***Review Article***

# Research Progress on the Mechanical Propertiesand Frost Resistance of Ultrafine Fly Ash Concrete



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## ABSTRACT

Fly ash, a fine residue captured from the flue gas of coal combustion, can be incorporated into concrete to transform waste into valuable material, achieving environmental benefits such as energy savings and emission reductions. Additionally, it enhances the mechanical properties and frost resistance of concrete. Therefore, fly ash is commonly used as a partial replacement for cement in concrete to reduce cement consumption. However, incorporating fly ash can decrease the early strength and durability of concrete, significantly limiting its application. By mechanically grinding raw fly ash, ultrafine fly ash with finer particles and a larger specific surface area can be produced, exhibiting improved morphology and reactivity. Consequently, the activity and micro-aggregate effects of ultrafine fly ash can be fully utilized, forming denser C-S-H gel, optimizing the concrete microstructure, and significantly enhancing the mechanical properties and frost resistance of concrete. This provides a foundation for further research on the application of ultrafine fly ash in concrete.


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*Keywords: Ultrafine fly ash; Mechanical properties; Frost resistance; Microstructure.*

## 1. INTRODUCTION

Fly ash, a by-product of coal-fired power plants, is predominantly composed of spherical or hollow particles[1]. Its ineffective utilization poses risks to human health and production processes. As a mineral admixture for concrete, fly ash can partially replace cement, thereby contributing to energy savings and emission reductions. The latent activity of fly ash enhances the workability, durability, and physical-mechanical properties of concrete, reduces the required amount of cement, and lowers concrete production costs[2]. Additionally, fly ash exhibits three primary effects: morphological effect, activity effect, and micro-aggregate effect[3]. However, the reactivity of conventional fly ash is limited, leading to minimal improvements in the mechanical properties and durability of concrete. This necessitates further research and analysis into the application of ultrafine fly ash.

Ultrafine fly ash is produced through ultrafine grinding of fly ash, resulting in sub-micron, spherical microbeads with a finer fineness than ordinary fly ash. The average particle size is generally less than 10 μm, and the specific surface area exceeds 600 $m^2/kg$. Its morphology differs from that of ordinary fly ash[4], characterized by smooth surfaces and regular spherical shapes, which confer a higher specific surface area and enhanced morphology and activity. It has a low water demand and exhibits higher early activity compared to ordinary fly ash, making it more valuable for practical applications[5]. Ultrafine fly ash is considered a high-quality additive, providing better particle gradation in cementitious materials. Additionally, it fully utilizes the three main effects of fly ash[6].

The fineness of fly ash is a critical factor influencing its performance. Li Hui [7]discovered that the activity of ultrafine fly ash increases with its fineness. This enhancement is attributed to the increased specific surface area of the spherical particles, which boosts the likelihood of contact with the smooth surface of cement particles, thereby improving its activity[8]. Wang Wusuo and colleagues[9] compared the effects of ultrafine fly ash and ordinary fly ash on concrete performance, finding that ultrafine fly ash significantly enhances the mechanical properties of concrete. This improvement is due to the secondary hydration reaction of ultrafine fly ash particles in the highly alkaline environment of the paste, which increases its pozzolanic activity. Additionally, ultrafine fly ash can better exert the micro-aggregate effect[10].

Against this background, this paper summarizes the characteristics of ultrafine fly ash and its impact on concrete. Experimental tests and analyses by previous scholars have evaluated the mechanical properties and frost resistance of ultrafine fly ash concrete. These research findings are crucial for promoting the application and development of ultrafine fly ash concrete, thereby advancing the realization of green buildings.

## 2. CHARACTERISTICS OF ULTRAFINE FLY ASH

### 2.1 Physical properties and chemical composition of ultrafine fly ash

Fly ash comprises fine, powdery particles that are predominantly spherical and mostly glassy. The color of fly ash can range from brownish to gray to black, contingent upon the unburned carbon content present[11]. Typically, the specific gravity of fly ash falls within the range of 2.1 to 3.0, while its specific surface area can vary from 170 to 1000 $m^2/kg$. The average particle size measures less than 20 μm, with a corresponding specific surface area typically ranging from 300 to 500 $m^2/kg$. The specific surface area of fly ash is influenced by factors such as surface roughness and porosity, where a higher specific surface area indicates greater porosity[12].

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Ultrafine fly ash is produced by grinding raw fly ash, which exhibits higher reactivity compared to its raw form. Post-grinding, it forms uniform, small-sized particles with minimal variance. Typically, solid glass spheres within fly ash remain intact but surface scratched during grinding, facilitating chemical reactions and particle bonding[13]. Mechanical grinding destroys larger hollow particles while leaving smaller particles unaffected, thus creating additional active surface sites. Although small particles may not break during grinding, their inert surface layer is compromised, heightening surface activity and enhancing fly ash reactivity[14]. Research indicates that ultrafine fly ash obtained post-grinding possesses particles smaller than 10 μm and a specific surface area of 600 $m^2/kg$. Ultrafine fly ash exhibits small particle size, high specific surface area, and significant agglomeration effects[15]. Zhou Zhou[16]et al. observed that incorporating fly ash reduces internal structure defects in concrete, promoting uniform slurry and notably decreasing dry concrete density. However, excessive usage can reduce early concrete mechanical properties. Additionally, ultrafine fly ash's lower density enhances workability and performance.

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The chemical properties of fly ash are significantly influenced by the type of coal combusted. According to the American ASTM C618-80 standard, fly ash is categorized into anthracite, bituminous, sub-bituminous, and lignite types. The major constituents of fly ash are oxides such as $SiO_2$, $Al_2O_3$, $Fe_2O_3$, and CaO, with $SiO_2$ and $Al_2O_3$constituting over 60% of its total mass. Li Qiao et al. [17]observed that fly ash comprises a blend of crystalline and amorphous minerals, displaying substantial variability in mineral composition. Crystalline minerals typically include quartz, mullite, iron oxide, magnesium oxide, lime, and anhydrite, while amorphous minerals appear glassy. The chemical composition of fly ash particles varies, leading to distinct phases during production. Even within the same type of fly ash, both chemical and mineral compositions differ with particle size. XRD phase analysis indicates that as particle size decreases, the concentration of metallic elements increases, suggesting higher enrichment in smaller particles. Fine particle fly ash exhibits lower crystallinity compared to coarser particles, thereby reducing its reactivity. Furthermore, fine particle fly ash contains active components like calcium sulfate and potassium aluminosilicate, underscoring the significant influence of particle size on composition distribution and reactivity, consistent with findings from other researchers[18-19].

## 2.2 Fineness of Ultrafine Fly Ash

Mechanical grinding is the predominant method for producing ultrafine fly ash. Throughout the grinding process, particle size primarily decreases through the refinement of larger particles. Initially, fly ash comprises numerous coarse particles that are easily fragmented, thereby optimizing grinding efficiency. However, as the process advances, the accumulation of particle energy state charges impedes further size reduction. This phenomenon diminishes grindability, lowers grinding efficiency, and widens the distribution of particle sizes[20].

Ultrafine fly ash typically refers to fly ash with an average particle size below 10 μm and a specific surface area exceeding 600 m²/kg. Greater fineness enhances its pozzolanic reactivity significantly. Through grinding, the specific surface area of fly ash continues to increase, reducing particle size and enhancing activity. Zhou Shiqiong et al.[21] extensively researched the particle size distribution and morphology of ultrafine fly ash, highlighting its substantial benefits in water reduction and strength enhancement. Initially, ultrafine fly ash enhances strength primarily through dense filling and micro-aggregation. Over approximately 14 days, its inherent pozzolanic properties gradually emerge, further bolstering strength. Xue Yaodong[22]proposed that ball-milled fly ash with fineness ≤12.0% is Grade I, ≤25.0% is Grade II, and ≤45.0% is Grade III. Wang Peiyi[23]observed that finer ultrafine fly ash requires less water and exhibits higher activity. Therefore, incorporating ultrafine fly ash can notably enhance the workability and mechanical properties of concrete, with finer particles yielding more pronounced improvements.

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## 3.IMPACT OF ULTRAFINE FLY ASH ON CONCRETE

### 3.1Mechanical properties of Ultrafine Fly Ash Concrete

Mechanical properties serve as fundamental indicators to assess concrete performance and are crucial requirements in practical engineering applications. The strength of concrete exhibits notable variations with varying dosages of ultrafine fly ash[24-26]. Figure 1 illustrates the compressive strength at 28 days across three studies, each evaluating different levels of ultrafine fly ash content.

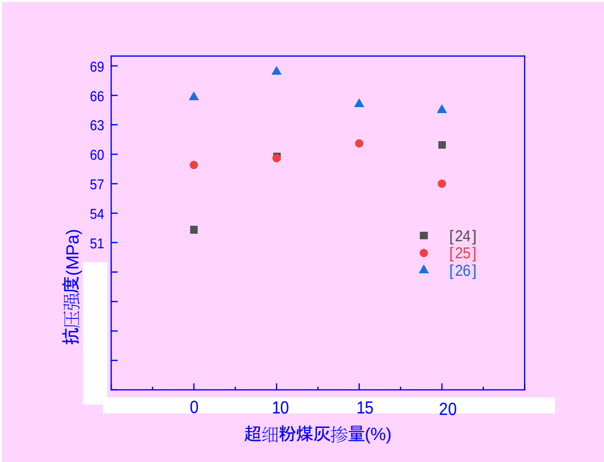


**Fig. 1. Compressive strength of concrete with different Ultrafine Fly Ash Contents**

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Fly ash is a typical industrial solid waste with significant morphological, activity, and micro-aggregate effects. It is valuable for optimizing the microstructure and enhancing the strength of concrete[27]. Ultrafine fly ash can further enhance the micro-aggregate filling effect, increase the specific surface area of particles, reduce mineral crystallinity, and significantly boost reactivity and synergistic hydration with cement. The resulting low-alkalinity, high-density C-S-H gel improves the hydrated cementitious material and the microstructure of concrete, thereby enhancing its mechanical properties[8].

With increased ultrafine fly ash content in concrete, its early compressive strength is slightly lower than that of the control group concrete, but its later compressive strength increases significantly. Zhang Yuan and colleagues analyzed that[4], in the early stage, due to the low hydration degree of cement, the hydration reaction of active components in ultrafine fly ash is limited, primarily playing a physical filling role in the paste, leading to a decrease in compressive strength. However, as the age extends, ultrafine fly ash particles start to undergo secondary hydration reactions in the highly alkaline environment within the paste, resulting in an increase in later compressive strength.

Pu Daijun[28] conducted compressive strength tests on the effect of different dosages and fineness of fly ash on concrete's compressive performance, showing that concrete strength increases with age when fly ash of the same fineness is added. For fly ash of different fineness, as the fineness increases, concrete strength decreases, indicating a higher practical application value of ultrafine fly ash for high-strength concrete.

Sun Yao [29]designed three dosages of 10%, 20%, and 30% ultrafine fly ash to replace part of the cement, comparing and analyzing the effect of ultrafine fly ash and regular fly ash on the mechanical strength of concrete at 3, 7, 14, and 28 days. The results show that adding ultrafine fly ash effectively improves the early mechanical properties of concrete, with an optimal dosage of 10%. Compared to ordinary concrete, the compressive strength at different ages increased by 20.2%, 15.5%, 13.9%, and 13.7%, respectively.

Xiang Xue-Min and colleagues[30] investigated the impact of varying fly ash contents on concrete performance. They used XRD and SEM micro-tests to examine the changes in the concrete microstructure at 28 days with different ultrafine fly ash contents. Active components, such as silicates in ultrafine fly ash, react with $Ca(OH)_2$ in the cementitious system to form new hydration products like calcium silicate hydrate and calcium aluminate hydrate. Fly ash particles effectively fill the voids within the concrete and gradually undergo hydration reactions with increased curing age, producing new hydration products. Consequently, the activity and micro-aggregate effects of ultrafine fly ash are fully realized, enhancing the mechanical properties of concrete.

Extensive experimental tests and data analysis are often necessary when investigating the mechanical properties of ultrafine fly ash concrete. These tests can be conducted according to international standards to ensure accuracy and reliability. Additionally, numerical simulations can further compare and verify the mechanical behavior of ultrafine fly ash concrete. Although ultrafine fly ash concrete holds potential in green building, challenges and limitations remain, such as the interface transition zone strength between ultrafine fly ash and the concrete matrix and the feasibility of large-scale application. Ongoing research aims to address these issues, promoting the practical application of ultrafine fly ash concrete. Nevertheless, many unresolved problems and challenges persist, underscoring the importance of continuous research.

### 3.2Frost resistance of Ultrafine Fly Ash

The frost resistance durability of concrete reflects its ability to withstand static water pressure, osmotic pressure, and ice swelling pressure caused by phase changes within matrix pores under alternating temperature conditions, especially while in a saturated or humid state for prolonged periods[31]. Freeze-thaw damage in concrete manifests as the continuous generation and expansion of micro- and fine cracks in the matrix, leading to macro-level erosion, cracking, and even sudden failure from the exterior inward[32]. Current research on the mechanisms of freeze-thaw damage in various concretes primarily includes theories of static water pressure, osmotic pressure, and ice swelling pressure. Powers[33] proposed the static water pressure hypothesis for concrete freeze-thaw, suggesting that during cooling, part of the water in the concrete pores freezes and expands, causing the unfrozen water to flow into surrounding pores, thereby generating static water pressure. Powers and others[34] believed that the vapor pressure difference between ice and water drives the unfrozen water to migrate to the freezing zone, known as osmotic pressure, with Powers himself favoring the osmotic pressure theory.

Ultrafine fly ash has potential application value in enhancing the micro- and fine-pore structure of concrete and improving the matrix's resistance to freeze-thaw cycles. Qin Li and colleagues [35]pointed out that the pozzolanic reaction of low-dosage fly ash, when coordinated with the cement hydration reaction, generates a denser gel matrix. This process enhances the density of recycled concrete and blocks micro- and fine-pore structures that are detrimental to frost resistance, thereby improving the frost resistance of concrete. Fan and others[36] found that due to the limited activity of fly ash and cement hydration products, excessive fly ash content is detrimental to concrete's frost resistance. However, a fly ash content of 25% demonstrated good frost resistance.

Therefore, grinding fly ash into ultrafine fly ash increases its specific surface area and reduces mineral crystallinity. This process significantly enhances the micro-aggregate filling effect and pozzolanic activity of fly ash, potentially improving the frost resistance durability of concrete.

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## 4. CONCLUSION

In recent years, ultrafine fly ash has garnered significant attention from scholars due to its finer particle size, larger specific surface area, improved morphology, and enhanced activity. The morphological, activity, and micro-aggregate effects of ultrafine fly ash can be fully realized, forming a substantial amount of low-alkalinity, high-density C-S-H gel. This improvement in the hydrated cementitious material and the microstructure of concrete enhances the interface transition zone strength of ultrafine fly ash concrete, thereby further improving its mechanical properties and frost resistance durability.

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