Research Progress on the Effect of Silica Fume on Concrete Properties

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Abstract: In China, silica fume is usually used as an admixture in the concrete industry. Studies have confirmed that the performance of concrete will be affected by a large number of factors, and the appropriate addition of active silica fume plays a very important role in improving the mechanical properties of concrete, such as compressive strength and segregation strength. At the same time, it can also optimize the durability of concrete, prolong its service life, meet the relevant index requirements of high-performance concrete, and improve the project quality. This paper analyzes the influence of silica fume on the mechanical properties and durability of concrete, and looks forward to the research prospect of composite admixtures to improve the performance of concrete.

Keywords: silica fume; concrete; mechanical properties; working performance; durability

1. Introduction

Silica fume is a kind of fly ash collected from smoke and dust when smelting ferrosilicon alloy or metal silicon in ferrosilicon alloy factory and metal factory. The annual output of silica fume is large. If it cannot be reasonably utilized and directly discharged into the environment, it will cause major pollution to the environment. Therefore, in recent years, the recovery and utilization of silica fume and the conversion of silica fume into treasure have attracted extensive attention of material researchers [1].

Concrete is an artificial stone made of cementitious materials, water and coarse and fine aggregates mixed in an appropriate proportion and hardened for a certain time. Because of its good performance, abundant raw materials and low price, it has become one of the most widely used and important civil engineering materials. In China, silica fume is usually used as an admixture in the concrete industry. On the one hand, it can save cement clinker, reduce the production cost of concrete, effectively reduce environmental pollution and protect the environment. On the other hand, silica fume has good activity, which can improve the performance of concrete [2], prolong the service life of concrete and improve the project quality. Fu et al. [3] believe that adding silica fume (5%~10%) into concrete can improve the fluidity, filling, stability, mechanical properties and durability of concrete, so it is widely used in concrete structure projects with large pouring volume, deep pouring depth or high pouring height, dense reinforcement, special shape and other vibration difficulties, which brings great convenience to engineering design and construction. Therefore, developing the application of silica fume in concrete has important practical significance for promoting energy conservation and emission reduction, resource utilization of waste and environmental protection, developing circular economy, and building a resource-saving and environment-friendly society. Its technology, economy and benefits are remarkable and its application prospect is broad. This paper summarizes the research on the influence of silica fume on the performance of concrete in recent years.

2. Physical and Chemical Properties of Silica Fume

Physical and chemical properties of silica fume silica fume is an ultra-fine silica powder material formed by the rapid oxidation and condensation of SiO_2 and Si gas produced by metallurgical electric furnace at high temperature above 2600 ℃ and oxygen in air. More than 98% of the components in high-quality silica fume are amorphous SiO_2, which has high potential activity. The main components are shown in Table 1 below,

Table 1. Chemical composition

project	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	NaO	PH
average value	75-96%	1.0±0.2%	0.9±0.3%	0.7±0.1%	0.3±0.1%	1.3±0.2%	neutral

Silica fume is collected in different colors according to different devices with or without heat recovery system. Generally, the products are white or gray. The density of silica fume is about 2/3 of cement, but the bulk density is only 1/6 of cement. During the formation of silica fume, due to the effect of surface tension in the process of phase transformation, amorphous spherical particles with smooth surface are formed, and some are aggregates with multiple spherical particles stuck together. It is a kind of volcanic ash material with large specific surface area and high activity [4].

3. Micro Mechanism of Silica Fume Improving Concrete Performance

Compared with ordinary concrete, one of the main characteristics of concrete containing silica fume is a more uniform microstructure. When silica fume is added at low water binder ratio, the microstructure of cement paste is mainly composed of poorly crystallized hydrate to form a denser matrix with low porosity. With the increase of silica fume content, the amount of $Ca(OH)_2$ transformed into calcium silicate hydrate increases, that is, the CH content in cement stone decreases with the increase of silica fume content. Compared with Portland cement without silica fume, the remaining ch is easy to form finer grains. When silica fume is added into ordinary portland cement, Ca/Si in hydrate decreases, and hydrate can combine with other ions. As a result, the ability of cement stone to resist ion intrusion and inhibit alkali aggregate reaction is improved. At the same time, the concrete mixed with silica fume can fill the dense amorphous C-S-H phase around the aggregate, so as to significantly improve the interface transition zone between coarse aggregate and cement stone. Li et al. [5] studied the effect of 10% silica fume on the microstructure of cement mortar. It was found that the total porosity of the sample after hydration for 28 days was 8% higher than that without silica fume. At the same time, the pozzolanic reaction between silica fume and $Ca(OH)_2$ is also evenly distributed, which is not concentrated in the interface area, but mainly occurs in the capillary structure of the slurry, which blocks the capillary structure inside the slurry to a great extent, reduces the porosity and improves the strength of the sample in the later stage of hardening.

4. Effect of Silica Fume on Mechanical Properties of Concrete

Strength is an important mechanical property of fresh concrete after hardening, and it is also the main index of concrete quality control. It is found that the addition of silica fume can affect the strength of concrete (compressive strength, tensile strength, flexural strength) [6]. Murat et al. [7] believe that the addition of silica fume improves the early compressive strength of concrete, but reduces the long-term compressive strength of concrete. Tahir et al. [8] studied the influence of silica fume and fly ash and the mixture of silica fume and fly ash on the pressure resistance of concrete and the compressive strength of concrete. It was found that silica fume most significantly improved the compressive strength of concrete, and the strength of concrete was 72 MPa at 28d.Wang et al. [9] found that when the water binder ratio is 0.3 and the content of silica fume is within a certain range (about 5%~9%), the compressive strength of concrete shows an increasing trend. If compared with the compressive strength of concrete without silica fume, whether it is 7d or 28d compressive strength, adding 3% silica fume, the compressive strength of concrete basically does not change; When the content is more than 9%, the compressive strength of concrete shows a downward trend. After adding silica fume, the splitting tensile strength of concrete also shows an increasing trend. When the content of silica fume is 6%, the splitting tensile strength of concrete at 7d and 28d is 24% and 16% higher than that of concrete without silica fume, respectively. However, when the content of silica fume exceeds 6%, the splitting tensile strength at 7d or 28d begins to decline. It can be seen that when the water binder ratio is 0.3, the silica fume content is about 6%, which is very beneficial to improve the splitting tensile strength of concrete. Bhanja et al. [10] expert specially studied the influence of silica fume alone on the strength of concrete when the water binder ratio changed from 0.26 to 0.42.It is found that the best substitution ratio of silica fume on the compressive performance of concrete is not a fixed value, which is related to the water binder ratio, but in the range of 15%~25% [11].For the splitting tensile strength, although the addition of silica fume increases the splitting tensile strength of concrete, the high silica fume substitution ratio is not the main factor affecting the splitting tensile strength, and the silica fume substitution ratio will not exceed 15%.And under all water binder ratios, 5%~10% silica fume substitution ratio significantly improves the splitting tensile properties of concrete. For the flexural tensile strength, silica fume significantly improves the flexural tensile strength of concrete, and even the effect of high silica fume substitution ratio is more obvious. When the silica fume substitution ratio is 5%, 10%, 15%, 20% and 25%, the average growth rate of flexural tensile strength at 28 days is 10.2%, 14.5%, 27%, 31% and 26.6% under all water binder ratios. It can be seen that the flexural tensile strength of concrete is significantly improved when the silica fume replacement rate is about 20%.

5. Effect of Silica Fume on Working Performance of Concrete

Adding silica fume into concrete can improve the “stability” of concrete, that is, it can reduce the segregation and bleeding degree of concrete. Due to the large size of sand and stone used in concrete, the mixing water in concrete can flow through the pores between these aggregates, while silica fume can block these pores and cut off the flow channel of bleeding process due to its small particle size. The addition of silica fume can increase the contact point between solid and solid and increase the cohesion of concrete. However, when the content of silica fume in concrete is more than 20%, the viscosity of concrete increases greatly, which will increase the difficulty of construction; when the content of silica fume is less than 10%, it can ensure that the water consumption and the amount of water reducing agent are not increased and the concrete has better fluidity. When the slump of concrete is constant, the water consumption of concrete increases in proportion to the content of silica fume. In this case, an appropriate amount of superplasticizer can be added to reduce the water consumption of concrete. When the content of silica fume in concrete is 10%~ 20%, in order to ensure the slump and fluidity of concrete, the amount of water reducing agent should be increased under the condition of constant water cement ratio, so as to improve the strength and durability of concrete [12].

6. Effect of Silica Fume on Durability of Concrete

6.1. Influence of Silica Fume on Impermeability of Concrete

The durability of concrete against erosion water generally depends on the impermeability of concrete. Due to the small particle size of silica fume, the size and quantity of pores in concrete can be improved. When the content of silica fume in concrete is 10%, the concrete basically remains impermeable at the age of 7d and 28d, which can effectively reduce the pore diameter in concrete. Hustad et al. [13] conducted experimental research on the impermeability of concrete mixed with silica fume. It is found that silica fume has a significant effect on the impermeability of concrete. The test shows that the impermeability of concrete with 100 kg /m_3 cement, 20% silica fume and a certain amount of superplasticizer is the same as that of concrete with 250 kg/m_3 cement, but without silica fume and superplasticizer.

6.2. Effect of Silica Fume on Freeze-thaw Resistance of Concrete

The environment of many hydraulic concrete buildings is alternating between positive and negative temperatures. In the process of use, the concrete will be damaged by freeze-thaw cycle, resulting in freeze-thaw damage. Especially for hydraulic structures in cold areas, the lack of frost resistance of concrete is the main cause of structural damage. Therefore, solving the frost resistance of concrete materials is an important way to improve the durability of concrete.

Cwirzen et al. [14] measured that when the water binder ratio was 0.3, after 56 freeze-thaw cycles, the scaling of the concrete surface added with silica fume was less than 500 g /m^2, and the dynamic elastic modulus was more than 90%, with little difference. Chen et al. [15] studied the improvement of frost resistance of recycled concrete by silica fume and air entraining agent. The experiment uses 5% and 10% silica fume to replace cement, and explores the effect of silica fume on improving the frost resistance of recycled aggregate concrete. It is found that the decline value and trend of relative dynamic elastic modulus of the specimens mixed with silica fume are less than those of the control specimens (without silica fume). When 300 freeze-thaw cycles are reached, the relative dynamic elastic modulus of the control specimen and the specimen with 5% and 10% silica fume are 81.3%, 92.1% and 93.3% respectively. At the same time, in the first 100 freeze-thaw cycles, the specimen with silica fume has almost no mass loss. In 150 ~ 200 freeze-thaw cycles, the mass loss increases slightly, and the freeze-thaw damage is relatively slight, while the mass loss of the control specimen has reached more than 0.2% in 100 freeze-thaw cycles. Wu et al. [16] studied the influence of silica fume on the frost resistance of concrete in different concentrations of chlorine salt. The research found that the mass loss of concrete without silica fume after 200 freeze-thaw cycles in 5% chlorine salt is 8.45%, and the relative elastic modulus is about 40%, while the mass loss of concrete with silica fume under the same conditions is less than 2%, and the relative elastic modulus is basically unchanged, about 90%.By testing the pulse propagation speed of concrete, Assem et al. [17] found that when the content of silica fume increased from 3% to 8%, the reduction rate of pulse propagation speed decreased all the time, and the reduction rate of pulse propagation speed was about 15% in 210 freeze-thaw cycles, but when the content of silica fume increased to 11%, the reduction rate of pulse propagation speed reached more than 70% in 150 freeze-thaw cycles. That is, the best content of silica fume to improve the freeze-thaw resistance of concrete should be about 10%.

6.3. Effect of Silica Fume on Corrosion Resistance of Concrete

Sulfate attack is another important content affecting the durability of concrete. At the same time, it is also an environmental water attack with the most complex influencing factors and the greatest harm. In general, the smaller the water cement ratio and the greater the compactness, the more difficult it is for the sulfate solution to erode into the concrete and the stronger the corrosion resistance. The addition of silica fume improves the compactness of concrete and enhances the corrosion resistance of concrete. However, different content will have different effects on the corrosion resistance of concrete. Through literature review and experimental research, it is shown that the mixture of high alumina cement and Portland cement mixed with silica fume has sulfate corrosion resistance. When the content of high alumina cement containing silica fume is 15% and the content of Portland cement is 85%, its sulfate corrosion resistance is enhanced. By testing the content of sulfate diffusion in concrete, the effect of adding silica fume to concrete on sulfate corrosion resistance was studied. Taking the test results of 14 weeks as an example, when the silica fume content in Na_2SO_4 solution is 0%, 5%, 10% and 15%, the corresponding content of concrete sulfate is 0.09%, 0.072%, 0.06% and 0.05% respectively. That is, adding silica fume can significantly improve the corrosion resistance of concrete to sodium sulfate solution [18].

6.4. Effect of Silica Fume on Corrosion Resistance of Concrete

Alkali aggregate reaction refers to the phenomenon that the cement, mixture and alkali in the surrounding environment in the wet environment gradually react with the active components in the aggregate several years after the concrete is poured and formed, and the reaction products absorb water and expand, resulting in the expansion and cracking of concrete and loss of design performance. AAR reaction includes three types: alkali silicic acid reaction (ASR); alkali carbonic acid reaction (ACR); alkali silicate reaction. Jan and others believe that silica fume, as a highly active additive, can well reduce ASR expansion at a low substitution level (8% ~ 10%). Yu Yang and others studied the effect of silica fume on the expansion rate of mortar bar by using the rapid method of mortar bar. It is found that each content of silica fume can reduce the expansion rate of the sample, and the expansion rate decreases with the increase of silica fume. When the content of silica fume exceeds 15%, the expansion rate of the sample for 14d is less than 0.10%, indicating that silica fume has a good inhibitory effect on AAR. The main reason is that the volcano ash reaction occurs after mixing silica fume, which causes the $Ca(OH)_2$ to be absorbed in large amounts, forming a C-S-H gel with low calcium to silicon ratio. Such C-S-H gel can exhibit a strong ability to absorb alkali, thus reducing the alkali equivalent of cement mortar, reducing the erosion of alkali to active aggregate, and inhibiting the expansion caused by alkali silica reaction, thus achieving the effect of inhibiting AAR. Andrew found that the aggregate size of silica fume is not the factor causing ASR reaction. Whether it is large or small, it reduces the expansion of concrete. Juenger and others studied the effect of silica fume on ASR from the microstructure and aggregation morphology of silica fume and found that only sintered silica fume (aggregation size is 150 μm ~ 4.75 mm) exceeds 0.7% at 14d, and the change of expansion length without silica fume is less than 0.4%, while the change of expansion length of concrete with other aggregate sizes of silica fume is less than that without silica fume, but there is no obvious difference between them [19].

7. Conclusion

To sum up, because silica fume has unique fineness and mineral phase structure, it can improve the concrete by adding it into the concrete. Because silica fume has good activity, its addition to concrete can improve the performance of concrete. Proper addition of silica fume can improve the compressive and flexural strength of concrete, and improve the indexes of impermeability, freeze-thaw resistance, alkali aggregate reaction and so on. The application of silica fume in concrete has achieved good economic and environmental benefits. The concrete content and other effects of silica fume in concrete need to be further studied.

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