesizing waterborne acrylic resins. This method employs water as the dispersion medium, where monomers are dispersed via emulsifiers and polymerized under initiators. Commonly used monomers encompass acrylic acid, methyl methacrylate, butyl acrylate, and styrene. Typical emulsifiers include anionic (e.g., sodium dodecyl sulfate) or nonionic emulsifiers, while water-soluble initiators such as ammonium persulfate or potassium persulfate are frequently utilized.

Li et al.[5] developed an acrylic-PDMS composite emulsion by blending modified polydimethylsiloxane (PDMS) with acrylate monomers through emulsion polymerization. Experimental characterization revealed that the cured coatings derived from this composite emulsion exhibited low surface tension, enhanced toughness, and exceptional weather resistance, demonstrating promising applications in corrosion protection. Notably, this method features mild reaction conditions, operational safety, and scalability for industrial production. The resultant acrylic resin emulsion demonstrates superior film-forming capability, weather resistance, and adhesion, making it suitable for eco-friendly coatings and environmentally benign adhesives

1.2.Solution Polymerization

Solution polymerization[6] involves dissolving monomers in organic solvents, initiating polymerization via initiators, and subsequently removing the solvent or replacing it with water to obtain waterborne acrylic resins. Common solvents include acetone, methyl ethyl ketone (MEK), and isopropanol. Similar to emulsion polymerization, acrylic acid and its ester monomers are typically selected, with oil-soluble initiators such as azobisisobutyronitrile (AIBN) or benzoyl peroxide (BPO) being commonly employed. Fan et al. [7] synthesized an acrylic resin with a solid content of up to 80% using methyl methacrylate (MMA), methyl acrylate (MA), hydroxyethyl methacrylate (HEMA), n-butyl acrylate (BA), and styrene as monomers via solution polymerization. This method is conducted under an inert gas atmosphere, where monomers and initiators are added to the solvent and heated to initiate polymerization. The reaction proceeds rapidly with controllable molecular weight, making it suitable for synthesizing high-solid-content resins

1.3.Bulk Polymerization

Bulk polymerization [8] is a solvent-free process where monomers are directly heated to initiate polymerization. Monomers and initiators are mixed and heated to a specific temperature to drive the reaction. Chen et al. [9] optimized reaction parameters, including temperature, initiator dosage, and monomer ratios, through orthogonal experiments. The resulting products were characterized using Fourier transform infrared spectroscopy (FTIR) and gel permeation chromatography (GPC). Experimental results indicated that the optimal conditions were a reaction temperature of 80°C, initiator dosage of 0.5%, and monomer ratio of MMA:BA:AA = 60:30:10. The optimized resin exhibited excellent film-forming properties and adhesion. This method offers simplicity in process and high-purity products, though challenges such as intense exothermic reactions and difficulties in temperature control must be addressed.

1.4.Emulsifier-Free Emulsion Polymerization

Emulsifier-free emulsion polymerization [10] employs functional monomers (e.g., acrylic acid, methacrylic acid) instead of traditional emulsifiers to stabilize the emulsion, enabling polymerization without surfactants. Wang et al. [11] determined the optimal formulation for resin synthesis via single-factor and orthogonal experiments: MMA:BA:AA = 50:40:10, reaction temperature of 80°C, and reaction time of 4 h. The resulting resin displayed uniform particle size distribution, a tensile strength of 15 MPa, and an elongation at break of 300%. Qiu Shiqi et al. [12] further modified the emulsifier-free emulsion polymerization process by introducing crosslinking agents and functional monomers, enhancing the adhesive properties, water resistance, and chemical resistance of the resin. This method eliminates the need for conventional emulsifiers, yielding products with higher purity, improved water resistance, enhanced stability, and superior environmental compatibility.

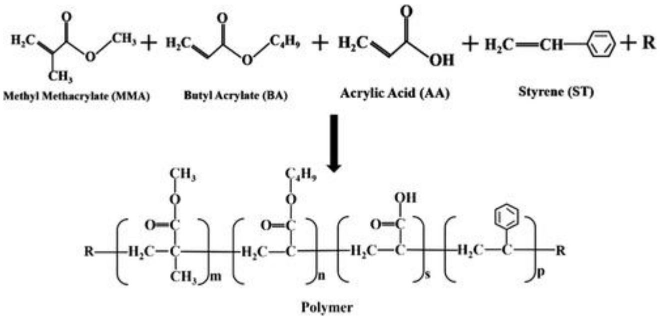

Fig.1. Waterborne acrylic resin and its monomer structure[3]

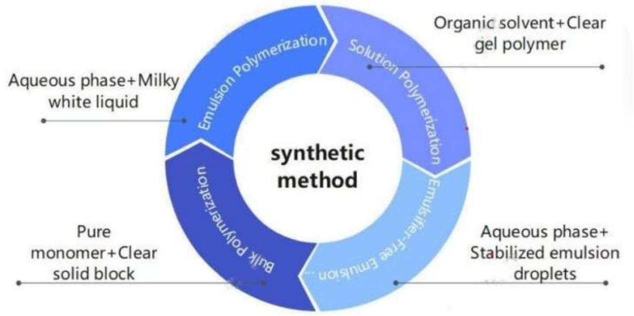

Fig.2. Synthetic method

2.Incorporation of Waterborne Acrylic Resin in Concrete

The application of waterborne acrylic resin in concrete is widespread, primarily attributed to its environmental friendliness, durability, and excellent adhesion [13 – 17]. The internal incorporation method [18], as a core technique for modifying concrete with waterborne acrylic resin, involves adding pre-treated resin emulsions into the concrete mixture through precise proportioning design. Leveraging the flexible chain segments and active functional groups of the resin molecules, nanoscale three-dimensional penetration within the pores of the concrete is achieved. This process enhances the concrete's compactness, compressive strength, and bonding performance.

2.1.Enhancement of Bonding Performance

The overall strength of concrete primarily depends on the bonding strength between the cement paste and aggregates. Poor bonding can result in weak interfacial connections, leading to crack formation at the interface under stress. This premature structural failure prevents full utilization of material strengths, thereby reducing the compressive, tensile, and shear strength properties of concrete [19 – 22]. Numerous factors influence concrete bonding performance. For instance, inadequate mixing during construction causes uneven distribution of concrete components, compromising the adhesion between cement paste and aggregates. This results in excessive pores and voids within the concrete, diminishing its overall strength and bonding capacity.

The long-chain polymer structure of acrylic resin endows it with excellent adhesion, flexibility, and transparency. Its low viscosity enables effective penetration into the micro-pores of concrete, thereby enhancing interfacial adhesion. Guo et al. [23] introduced epoxy resin into the molecular structure of waterborne acrylic resin. By combining epoxy resin with aqueous dispersion techniques, they synthesized waterborne epoxy-acrylic resin, which was subsequently incorporated into concrete as a hydrogel during the mixing process. As shown in Figure 3, when the resin content reached 5%, the tensile bond strength of the resulting concrete measured 4 – 5 MPa. The internal incorporation of waterborne acrylic resin emulsion into concrete acts as a "bridge" to fill the interfacial transition zone between cement paste and aggregates. This densifies the internal structure of concrete, significantly improves bonding performance, and reduces the risk of debonding [24 – 26]

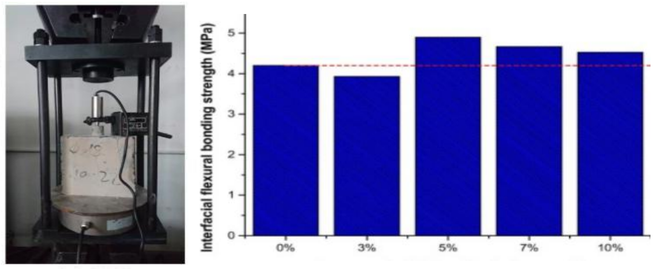

Fig.3. Concrete bonding performance testing[23]

2.2.Optimization of Mechanical Properties

Poor mechanical performance of concrete, caused by issues in raw materials, construction processes, environmental factors, or long-term degradation, may lead to safety hazards or economic losses [27].

When acrylic resin is incorporated into concrete in emulsion or solution form, it forms continuous polymer films during hardening. These films fill capillary pores and microcracks within the cement mortar, effectively dispersing and transmitting stress. Cui Weirong et al. [28] demonstrated that adding 3% waterborne acrylic resin via internal incorporation improved interfacial bond strength by 25%–40%, thereby enhancing concrete's compressive strength (by approximately 10%–15%) and splitting tensile strength (by approximately 15%–20%). Current modification techniques for waterborne acrylic resin, such as fluorination, silane coupling, or incorporation of nanomaterials (e.g., steel fibers, rubber), have matured. Liang Bingkang et al. [29] synthesized silane coupling agent-modified waterborne acrylic resin, where the hydrolysis of silane formed Si–O–Si crosslinked structures. This modification significantly enhanced the bonding between the resin and concrete aggregates. Experimental tests revealed a 12.4 MPa increase in flexural strength and a 159% improvement in tensile strength. The incorporation of acrylic resin into concrete enhances compactness, reduces porosity, and strengthens compressive capacity. Furthermore, crack suppression improves flexural and tensile performance [30–32].

2.3.Improvement of Freeze-Thaw Resistance

Traditional cement-based matrices exhibit high brittleness and lack ductile buffering capacity, rendering them vulnerable to repeated stresses during freeze-thaw cycles. This results in poor freeze-thaw resistance. In northern road engineering, combined salt-freeze effects accelerate concrete deterioration, significantly shortening service life and increasing maintenance costs.

Waterborne acrylic resin possesses exceptional elasticity and deformation capacity. When internally incorporated into concrete, it forms a flexible network structure that absorbs energy through elastic deformation during stress concentration caused by freeze-thaw cycles, thereby delaying crack propagation. Shi et al. [33] experimentally demonstrated that ordinary concrete exhibits a mass loss rate >5% after 50 freeze-thaw cycles, whereas concrete with 10% acrylic resin shows a mass loss rate <2% and modulus retention >85% even after 100 cycles. In a practical case in China [34], 12% acrylic resin-modified concrete was used for permafrost road repair on the Qinghai-Tibet Highway. The freeze-thaw resistance increased from 50 to 200 cycles, extending the maintenance interval by threefold. Internal incorporation of acrylic resin provides an effective solution for enhancing concrete's freeze-thaw resistance, toughness, and impermeability. However, challenges such as cost, long-term stability, and material compatibility must be addressed for large-scale applications [35].

3.External Coating Application of Waterborne Acrylic Resin in Concrete

Concrete, when exposed to air over extended periods, is susceptible to water infiltration and chemical corrosion (e.g., chloride ions, acid rain). These factors trigger electrochemical corrosion chain reactions within the pore solution of concrete, accelerating steel reinforcement rusting and matrix dissolution, thereby shortening structural service life. The external coating method [36], as an innovative surface protection technology, involves uniformly applying synthesized waterborne acrylic resin emulsions onto concrete surfaces via brushing or spraying. After natural drying or curing, a dense, continuous molecular-level protective film is formed. Leveraging high crosslinking density and low surface energy, this film establishes a multifunctional barrier system with carbonation resistance, corrosion protection, and anti-fouling properties, achieving "one-coat multi-functionality" for concrete surface protection [37-38]. This method is primarily employed for rapid repair and long-term preservation of existing structures.

3.1.Improvement of Carbonation Resistance

The carbonation mechanism of concrete [39] involves the reaction of carbon dioxide with calcium hydroxide (a cement hydration product) to form calcium carbonate and water, reducing concrete alkalinity. This process destabilizes the passive film on steel reinforcement, leading to corrosion. Waterborne acrylic resin inhibits carbonation through physical isolation, chemical modification, and microscopic repair:

Physical Isolation:The cured coating forms a continuous film that seals surface micropores and microcracks, blocking CO_2 and moisture diffusion pathways. Experimental data indicate that the CO_2 diffusion coefficient of coated concrete is reduced by 80% – 90%. Fan et al. [40] compared coated and uncoated concrete samples by applying waterborne acrylic resin emulsion and testing chloride ion penetration resistance after 12 – 270 days of salt corrosion. As shown in Figure 4, at a depth of 5 mm, chloride ion content in uncoated specimens exceeded 6000 mg/kg, whereas coated specimens exhibited levels below 3500 mg/kg.

Chemical Modification:Carboxyl groups in the resin react with Ca^{2+} in concrete to form organic-inorganic composites (e.g., calcium acrylate), enhancing coating adhesion and preventing delamination. Wang Si et al. [41] synthesized siloxane-modified waterborne acrylic resin via emulsion polymerization. When siloxane content reached 8%, the coating demonstrated optimal thermal stability, water resistance, and carbonation resistance.

Microscopic Repair:Certain waterborne acrylic resins contain microencapsulated healing agents that release reactive substances upon microcrack formation. These substances react with infiltrating CO_2 to generate calcium carbonate, enabling self-healing. Song et al. [42] evaluated the protective effects of modified waterborne acrylic resin and epoxy resin by applying them to concrete specimens and conducting salt freeze-thaw cycling tests. Chloride ion penetration depth and content measurements revealed that specimens coated with modified waterborne acrylic resin exhibited significantly slower chloride ingress and delayed failure compared to epoxy-coated specimens.

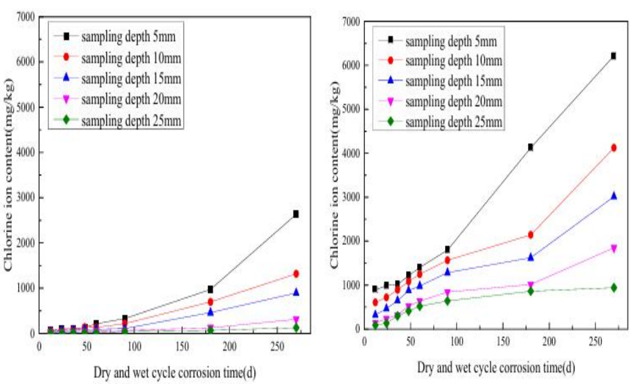

Fig.4. Comparison chart of concrete's resistance to chloride ions[40]

3.2.Enhancement of Elastic Recovery Capability

Elastic recovery capability [43] refers to the ability of a material to return to its original state after deformation under stress. Concrete, as a brittle material, inherently contains numerous microscopic defects, leading to poor elastic recovery. When subjected to external forces, concrete struggles to rebound, often resulting in irreversible permanent deformation or even cracks. These cracks act as "channels," allowing water and harmful substances to infiltrate the concrete matrix. Such ingress can corrode reinforcing steel, triggering expansion-induced cracking, which further propagates the damage in a vicious cycle, severely compromising the structural integrity of concrete [44-46].

By applying a waterborne acrylic resin coating to the concrete surface, a flexible protective layer is formed, enhancing the elastic recovery capability of concrete through both physical and chemical mechanisms [47-49]. Zheng et al. [50] synthesized a waterborne acrylic resin with excellent weather resistance and chemical stability via free-radical solution polymerization for concrete crack repair. Experimental results demonstrated that the resin achieved autonomous crack healing at the early stages of crack formation, significantly improving concrete durability. Peng Jiaming et al. [51] evaluated the performance of waterborne acrylic resin as a concrete sealer. Their study revealed that the resin effectively filled surface pores, enhancing waterproofing and stain resistance. However, the practical application of waterborne acrylic resin coatings still requires optimization in terms of weather resistance, adhesion, and compatibility with specific environmental and engineering requirements.

3.3Improvement in Anti-Fouling and Aesthetic Properties

The capillary pores and microcracks in concrete readily adsorb pollutants such as dust, oil stains, and microorganisms, leading to surface staining. In humid environments, these pores become breeding grounds for microbes, causing discoloration and mildew growth [52-54].

By incorporating low-surface-energy modifiers (e.g., fluorine or silicone) into the resin, a "lotus leaf effect" [55] can be imparted to the coating, enabling self-cleaning properties when applied to concrete. Peng Panpan et al. [56] enhanced the hydrophobicity of coatings by introducing silicone-modified polyurethane. When the silicone-polyurethane content reached 3%, the modified waterborne acrylic resin exhibited exceptional performance (Figure 5): a contact angle of 96.1°, an elongation at break of 385%, and a tensile strength of 9.4 MPa. Salt spray tests confirmed that the coated concrete surface remained smooth and free of scaling.

Traditional concrete lacks color diversity and textural design, while modern architectural demands increasingly emphasize aesthetics, particularly in public spaces or corporate settings, where visually appealing structures enhance overall image and market appeal. Jana et al. [57] synthesized silicone-modified waterborne acrylic resin and explored its application in decorative concrete coatings, including colored flooring and stone-like finishes. The modified resin demonstrated excellent decorative performance and environmental compatibility, making it suitable for diverse architectural scenarios. These case studies validate the practicality and reliability of waterborne acrylic resin as a concrete coating. Furthermore, the resin can be blended with pigments to create colored concrete flooring, achieving a dual upgrade in both "functionality and aesthetics" [58-61].

Sample	adhesion/grade	hardness	water contact angle
PISA0	4	HB	67.8
PISA1	3	HB	74.3
PISA2	2	H	86.6
PISA3	1	2H	96.1
PISA4	1	2H	97.2

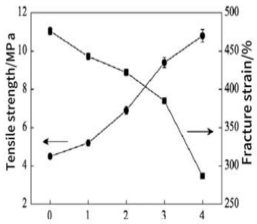

Fig.5. XPerformance tests under different polyurethane contents[56]

3.4.Enhancement of Corrosion Resistance

Concrete corrosion [62] is a global issue prevalent in various infrastructures, with common types including steel reinforcement corrosion, microbial corrosion, and chemical-physical erosion. The eco-friendly and water-resistant properties of waterborne acrylic resin make it directly applicable to processes requiring corrosion resistance. Data [63] indicate that submerged pier concrete of a cross-sea bridge, subjected to chloride ion erosion, exhibited over 15% steel reinforcement corrosion rate and surface longitudinal cracks along the reinforcement bars after five years. After applying two coats of waterborne acrylic resin with a thickness of 0.4 mm, monitoring results over a decade revealed a chloride ion penetration depth of only 1.8 mm and a steel reinforcement corrosion rate of <3%, with the expected service life extended to 30 years. This demonstrates a viable solution for enhancing concrete durability.

Traditional acrylic resins remain limited in corrosion protection applications. Researchers have optimized their performance through modification to overcome their single-function drawbacks. Bi et al. [64] successfully synthesized an acrylic resin with exceptional water resistance, corrosion resistance, and thermal stability by introducing octafluoropentyl methacrylate and phosphate ester-based anticorrosion functional monomers. Compared to unmodified acrylic resin, the modified resin exhibited an increased contact angle from 40° to 120° and an elevated initial decomposition temperature from 264°C to 305°C. Fan et al. [65] developed a corrosion protection strategy for concrete by incorporating microcapsules containing corrosion inhibitors into waterborne acrylic resin. Electrochemical impedance spectroscopy (EIS) analysis of samples immersed in sodium chloride solution and deionized water (Figure 6) showed that the microcapsule-coated samples exhibited higher inert corrosion potentials of −532 mV_{SCE} and −513 mV_{SCE} compared to the control group, providing a novel approach for preparing eco-friendly, stable, and corrosion-resistant waterborne acrylic resins.

Although modified acrylic resin coatings demonstrate excellent anticorrosion performance in laboratory settings, their long-term protective mechanisms in real-world engineering applications require further investigation [66-68]. Concrete structures are exposed to complex environmental stressors such as ultraviolet radiation, sand/gravel impact, and temperature fluctuations, which challenge the durability of these coatings.

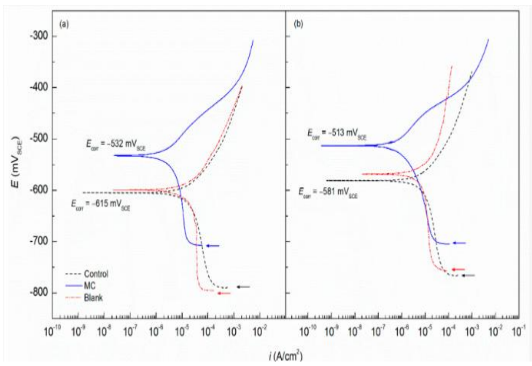

Fig.6. Comparison of potentiodynamic polarization curves[65]

4.Future Perspectives

While waterborne acrylic resins demonstrate significant advantages in concrete applications, several technical challenges remain unresolved. Concurrently, their water resistance and weather resistance require further enhancement to meet long-term durability demands under extreme environmental conditions [69-72]. The interfacial bonding mechanisms between waterborne acrylic resins and concrete also necessitate in-depth investigation. The selection of internal incorporation versus external coating strategies for concrete applications is evaluated as follows:

1. Internal Incorporation: Preferred for high-demand structures, such as marine engineering projects, chemical plant saline-alkali grounds, or environments with prolonged exposure to corrosive media, where comprehensive improvements in concrete durability and mechanical performance are required, and budgets permit.
2. If the main purpose is for surface protection, quick repair, or low-cost improvement (such as crack sealing, waterproofing, or protecting garage floors from oil stains), prioritize exterior coatings;
3. (3) Hybrid Approach: For extreme scenarios, a combination of internal incorporation (to enhance bulk concrete properties) and external coating (to reinforce surface protection) can be adopted.
4. Efforts should be intensified to advance research on the composite applications of waterborne acrylic resins. In-depth exploration of their integration with nanomaterials and fiber-reinforced materials is essential to unlock synergistic enhancement potential and drive material innovation. Currently, the interaction mechanisms of waterborne acrylic resins within concrete systems remain incompletely understood, and the performance evaluation of resin-concrete composites requires further behavioral studies to establish a robust scientific assessment framework.In the realm of novel concrete technologies, accelerated exploration of waterborne acrylic resins in permeable and lightweight concrete is imperative. Research should focus on elucidating their mechanisms for optimizing pore structures and enhancing performance, thereby facilitating the development of new building materials that integrate environmental sustainability with high performance. These advancements will propel the construction materials industry toward greener practices and high-performance solutions.

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