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Review on the Role of Ultra-fine Fly Ash on the Performance of Concrete

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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Review Article

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ABSTRACT

Fly ash is mainly the solid waste emitted by coal-fired fossil fuel power stations, which is collected through the flue gas emitted. At present, the comprehensive utilization of fly ash has been widely promoted and applied in actual production. The application of fly ash to concrete can not only improve the strength of concrete, but also save cement. However, its hydration rate is slow, and the incorporation of concrete will reduce the early strength of concrete. In order to improve the activity and other properties of fly ash, ultrafine fly ash with small particle size is obtained by grinding fly ash. Ultrafine fly ash has finer particle size than fly ash and larger spherical shape than original fly ash. Water demand decreases, density increases and activity increases. It can better fill the cement void, improve the internal compactness of concrete, and improve the interface structure of materials. Research has shown that adding 10% to 20% fly ash can achieve better performance than conventional concrete. For higher fly ash content, the strength decreases with the increase of fly ash content.

Keywords: Concrete; ultra-fine fly ash; performance.

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1. INTRODUCTION

1.1 Definition and Application Status of Ultra-fine Fly Ash

Fly ash is a fine powder collected from boiler flue gas, with a smooth surface and mostly spherical shape [1]. Fly ash, as a cementitious auxiliary material in ordinary concrete, replaces some cement and belongs to the utilization of solid waste resources. It can reduce the dosage of cementitious materials, reduce the hydration heat release of cementitious materials, optimize their working performance and workability, enhance their later strength, improve the internal structure of concrete, and improve their durability; In addition, fly ash has morphological effects, micro aggregate effects, and activity effects. Ultrafine fly ash is ground from ordinary fly ash, with an average particle size of less than 10 μm When the specific surface area is greater than 600 m^2/kg, after grinding, the finer particles wrapped inside the original fly ash particles can be released. The finer particles are filled in the concrete matrix, further strengthening the hydration reaction of fly ash in the concrete, and producing fibrous microcrystals, which play a toughening role of microfibers [2]. Ultrafine fly ash belongs to one of the resources of active fine powder minerals. The specific surface area of ultrafine fly ash is relatively large, and the different particle sizes of fly ash can significantly change the performance of concrete [3]. When its fineness is different, the impact on the hydration products of its silicate will also be different. The finer the fineness of fly ash, the higher its activity. Ravina [4] found that when coarse fly ash particles are replaced by finer particles, mortar has higher compressive strength, indicating that appropriately reducing the size of fly ash particles is beneficial for improving the performance of concrete. Long [5] found that the addition of ultrafine fly ash can increase the stacking density of cement slurry and significantly improve the flowability of cement-based material slurry with extremely low water binder ratio. Collins et al. [6] found that replacing some slag with ultra-fine fly ash significantly improved the flowability of high-strength concrete.

1.2 Mechanism of Action of Ultrafine Fly Ash

The main feature of ultra-fine fly ash is that its fineness is much smaller than that of ordinary fly ash, so it shows some unique effects, which can be summed up into three main effects, namely, active effect, micro aggregate effect and morphological effect [3]. Its action process is as follows:

(1) active effect: or Volcanic ash active effect The fly ash material contains a large amount of Al_2O_3 and SiO_2, which are mixed into the cement base, First, it slowly reacts with Ca $(OH)_2$ for the second time, which has the following functions: ①after reaction, Calcium aluminates hydrates as the gelling material, closely cements each aggregate, and makes the concrete material structure more compact; ② Because a large amount of $(OH)^{-1}$ is consumed in the reaction, a low alkalinity environment is formed, which is further conducive to the formation of hydrated Aluminate and beneficial to the later strength of the material;

(2) Micro aggregate effect: Due to the fact that the fineness of ultrafine fly ash is much lower than that of cement particles, the small particles react fully with cement, and the unreacted parts can also fully fill the gaps and cracks in the material, improving the microstructure of hydration products and greatly increasing their compactness;

(3) Morphological effect: due to the existence of a large number of spherical glass beads in the fly ash, together with the fine particles, they are filled in the cement particles, playing a role in lubrication, improving the early fluidity of concrete materials, and also having a certain water reducing effect, which can effectively reduce the Water–cement ratio by about 7%~9% [4].

1.3 Ultrafine Fly Ash Action Stage

The performance of concrete is related to the changes in the structural state of materials. Ultrafine fly ash concrete, due to its dynamic, long-term, and variable chemical reactions, gradually shifts from unstable to stable, and can be divided into three stages:

(1) Fresh concrete stage: Some smaller particles in fly ash fully react with cement-based materials, reducing unit water consumption on the one hand, and in addition, It also significantly improves the workability, fluidity, and water retention of concrete, effectively reducing bleeding phenomena;

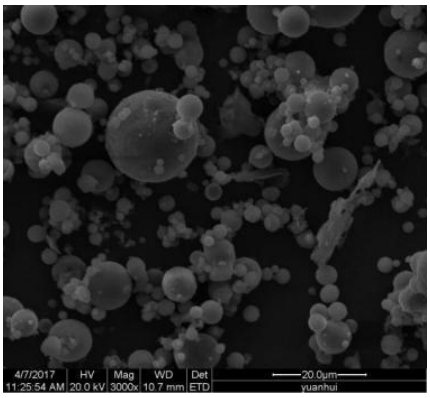

Fig. 1. Morphology of raw fly ash particles

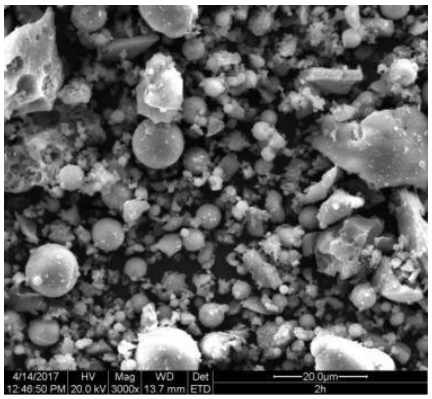

Fig. 2. Morphology of ultrafine fly ash particles

(2) Stage of tending to harden concrete (early concrete strength): Due to the replacement of some cement content with ultra-fine fly ash, its early strength will be lost. However, considering the long active effect time of ultra-fine fly ash, when the curing age reaches 28 days, it is still in the early stage. It can be foreseen that after 28 days, the mechanical properties of concrete will still improve;

(3) Hardening concrete stage: As the age increases, the internal chemical reactions become more sufficient, and its strength can still increase by 15% to 20% in the later stage of the 90 days age. If the concrete is redesigned according to this later strength, it can save cement dosage from 20 kg/m^3 to 35 kg/m^3, which has obvious economic benefits.

In summary, ultra-fine fly ash, due to its unique mechanism and stage of action, has undergone a long-term process of affecting the mechanical properties of concrete. It is necessary to extend the curing period and conduct a comprehensive assessment of the mechanical properties of concrete.

2. APPLICATION OF ULTRAFINE FLY ASH IN CONCRETE

2.1 Effect of Ultrafine Fly Ash on Working Performance of Concrete

The workability of freshly mixed concrete is mainly affected by the internal pore structure, porosity and particle size of coarse and fine aggregate at the initial mixing stage. The addition of ultrafine fly ash into concrete can significantly improve its working performance. Moreover, with the increase of ultrafine fly ash content, the slump of concrete mix becomes larger and larger, and the workability becomes better and better, which is mainly attributed to the shape effect of ultrafine fly ash, that is, the shape of ultrafine fly ash is spherical glass body of different sizes, and its surface is smooth and dense. In addition, the bulk density of ultrafine fly ash is only two-thirds of that of cement, so mixing it with cement not only improves the pore structure and porosity of concrete to a large extent, but also reduces the relative friction resistance between particles due to the glass microbead spherical particles contained in ultrafine fly ash, and the internal structure becomes more and more dense. The fluidity of the whole structure becomes better and better, and the addition of ultrafine fly ash effectively improves the workability of concrete during the mixing period [5]. Wang Rui [6] prepared high-strength concrete test blocks by mixing different admixtures (silica ash, raw ash and ultrafine fly) in the cement base instead of 10% cement content respectively, and compared the effects of different admixtures on the working performance of concrete (slump and slump loss). Finally, it is found that the initial slump of newly mixed concrete can be improved by using ultrafine fly ash, fly ash and wollastonite as admixtures, among which the increase of initial slump of concrete by ultrafine fly ash and wollastonite is more obvious, reaching 210mm. In addition, the inhibition effect of the three admixtures on the slump loss of concrete is as follows: ultrafine fly ash > fly ash > wollastonite. Ultrafine fly ash as admixture can better inhibit the slump loss of concrete. Li Hui [7] mixed 2μm, 4μm and 6μm ultrafine fly ash with different particle sizes into cement mortar and concrete to study the working performance of concrete mix. The results

showed that the activity of ultrafine fly ash increased with the increase of its fineness. It has a very positive effect on the working performance of concrete in many aspects during the mixing period. Among them, as the fineness of ultra-fine fly ash becomes finer and finer, it is more favorable to the working performance of concrete. The pore volume of harmless pores smaller than 20nm in the concrete mixed with ultrafine fly ash with an average particle size of 4μm is significantly larger than that of the concrete mixed with other two ultrafine fly ash (2μm, 6μm). A.K.H.Kwan et al. [8] studied the effect of mixing ultrafine fly ash into cement mortar by testing the filling density, fluidity and strength of ultrafine fly ash with content between 0 and 60%. The results showed that: Up to 40% of ultrafine fly ash can significantly increase the packing density of cementing materials. When ultrafine fly ash partially fills the void and releases the same volume of water, the addition of ultrafine fly ash can increase the water film thickness of cement slurry. Therefore, the addition of ultrafine fly ash can improve the fluidity and increase the strength under the same strength. The final conclusion is that ultrafine fly ash is an effective gelling filler to improve the performance of cement slurry and concrete. Y.Li [9] et al. studied the influence of ultra-fine fly ash on the hardening performance of freshly mixed mortar. They measured the packing density of solid particles in mortar by wet layup method and found that the addition of ultra-fine fly ash could effectively improve the packing density of mortar and reduce the voidage, which allowed the water-binder ratio to be reduced to increase the strength under the same fluidity requirements.

2.2 Effect of Ultrafine Fly Ash on Mechanical Properties of Concrete

When superfine fly ash is added into concrete, with the increase of the content of superfine fly ash, the superfine fly ash can obviously enhance the strength of concrete in the later stage. Ultrafine fly ash mainly changes the hydration rate and secondary hydration process through the influence of its own activity characteristics on the hydration conditions and hydration products of cement, so as to improve the late strength of concrete.

In the case of constant environmental conditions, when the concrete preparation material is fixed, the development trend of the late strength of the concrete mixed with ultra-fine fly ash is mainly determined by the activity effect of ultra-fine fly ash in cement hydration. When the water-binder ratio is high, a large amount of water separates the cement particles, and the hydration reaction environment is excellent, providing a good platform for the generation of hydration compounds. In the case of low water-cement ratio (for example, about 0.3), due to the slow hydration of fly ash, the actual "water-cement ratio" of concrete increases, thus speeding up the hydration of cement and improving the later strength of concrete. The more fly ash is added, the more obvious this effect will be [10]. Yao Weijing [11] et al. designed three kinds of concrete with different strength grades to make a comparative study on the influence of ultrafine fly ash and fly ash on the mechanical strength of concrete, and mixed different amounts of ultrafine fly ash into concrete to study the change law of its mechanical strength at a longer age of 28d, 60d and 90d. The results show that the ultrafine fly ash has obvious advantages compared with fly ash, and the optimal dosage is 20%, and the compressive and tensile strength of 90d is 16.5% and 16.8% higher than that of 28d. Compared with the growth rate of ordinary concrete itself, the growth rate is 10.6% and 5.5%, which is about 5% ~ 10% higher. Li Yijin et al. [12] applied the multiple regression analysis method to high performance concrete with ultra-fine fly ash. By analyzing and studying the changing trend of mechanical properties of high performance concrete at different maintenance ages after the addition of ultra-fine fly ash, they found that the addition of ultra-fine fly ash can promote the continuous growth of long-term compressive strength of concrete. The internal particles have stronger adhesion to the reinforcement, and have little influence on the shear strength and stress-strain curve. Li Hui et al. [13] studied the influence of fly ash with different content and different average particle size into high-strength concrete to study its working performance and mechanical properties. By means of SEM and XRD, the influence of the addition of ultra-fine fly ash on the microstructure and hydration products of concrete was discussed. When the ultrafine fly ash powder is ground to a sufficient fineness, it can release the fly ash microbeads wrapped in smaller spherical microbeads, weaken the influence of the appearance of non-spherical particles, and improve the workability of the concrete mix. When the ultrafine fly ash is processed and finely ground, the surface area of the fly ash can be greatly improved. The activity effect and micro-aggregate effect of fly ash can be fully expressed in concrete, so that the compressive strength of

concrete is significantly enhanced. Pan Ganghua et al. [14] replaced cement with 15% ultrafine fly ash, 15% silica fume and 7.5% silica fume +7.5% ultrafine fly ash to measure its mechanical properties and found that the effect of compounding silica fume and ultrafine fly ash was better than that of single addition.

2.3 Effect of Ultrafine Fly Ash on Durability of Concrete

Influence on concrete impermeability: concrete impermeability is mainly affected by the structure of concrete holes, and the size, number, curvature and distribution of holes in the structure are crucial to the evaluation of concrete impermeability. After the fly ash is mixed into concrete, its fine particles are evenly mixed with cement particles, and secondary C-S-H gel is generated through the volcanic ash effect. This gel product improves the pore structure in the concrete structure by filling the pores between the particles, thus reducing the overall porosity, the number of large pores, and the pore structure is further refined and distributed more evenly. It makes the structure on the concrete more dense and effectively improves the impermeability. The reason why the impermeability of fly ash concrete is better than that of ordinary concrete is its volcanic ash effect, which converts the unstable calcium hydroxide generated by the primary hydration of ordinary concrete into a dense and stable cementing substance through secondary hydration, thus improving the impermeability of concrete as a whole. The pozzolanic reaction of fly ash is a long-term reaction process. With the continuous progress of pozzolanic reaction, the pore structure of concrete will be further optimized, and the improvement of its impervious property will be further enhanced [15-16].

Influence on freezing resistance of concrete: The freeze-resistance of concrete is mainly affected by the pore size and gas content of concrete. During the 28d age, the change of pore structure caused by the incorporation of fly ash into concrete is larger than that of the base concrete. Therefore, the influence of fly ash on the early freeze-resistance of concrete shows a decreasing trend, but with the increase of curing age, the degree of freeze-resistance decline becomes smaller and smaller. The amount of gas content of concrete is also one of the main aspects affecting the frost resistance of concrete. For fly ash concrete projects in low negative temperature environment, the incorporation of appropriate air entrainment agent can effectively improve the frost resistance of concrete, while the carbon content, firing loss, carbonization properties, fineness and the content of fly ash will affect the air content of concrete. Under the condition that the amount of air entraining agent is the same, the more fly ash is added, the less gas content in concrete will be, and the worse the influence on the frost resistance of concrete will be [17-19].

Zhou Mingxia [20] et al., by adding C40 high-performance concrete with a content of 25% ultrafine fly ash, studied the addition of ultrafine fly ash and conducted an experimental study on the durability of high-performance concrete. The analysis of the experimental results found that ultrafine fly ash improved the freeze resistance and impermeability of high-performance concrete. The wear amount per unit area of superfine fly ash high performance concrete has been reduced to different degrees, and has excellent reinforcement performance. Sun Xinpeng [21] et al. studied the influence of ultra-fine fly ash obtained from the air separation process of electric dust collection into high-performance concrete to study the durability of concrete, and found that the chloride ion resistance of high-performance concrete with large fly ash content changes with age. The higher the strength, the lower the chloride ion permeability. When the content of ultra-fine fly ash is less than 50%, the lower the chloride ion permeability is. The dry shrinkage rate of high performance concrete is lower than that of the reference concrete with the same slump, especially it has a significant improvement effect on the early strength and dry shrinkage performance of concrete, and also improves the tensile strength, which plays a role in strengthening the toughness and reducing the brittleness. Niu Quan Lin et al. [22] used ASTMC441 method to test and analyze the effect and mechanism of ultrafine fly ash on inhibiting the alkali-aggregate reaction, Cl- diffusion and penetration of concrete and improving the sulfate corrosion resistance of concrete, etc. It was found that the addition of 30% ultrafine fly ash not only had a good inhibition effect on the alkali-aggregate reaction of concrete, but also had a good inhibition effect on the alkali-aggregate reaction of concrete. Moreover, it can effectively inhibit the Cl-diffusivity and permeability of concrete [23,24]. At the same time, the addition of ultrafine fly ash greatly enhances the hydration degree of cement through its activity effect, increases the amount of gel substances

produced by hydration, and makes the structure more dense, which is of great help to the resistance of ultrafine fly ash concrete to sulfate erosion [24,26]. So ultrafine fly ash has a good effect on concrete durability.

3. CONCLUSION

Ultrafine fly ash has obvious improvement on the working performance of concrete, and the workability of concrete is getting better and better with the increase of the dosage, mainly due to the morphological effect of ultrafine fly ash. Compared with cement and raw fly ash, ultrafine fly ash has better late development ability, this is because fly ash particles mainly act as a pozzolanic binder. From the perspective of social and economic benefits, concrete mixed with ultrafine fly ash not only greatly improves the bearing capacity of concrete members in the later stage, but also greatly saves the amount of cement, and thus saves the cost of actual projects.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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