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Performance and Durability Evaluation of New Admixtures in Concrete Production

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Abstract

To address the drawbacks of high energy consumption and insufficient durability in traditional concrete, and to promote the greening and high-performance development of concrete, this study focuses on the application performance and durability of new industrial solid waste admixtures in concrete. Through single-factor variable experiments, the influence of different admixture dosages on the workability and mechanical properties of concrete was explored. Various testing methods were used to evaluate its impermeability, freeze-thaw resistance, chemical erosion resistance, and carbonation resistance, and the mechanism of action was analyzed using microscopic testing. The results show that, at appropriate dosages (15%–25%), the new admixtures can significantly optimize the workability and mechanical properties of concrete and improve durability indicators. A durability evaluation system based on multi-dimensional indicators was established, providing theoretical support and technical basis for the engineering application of the new admixtures.

Keywords

Concrete; New Admixture; Application Performance; Durability; Experimental Evaluation.

1. Introduction

Traditional concrete commonly suffers from high energy consumption and insufficient durability in engineering applications, especially prone to cracking and erosion under complex service environments, affecting structural safety and service life. New admixtures, as core materials for the high-performance and green development of concrete, can effectively utilize industrial solid waste and optimize the internal structure of concrete, becoming a key path to solve the pain points of traditional concrete. Currently, the types of new admixtures, such as industrial solid waste-derived admixtures and novel mineral admixtures, are constantly increasing [1]. However, related research mostly focuses on single performance evaluations, lacking sufficient research on adaptability and clarity on the durability mechanism under complex environments, making it difficult to meet the industry's demand for large-scale application of new admixtures.

This study takes a novel industrial solid waste admixture as the research object, aiming to clarify its influence on the workability, mechanical properties, and other application performance of concrete, establish a scientific durability evaluation system, reveal its core mechanism for improving concrete performance, provide reliable theoretical support and technical parameters for the engineering application of new admixtures in concrete production, and promote the green and low-carbon development of the concrete industry [2].

2. Experimental Design

2.1 Selection and Performance Indicators of Experimental Raw Materials

The experiment used P·O 42.5 grade ordinary Portland cement, with the following chemical composition: SiO_2 21.5%, Al_2O_3 6.8%, Fe_2O_3 3.2%, CaO 64.3%, 3-day compressive strength 28.6 MPa, and 28-day compressive strength 45.2 MPa. The coarse aggregate was 5~25mm continuously graded crushed stone with a bulk density of 1680 kg/m³ and a mud content of 0.8%. The fine aggregate was medium sand with a fineness modulus of 2.6, a bulk density of 1520 kg/m³, and a mud content of 1.2%. The admixture was a polycarboxylate-based high-efficiency water-reducing agent with a water reduction rate of 25%, added at a dosage of 0.8% of the total cementitious material [3]. The new admixture was prepared by grinding and modifying industrial solid waste from a steel plant. Its main chemical components were SiO_2 42.3%, Al_2O_3 23.5%, and CaO 12.8%, with the mineral phase primarily consisting of glass. The particle size distribution ranged from 0.1 to 50 μm, and the specific surface area was 420 m²/kg. The experimental water was tap water, meeting the requirements of the "Standard for Water Used in Concrete Mixing" (JGJ 63-2006), with a pH of 7.2 and a total hardness of 120 mg/L.

2.2 Concrete Mix Design

The experiment was based on the benchmark concrete mix design, using the dosage of the new admixture as a single-factor variable (dosages of 0%, 10%, 15%, 20%, 25%, and 30%) to ensure consistent benchmark concrete performance [4]. The baseline concrete mix proportion was a water-cement ratio of 0.45, a sand ratio of 38%, and a total cementitious material content of 400 kg/m³, comprising 400 kg/m³ cement, 180 kg/m³ water, 684 kg/m³ sand, and 1126 kg/m³ crushed stone.

The total cementitious material content in each experimental group was kept constant by adjusting the amount of new admixtures and cement, while the amounts of other components were adjusted proportionally [5]. During the mix proportion verification phase, the baseline concrete underwent preliminary tests for slump, spread, and 28-day compressive strength. The test results were 220 mm, 550 mm, and 48.6 MPa, respectively, meeting the experimental design requirements and ensuring the rationality of the mix proportion.

2.3 Experimental Scheme and Test Methods

2.3.1 Application Performance Test Scheme

Workability testing was conducted according to the "Standard for Test Methods of Performance of Ordinary Concrete Mixtures" (GB/T 50080-2016), determining the slump, spread, inverted cone flow time, and initial and final setting times (Vicat method) of concrete with different admixture dosages. Mechanical performance testing was conducted according to the "Standard for Test Methods of Mechanical Properties of Concrete" (GB/T 50081-2019), preparing 100mm×100mm×100mm cube specimens and determining the compressive strength at 3d, 7d, 28d, and 56d; preparing 100mm×100mm×400mm prism specimens and determining the 28d axial compressive strength and flexural strength [6]. Volumetric stability testing employed a length profiler to determine the drying shrinkage rate at 1d, 3d, 7d, 14d, 28d, and 56d, and a creep meter to determine the creep coefficient over 6 months for long-term monitoring.

2.3.2 Durability Testing Scheme

For impermeability testing, the water penetration height was determined using the water penetration height method, based on the "Standard for Test Methods of Long-Term Performance and Durability of Ordinary Concrete" (GB/T 50082-2009), to assess the impermeability grade. For freeze-thaw resistance testing, a rapid freeze-thaw test (rapid freezing method) was conducted, setting the number of freeze-thaw cycles to 0, 50, 100, 150, and 200, and measuring the weight loss rate and strength loss rate of the specimens after different number of cycles [7]. Chemical erosion resistance was assessed using 5% Na_2SO_4 solution and 3.5% NaCl solution to simulate erosion environments. Immersion periods were 0, 30, 60, 90, and 120 days. Strength retention rate of the specimens was tested after different periods, and microscopic morphology changes were observed using scanning electron microscopy (SEM). Carbonation resistance was assessed using a carbonation test chamber (CO_2 concentration 20%±3%, temperature 20°C±2°C, relative humidity 70%±5%) to accelerate carbonation. Carbonation depth was tested at 0, 7, 14, 28, and 56 days.

2.4 Experimental Process Control and Quality Assurance

The mixing process used a forced concrete mixer. The feeding sequence was: aggregate → cement → new admixture → dry mixing for 30 seconds → water + admixture → wet mixing for 90 seconds, ensuring uniform mixing. Curing conditions were divided into three categories: standard curing (temperature 20°C±2°C, relative humidity ≥95%), dry curing (temperature 20°C±2°C, relative humidity 50%±5%), and low-temperature curing (temperature 5°C±2°C, relative humidity ≥95%).

Each experiment had three parallel samples, and the average value of the test data was taken to ensure data reliability [8]. Before the experiment, all instruments, including the slump cone, Vicat apparatus, compression testing machine, and freeze-thaw testing machine, were calibrated. The calibration error met the relevant standard requirements to ensure test accuracy.

3. Results and Analysis

3.1 Results of the Application Performance of New Admixture Concrete

3.1.1 Workability Results Analysis

The effects of different new admixture dosages on the workability of concrete are shown in Table 1. Table 1 shows that as the dosage of the new admixture increases, the slump and spread of the concrete first increase and then decrease, while the inverted cone method flow time first shortens and then lengthens; the initial setting and final setting times gradually lengthen with increasing dosage [9]. When the admixture dosage is 20%, the slump reaches its maximum value of 245 mm, the spread is 620 mm, and the inverted cone flow time is 12 s, representing improvements of 11.4% and 12.7% respectively compared to the baseline group (0% admixture), and a reduction of 16.7% in flow time. This indicates optimal workability.

When the admixture dosage is below 20%, the micro-aggregate filling effect of the new admixture optimizes the internal particle size distribution of the concrete, reduces interparticle friction, and improves workability. However, when the admixture dosage exceeds 20%, the larger specific surface area of the new admixture increases water demand, leading to a decrease in workability [10]. Furthermore, the new admixture adsorbs some of the admixture, delaying the cement hydration process and extending the setting time. When the admixture dosage reaches 30%, the initial setting time is extended by 3.2 hours compared to the baseline group, potentially affecting the construction progress. Optimization through adjustments to the admixture dosage is necessary.

Table 1. Workability Test Results of Concrete with Different New Admixture Doses

new admixture dosage (%)	Slump (mm)	Expansion (mm)	Inverted cone flow time (s)	Initial setting time (h)	Final setting time (h)
0	220	550	15	4.8	6.5
10	232	580	13	13	7.3
15	240	600	12.5	12.5	8.1
20	245	620	12	12	9.2
25	238	590	13.5	13.5	10.5
30	225	560	14.5	14.5	11.3

3.1.2 Analysis of Mechanical Properties

Figure 1 shows the variation of compressive strength of concrete at different ages with different amounts of the new admixture (the horizontal axis represents the amount of new admixture, ranging from 0% to 30%, with 5% intervals). As shown in Fig. 1, the compressive strength at each age initially increases and then decreases with increasing new admixture dosage, and the longer the age, the greater the strength increase. At 28 days, the compressive strength of the 20% admixture group reached its maximum value of 52.8 MPa, an increase of 8.6% compared to the baseline group; at 56 days, the strength of this group further increased to 55.3 MPa, an increase of 9.2%.

The pozzolanic activity of the new admixture is gradually activated in the later stages, undergoing a secondary hydration reaction with the cement hydration product $Ca(OH)_2$ to generate more C-S-H gel, filling the internal pores of the concrete, optimizing the microstructure, and thus improving the mechanical properties [11]. When the admixture dosage exceeds 20%, the activation of pozzolanic activity is insufficient, and the reduction in cement dosage leads to insufficient early hydration products, resulting in decreased strength. Furthermore, volume stability tests show that the 28-day drying shrinkage rate of the 20% admixture group was 285×10^{-6}, a decrease of 15.2% compared to the baseline group, and the creep coefficient was reduced by 18.3% compared to the baseline group, indicating that the new admixture can effectively improve the volume stability of concrete.

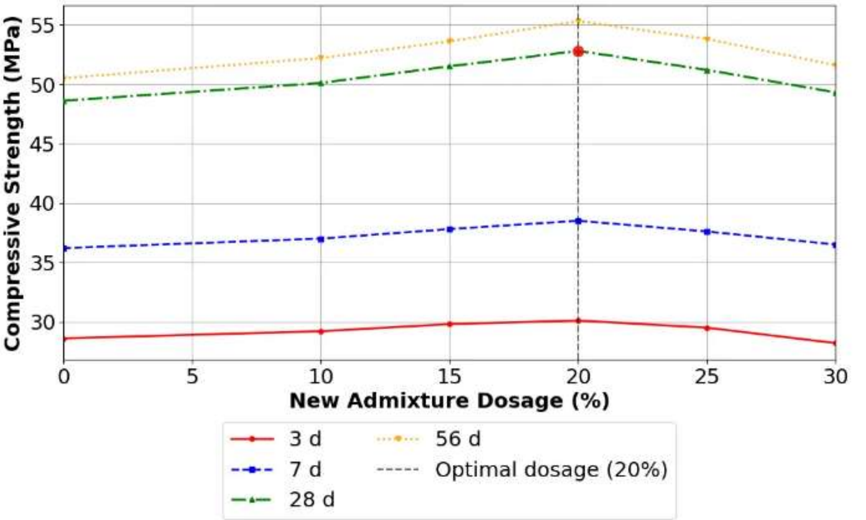

Fig. 1 Curves showing the variation of compressive strength of concrete at different ages with different amounts of new admixtures

3.2 Durability Results of Concrete with New Admixtures

3.2.1 Results of Impermeability Performance

Table 2 shows the test results of impermeability performance of concrete with different amounts of new admixtures. As shown in Table 2, with the increase of the new admixture dosage, the water seepage height of the concrete gradually decreases, and the impermeability grade gradually increases [12]. The baseline group (0% admixture) has a water seepage height of 45mm and an impermeability grade of P8; when the dosage reaches 20%, the water seepage height decreases to 22mm, and the impermeability grade increases to P12; after the dosage exceeds 20%, the rate of decrease in water seepage height slows down.

The filling effect and secondary hydration reaction of the new admixture can refine the internal pores of the concrete, reduce the number of interconnected pores, and lower the porosity, thereby improving the impermeability performance. When the admixture dosage was 20%, the concrete porosity decreased by 23.5% compared to the baseline group, and the average capillary pore diameter decreased from 180 nm to 105 nm, effectively hindering water penetration. Furthermore, the impermeability performance showed a positive correlation with compressive strength; the experimental group with higher compressive strength also exhibited superior impermeability performance.

Table 2. Test Results of Impermeability Performance of Concrete with Different New Admixture Doses

new admixture dosage (%)	Seepage height (mm)	Impermeability grade	Porosity (%)	Average capillary pore size (nm)
0	45	P8	18.6	180
10	38	P9	16.2	155
15	30	P10	14.5	132
20	22	P12	14.2	105
25	20	P12	13.8	100
30	19	P12	13.5	98

3.2.2 Results of Freeze-Thaw Resistance Performance

Figure 2 shows the changes in strength loss rate of concrete with different new admixture dosages after different freeze-thaw cycles (the horizontal axis represents the number of freeze-thaw cycles, ranging from 0 to 200 cycles, with 50-cycle intervals). As shown in Fig. 2, with the increase of the number of freeze-thaw cycles, the strength loss rate of each experimental group gradually increases, and the growth rate of the baseline group is significantly faster than that of the new admixture experimental group. When the number of freeze-thaw cycles reaches 200, the strength loss rate of the baseline group is 28.5%, while the strength loss rate of the 20% admixture experimental group is only 12.3%, meeting the excellent durability standard (strength loss rate ≤25%).

The new admixture optimizes the microstructure of concrete, reduces the internal free water content, and lowers the internal stress generated by ice crystal expansion during freeze-thaw cycles, thereby improving freeze-thaw resistance. When the admixture content is below 15%, the microstructure optimization effect is limited and the improvement in frost resistance is not significant; when the admixture content reaches 20%~25%, the frost resistance is optimal; when the admixture content exceeds 25%, the early strength of concrete is low, microcracks are prone to occur during freeze-thaw processes, and the strength loss rate increases slightly.

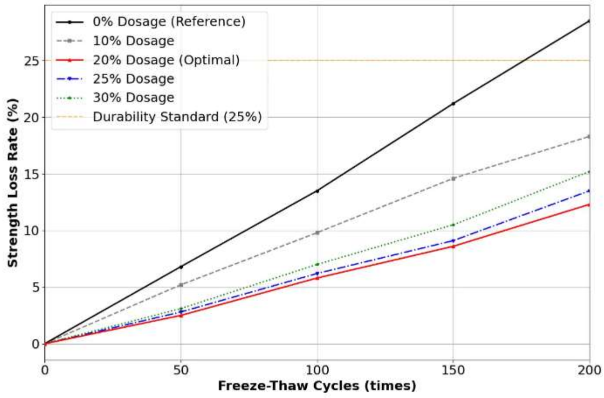

Fig. 2 Curves showing the variation of strength loss rate in concrete with different new admixture dosages under freeze-thaw cycles

3.2.3 Results of Chemical Attack and Carbonation Resistance

Fig. 3 shows the changes in strength retention rate and carbonation depth of concrete with different new admixture dosages under sulfate and chloride ion attack environments (horizontal axis represents attack/carbonation age, range 0~120d, interval 30d). As shown in Fig. 3(a), under sulfate and chloride ion attack environments, the strength retention rate of each experimental group gradually decreased with the extension of attack age. The strength retention rate of the new admixture experimental group was significantly higher than that of the baseline group. At 120d of attack, the strength retention rate of the 20% admixture experimental group was 85.6% in the sulfate environment and 83.2% in the chloride environment, representing increases of 18.3% and 16.5% respectively compared to the baseline group. The C-S-H gel generated by the secondary hydration reaction of the new admixture can fill pores, hindering the penetration of corrosive media, and simultaneously reducing the $Ca(OH)_2$ content inside the concrete, thus reducing the expansion and damage caused by sulfate reaction products. As shown in Fig. 3(b), the carbonation depth gradually increases with the extension of the carbonation age; the higher the dosage of the new admixture, the faster the carbonation depth increases. At 56 days of carbonation, the carbonation depth of the 30% admixture experimental group was 18 mm, an increase of 6 mm compared to the baseline group. This is because the new admixture consumes some $Ca(OH)_2$, reducing the alkalinity of the concrete and accelerating the carbonation process. Therefore, when using concrete with the new admixture in a carbonation environment, surface protection measures are necessary.

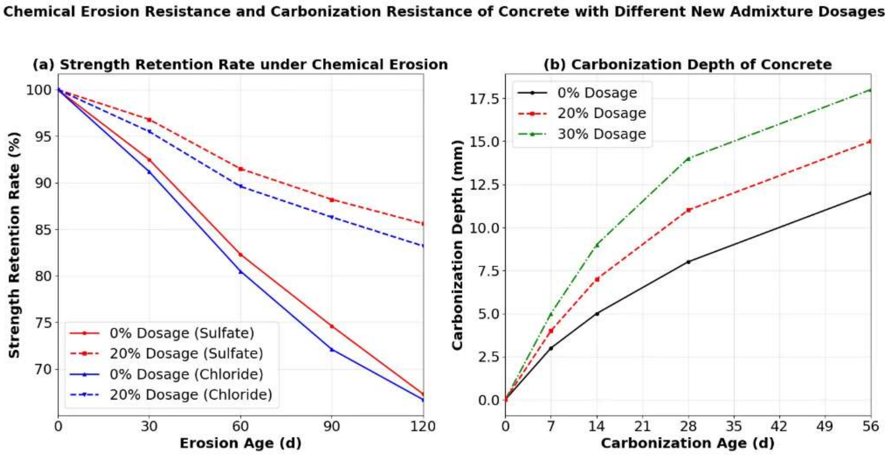

Fig. 3 Curves showing the changes in chemical attack and carbonation resistance of concrete with different amounts of new admixtures

4. Discussion

4.1 Mechanism of Action of New Admixtures on Concrete Performance

The improvement in concrete performance by new admixtures mainly stems from the synergistic effect of the micro-aggregate filling effect and the pozzolanic activity effect. Microscopic test results show that the new admixture particles can fill the voids in the interfacial transition zone between cement paste and aggregate, reducing interfacial defects and making the internal structure of concrete denser. Simultaneously, the active SiO_2 and Al_2O_3 in the new admixtures undergo a secondary hydration reaction with $Ca(OH)_2$ produced by cement hydration, generating a large amount of C-S-H gel, further filling pores and optimizing the pore structure.

XRD analysis showed that the intensity of the characteristic peak of $Ca(OH)_2$ in the hydration products of the 20% admixture experimental group decreased by 35.2% compared with the baseline group, while the intensity of the characteristic peak of C-S-H gel increased by 28.6%. SEM observation showed that the thickness of the interfacial transition zone in this experimental group decreased from 45 μm in the baseline group to 22 μm, and no obvious cracks were observed. Furthermore, the adsorption effect of the new admixture can regulate the cement hydration rate, delay the release of heat of hydration, and reduce the generation of temperature cracks, thereby improving the volume stability of concrete.

4.2 Mechanism of New Admixture in Improving Concrete Durability

The new admixture improves durability by optimizing the microstructure of concrete. Regarding the improvement of impermeability, the new admixture refines pores, reduces interconnected pores, and decreases water penetration channels. Simultaneously, the C-S-H gel can block capillary pores, further enhancing impermeability. Regarding improved freeze-thaw resistance, the dense microstructure reduces internal free water content, mitigating the destructive force caused by ice crystal expansion during freeze-thaw cycles. Simultaneously, the improved interfacial transition zone enhances the bond between aggregate and cement paste, reducing freeze-thaw spalling.

Regarding resistance to chemical attack, the new admixture consumes some $Ca(OH)_2$, reducing reactants in sulfate attack reactions. The dense structure also hinders the penetration of corrosive media. However, in terms of carbonation resistance, the reduction in $Ca(OH)_2$ lowers concrete alkalinity and accelerates the carbonation process. This contradiction indicates that the durability of the new admixture concrete is environmentally dependent. Furthermore, the new admixture exhibits an optimal dosage threshold (around 20%). Exceeding this threshold results in insufficient activation of pozzolanic activity, insufficient cement content leading to reduced hydration products, decreased microstructure density, and ultimately, reduced performance.

4.3 Comparison and Discussion of Experimental Results with Existing Research

The results of this study show both consistency and differences with similar studies both domestically and internationally. Compared with the study by Li Ming et al. (2024), the optimal dosage of the new admixture in this study (20%) is basically consistent with their experimental results (18%~22%), both indicating that the appropriate dosage of industrial solid waste admixture can significantly improve concrete performance. However, the decrease in carbonation resistance in this study is slightly smaller than that in their study, which may be related to the difference in mineral composition of the new admixture. The new admixture used in this study has a higher CaO content, which can compensate for alkalinity loss to a certain extent.

Compared with the study by Smith et al. (2023) abroad, the multi-dimensional durability assessment system proposed in this study is more in line with the actual engineering environment in my country, covering typical corrosive environments such as sulfate and chloride ions. The innovation of this study lies in combining microscopic testing and macroscopic performance to systematically reveal the mechanism of action of the new admixture, clarify the adaptability parameters under different environments, and make up for the shortcomings of insufficient in-depth mechanism analysis and insufficient environmental specificity in existing studies.

4.4 Feasibility and Precautions for Engineering Application

The new admixture has high feasibility for engineering application in concrete production. In terms of cost, the new admixture is a modified product of industrial solid waste, costing only 60% of cement. A 20% admixture can reduce concrete production costs by 8%–10%. Regarding process adaptability, the mixing, pouring, and curing processes for the new admixture concrete are basically the same as for ordinary concrete, requiring no additional specialized equipment and facilitating industrial production.

The following points should be noted in engineering applications: First, strictly control the admixture dosage to around 20% to avoid exceeding the optimal threshold; second, when used in carbonation environments, protective measures such as surface coatings and the addition of air-entraining agents are required; third, adjust the admixture dosage to compensate for the adsorption effect of the new admixture and optimize setting time; fourth, select curing methods according to the engineering environment, extending curing time in low-temperature environments to ensure strength development. Furthermore, when using the new admixture concrete in bridges, tunnels, and other projects, the mix proportion needs to be adjusted according to the specific service environment. In highly corrosive environments such as marine engineering, it is recommended to control the admixture dosage at 20%–25% and implement corresponding anti-corrosion measures.

5. Conclusion

This study systematically investigated the application performance and durability of a novel industrial solid waste admixture in concrete, drawing the following conclusions: The new admixture significantly optimizes the workability and mechanical properties of concrete, with an optimal dosage of 20%. At this dosage, the concrete slump and 28-day compressive strength are increased by 11.4%

and 8.6% respectively compared to the baseline group, while the drying shrinkage rate is reduced by 15.2%. At this dosage, the concrete's impermeability grade is improved to P12, and the strength loss rate after 200 freeze-thaw cycles is only 12.3%. The 120-day strength retention rate in sulfate and chloride ion environments exceeds 83%, although carbonation resistance is somewhat reduced. The new admixture improves concrete performance and optimizes the microstructure through the synergistic effect of micro-aggregate filling and pozzolanic activity. A technical scheme for the application of the new admixture in concrete engineering is proposed, suggesting a dosage control of 15%–25%, and the implementation of targeted protective measures based on the service environment. The application of this new admixture can realize the resource utilization of industrial solid waste, promote the green development of concrete, and has significant economic and environmental value. This study did not cover long-term service performance tracking. Future research could focus on the long-term performance of new admixture concrete, exploring the synergistic effects of composite admixtures, and establishing a more comprehensive durability assessment system to provide more comprehensive technical support for the widespread application of new admixtures.

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