**Effects of Steam Curing on Fly Ash-Based Concrete Performance: A Review**

**Abstract：**Steam curing is a method used to increase the strength of concrete at an early stage. Steam curing is based on applying hot water vapor at a certain temperature, and determining its constant temperature time and maximum temperature according to the characteristics, cost and production cycle of the target concrete. As a kind of cementing material, fly ash is more and more used in concrete. This study summarizes the previous literature on the effect of steam curing system on the performance of fly ash based concrete. The increase of fly ash content has obvious negative effects on the early compressive strength, splitting tensile strength and elastic modulus of concrete, while the early high temperature curing can significantly improve the early mechanical properties of fly ash based concrete. Concrete exposed to steam curing at low temperatures of 45°C to 80°C and for longer periods of time within a 24-hour cycle can achieve better concrete performance. By studying the effect of steam curing on fly ash base concrete, a suitable curing scheme is developed and applied in practical engineering.

**Key words:** Steam curing concrete strength fly ash based material

**1 Introduction**

Concrete is a kind of building material composed of cement, sand, stone and other materials. There are many factors affecting the raw materials. At present, due to the wide variety of parameters involved in the prediction model and the difficulty in determining the specific values of some parameters, it is difficult for relevant personnel to accurately judge the concrete strength through the prediction model[1][2]. Through standard curing, concrete strength can be directly determined, and concrete design and production personnel can quickly grasp the potential activity of the admixture and adjust and determine the concrete mix ratio in time [3][4]. The strength of natural curing is closely related to age, curing time, curing method and curing temperature, and the curing method directly affects the strength. Steam curing is a thermal curing with high moisture content used to accelerate cement hydration at atmospheric pressure. Therefore, the strength of concrete products is developed in a short period of time [22,23]. Steam curing of concrete at a specified temperature can accelerate the increase in strength because the hydration rate of cement increases with the increase in temperature and curing time. Steam curing is a special case of wet curing in which steam involves supplying water to concrete at atmospheric pressure. Due to the heating of water, water vapor is produced at atmospheric pressure at temperatures below 100 °C.The most important process after concrete placement is maintenance [24,25]. Whether the curing is proper and sufficient directly affects the strength development, deformation, size, cracking, and durability of the concrete. Therefore, the curing determines whether the performance of the concrete in the actual structure is consistent with the performance of the laboratory standard conditioned concrete, and whether the design performance of the concrete can be achieved.

**2. Influence of steam curing on concrete performance**

**2.1 Curing method of concrete**

The curing of concrete refers to the necessary measures (including the humidity and temperature required for hydration) taken for the continuous hydration reaction of cementing materials (including cement and mineral admixtures) in concrete. The curing methods adopted for concrete after pouring are different. In actual construction, water coating is generally used for curing, while in the laboratory, humidity above 95% is usually used. The standard curing temperature of 20±3℃, in order to improve production efficiency and improve the early strength of concrete in the prefab plant, steam curing is generally used[5].

Osama Mohamed[6]studied the curing technology involving compounds, and conducted a comparative study on the influence of three curing methods: soaking in water, high-temperature air curing and compound curing on the compressive strength of concrete. A total of 20 mixtures were tested. For all mixtures, the sample cured in air at 45 ° C produced the highest 28-day compressive strength compared to other curing methods. Similarly, concrete samples cured with the compound yielded higher compressive strength compared to conventional curing methods.

**2.2 Influence of steam curing on concrete performance**

“Steam curing is based on the application of hot water vapor at temperatures ranging from 40°C to 100°C within a limited time” [7]. The maximum temperature and the longest curing time are determined according to the characteristics, cost and production cycle of the target concrete. The application of steam curing in precast structural components is beneficial and economical. One of its purposes is to accelerate the construction speed and achieve superior mechanical properties at an early stage.

Abdullah M. Zeyad[7] reviewed the previous literature on the impact of steam curing systems on the performance of concrete. Steam curing has a negative effect on the microstructure of concrete, and this effect increases with rising temperature. Besides the cooling period, the curing period and pre-curing period also have an impact on the performance and strength of concrete. Previous studies have confirmed that concrete exposed to low temperatures ranging from 45°C to 80°C for a longer period within a 24-hour cycle can achieve better concrete performance.

Yun Duan[8] experimentally analyzed the hydration heat, temperature changes and microstructure under different steam curing temperatures, and studied the influence of steam curing temperature and curing time on the compressive strength of concrete in the constant temperature stage to determine an economical and practical steam curing scheme. The results show that the higher the steam curing temperature and the longer the curing time, the greater the loss of later strength of concrete. If the duration of the constant steam curing temperature stage is too short, the hydration products only cover a small area, and most of the cement remains unhydrated. This is more obvious at lower steam curing temperatures.

Liu Baoju and Xie Youjun[9] used ultra-fine fly ash (UFA)and slag to replace cement, and accelerated the hydration of cement and fly ash with steam curing and chemical activators, and compared it with standard curing. The influence of steam curing on the compressive strength of UFA concrete with and without slag was studied. The test results show that the early strength of UFA concrete is relatively low after steam curing for 13 hours, and the 28-day compressive strength of the concrete after steam curing for 13 hours is significantly different from that of the standard curing concrete. However, the early strength of the concrete is relatively high after UFA is mixed with CaSO4 or Ca(OH)2, which accelerates the reactivity of fly ash. Concrete containing UFA and ground slag was prepared, and the compressive strength of the concrete was improved. The compressive strength of UFA concrete after demolding and steam curing is relatively low, and the 28-day compressive strength is also relatively low, indicating that the steam curing adaptability of UFA is poor.

Cement type, curing time and curing temperature are important parameters in the steam curing process. Selcuk Tqrkela [10] prepared concrete cubes with a water-cement ratio (W/C) of 0.44 and conducted steam curing for 4, 8, 16, 24 and 36 hours at curing temperatures of 65℃ and 85℃. The aim of the study was to compare the performance of the new binder with traditional PC42.5 under steam curing. The compressive strength values and maturity changes under each condition were compared. The test results show that Portland composite cement (PKC/A42.5) can replace PC42.5 for normal pressure steam curing in precast concrete production. However, if early demolding and early high strength requirements are present for PKC/A42.5 cement concrete, the curing temperature should be increased to 85.8℃.

A.A. Ramezanianpour[11]investigated the influence of 36 different steam curing regimes on the compressive strength and permeability of self-compacting concrete mixtures, which were used for the prefabricated concrete elements of the Sadar Elevated Highway. Compressive strength tests indicated that within a certain total time, an increase in pre-temperature exposure time would lead to a decrease in immediate compressive strength. On the other hand, increasing the treatment temperature and total cycle time (which implies higher energy and time consumption) resulted in higher immediate compressive strength. Moreover, the durability test results showed that applying a cycle with a maximum temperature of 70°C had a negative impact on the durability performance of the reference SCC, such as surface resistivity and capillary absorption. Finally, based on three indicators of compressive strength, permeability, and energy consumption of the steam curing cycle, the optimal steam curing cycle was proposed and applied to the prefabricated concrete factory. The influence of steam curing on the compressive strength and permeability of aggregate-filled SCC was studied.

At present, the HDE problem of steam-cured concrete has not been well solved. Jinyan Shi, Baoju Liu[12]adopted two steam curing methods and four subsequent curing methods to cure the concrete. Through long-term compressive strength, surface permeability and microstructure tests, the influence of curing conditions on the performance of steam-cured concrete was analyzed. The results showed that stepwise curing was beneficial to the formation of pre-structure, thereby improving the long-term mechanical properties and impermeability of steam-cured concrete. Among the four subsequent curing conditions, saturated limestone soaking was the most favorable for the long-term performance of steam-cured concrete, while water soaking was the most unfavorable. Through a series of experimental analyses, the influence of staged curing, variable-rate curing and subsequent curing on the evolution of HDE was studied.

Shashi Kant Sharma[13]initially produced plain cement concrete with a 28-day compressive strength of 70 MPa and conducted tests on this concrete, while changing the binder composition, aggregate ratio, and application of on-site curing methods, thereby achieving the same strength with less binder content. Ground granulated blast furnace slag (GGBS), fly ash (FA), and silica fume (SF) were used under normal water (23°C) and hot water (40°C) for 24 hours, and steam (60°C) curing for 2 hours in a 6-hour cycle (four cycles of 24 hours) to achieve early strength and reduced shrinkage of pavement quality self-compacting concrete (PQSCC). The results showed that steam curing could achieve good results even without CaCl2, while hot water curing must be supplemented with CaCl2 to achieve high strength.

**2.3 Effects of Steam Curing on the Properties of Fly Ash-Based Concrete**

Gou Yu[14]conducted experiments to investigate the influence of steam curing temperature and fly ash on the properties of steam-cured concrete. The compressive strength of concrete with fly ash at a temperature of 60°C was tested. The results showed that at the studied temperature, the compressive strength of concrete with fly ash replacing the benchmark cement in equal amounts was lower than that of the benchmark concrete within the age range of 1 to 90 days. With the increase in steam curing temperature, the compressive strength of each concrete after 7 days of age showed a decreasing trend.

She Liang[15]prepared high-activity multi-component supplementary cementitious materials by using a combined activation method with fly ash microspheres, granulated blast furnace slag, and silica fume. The effects of different activation methods on the activity index of mortar and hydration products were studied. The influence of adding multi-component supplementary cementitious materials on the compressive strength and sulfate resistance of concrete was also explored. When 30% of the multi-component supplementary cementitious materials were added to replace cement, and after static curing for 7.5 hours and steam curing at 90°C for 4.5 hours, the compressive strength of the concrete was significantly improved, and its sulfate resistance was enhanced. This indicates that the multi-component supplementary cementitious materials made from slag, fly ash microspheres, and silica fume, after mechanical-chemical combined activation, can partially replace cement to prepare high-performance steam-cured concrete.

Zhao Xingli[16] prepared SCC with a high fly ash replacement rate and cured it in a standard curing box for 24 hours or in a steam curing machine at 60°C and 90°C for 24 hours, and then placed it in tap water for curing. The effects of different early curing conditions on the mechanical properties of fly ash-based SCC were analyzed, and the relationship between the mechanical properties of fly ash-based self-compacting concrete was discussed. The conclusion was drawn that an increase in the fly ash content had a significant negative effect on the early compressive strength, splitting tensile strength, and elastic modulus of SCC. However, early high-temperature curing could significantly improve the early mechanical properties of fly ash-based SCC. Considering the actual engineering requirements, the application of fly ash-based SCC in the production of prefabricated components is feasible.

In order to understand the brittleness characteristics of steam-cured concrete, Li Guang et al. [17] used the brittleness coefficient and impact toughness as evaluation indicators to study the effects of curing temperature (20, 45, 55, 65, 75°C) and mineral admixtures on the brittleness of concrete. The results showed that as the curing temperature increased or the curing age prolonged, the brittleness coefficient of concrete increased, and steam curing reduced the impact toughness of concrete. The combined addition of fly ash and slag powder admixtures could improve the brittleness and impact resistance of steam-cured concrete. Higher curing temperatures led to coarser crystallization of hydration products, the formation of microcracks in the interfacial transition zone, and an increase in the porosity of the matrix, thereby increasing the brittleness of steam-cured concrete. The combined addition of fly ash and slag powder admixtures improved the pore structure and microstructure of the interfacial transition zone of steam-cured concrete.

Zhang Yao et al.[18] studied the mechanical properties, chloride ion permeability, and volume stability of high-volume fly ash and slag steam-cured concrete under 60°C and 80°C steam curing conditions, and analyzed the reaction degree of fly ash and slag. The results showed that under 60°C steam curing conditions, when the slag content was high, the early strength of concrete slightly increased, while when the fly ash content was high, it significantly decreased. The later strength of both was only slightly lower than that of pure cement concrete. Under 80°C steam curing conditions, the early strength of high-volume fly ash specimens improved, while that of high-volume slag specimens decreased. The later strength of all three types of concrete decreased, but the strength degradation of fly ash and slag concrete was less than that of pure cement concrete. This was mainly because fly ash and slag could alleviate the delayed formation of ettringite, improve the chloride ion permeability and volume stability of concrete, and enhance the durability of steam-cured concrete.

Chen Hai et al.[19] studied the effect of addition of fly ash on the physical and mechanical properties of manufactured sand concrete under steam curing at 50℃, and concluded that steam curing at 50℃ for 24 h would rapidly improve the early strength of concrete. When the density of fly ash in cementing material increases, the cohesiveness of concrete increases.

By adjusting the steam curing process, Li Guyuan et al.[20]studied the effects of static stop time and steaming time on the mechanical properties and durability of concrete. By comparing the difference of mechanical properties between steam curing concrete and standard curing concrete and the same condition curing concrete, as well as the difference of frost resistance and impervious properties between steam curing concrete and standard curing concrete, the best steam curing process was determined to reduce the adverse effects of steam curing on concrete properties. Finally, the steam curing process is adopted to adjust the type of water reducing agent used in steam curing concrete and determine the type of admixture suitable for steam curing concrete, so as to further ensure the quality of steam curing concrete.

Wang Xianshu[21] selected the steaming system of large amount of fly ash through experiments based on economic conditions and practical projects: static time 6h, heating time 2h, constant temperature time 8h, constant temperature temperature 60℃, cooling rate 1h. Under the condition of steam cultivation, the strength of fly ash can be improved by selecting a better steam cultivation system, which is conducive to the wide application of fly ash in civil engineering materials.

**3 Conclusion**

This paper reports the effect of steam curing on the properties of fly ash based concrete. The following conclusions can be drawn:

(1) The early strength of the concrete with steam curing is obviously improved, and the selection of appropriate steam curing system makes the fly ash based concrete obtain better compressive strength. Steam curing accelerates the early hydration of concrete and improves the mechanical properties of concrete to a certain extent.

(2) At the temperature of 60℃, the compressive strength of the concrete with the same amount of fly ash replaced the reference cement is lower than that of the reference concrete during the age of 1 to 90 days; The compressive strength of each concrete after 7 days of age showed a decreasing trend with the increase of steaming temperature.

(3) The phenomenon of delayed formation of ettringite caused by high temperature evaporation is one of the reasons for the poor durability of steam cured concrete. The addition of mineral admixtures can effectively alleviate this phenomenon, and the inhibition effect of fly ash on volume expansion is greater than that of slag. The addition of mineral admixtures can greatly improve the chloride ion permeability resistance and volume stability of the steamed concrete, and greatly enhance the durability of the steamed concrete.

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