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Comparison of the properties between high-volume fly ash concrete and high-volume steel slag concrete under temperature matching curing condition

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HIGHLIGHTS

- Steel slag reduces more hydration temperature rise than fly ash.
- Temperature match curing does not promote the early strength of HVSS concrete so much.
- The effect of temperature match curing on the permeability of HVSS concrete is small.

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ABSTRACT

Massive concrete structures tend to have high cracking risk due to early temperature rise. High-volume mineral admixture concrete, which has low hydration heat, is suitable for massive concrete structures. In this paper, the properties of high-volume fly ash (HVFA) concrete and high-volume steel slag (HVSS) concrete were compared under two different curing conditions (standard curing condition and temperature match curing condition). The results show that the promoting effect of temperature match curing on the early strength of HVFA concrete is more obvious than that on HVSS concrete. Temperature match curing has negative effect on the late strength and elastic modulus of HVSS concrete. The promotion of temperature match curing to the elastic modulus development is not so obvious as that to the strength development. Temperature match curing can significantly decrease the chloride permeability of HVFA concrete, but its influence on the chloride permeability of HVSS concrete is inconspicuous. Though the adiabatic temperature rise of HVSS concrete is lower than that of HVFA concrete, which is beneficial to its application to the massive concrete structures, its strength especially the splitting tensile strength and resistance to chloride ion penetration need to be improved.

1. Introduction

With the rapid development of economy and urbanization, more and more high-rise buildings have been built or are under construction in China, such as China World Trade Center Tower (330 m), Tianjin World Financial Center (336.9 m) and PingAn International Financial Center (660 m). The foundation slabs of these high-rise buildings, usually having large volume and thickness, are typical massive concrete structures.

The ACI Committee 116 [1] defines massive concrete as 'any volume of concrete with dimensions large enough to require the measures be taken to cope with generation of heat of hydration from the cement and attendant volume change to minimize cracking'. Massive concrete structures tend to have high internal temperature rise due to cement hydration and slow heat dissipation at early ages [2–4]. In the cooling process, large tensile stresses might be generated in massive concrete structures, which may lead to the cracking of concrete. The cracks have obvious negative effects on the durability and even the safety of concrete structure.

In order to decrease the temperature rise and avoid the cracking of concrete, some approaches are adopted in the construction of massive concrete structures, such as embedding internal pipes in concrete with cooling fluids (usually air [4–7] or water [8–10]), precooling the materials before mixing operations [11,12] and so on. But these construction technologies are complex and usually extend the construction time. An efficient method to control the temperature rise of massive concrete structures is replacing a large part of cement by mineral admixtures whose hydration heat is much smaller than that of cement [13,14].

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Fly ash is a by-product of coal-fired power plants, belonging to pozzolanic materials. Different from cement, the main chemical components of fly ash are Al_2O_3, SiO_2 and Fe_2O_3. The mineral constituents of fly ash include a major vitreous phase and some minor crystalline phases (quartz, mullite, hematite and magnetite) [15,16]. During the hydration of cement-fly ash composite binder, fly ash can react with $Ca(OH)_2$ and produce calcium silicate hydrate (C-S-H) gel [17,18], namely pozzolanic reaction. But the pozzolanic reaction of fly ash is quite slow at early ages, so it mainly behaves as a microaggregate to fill the pore structure of concrete, making a physical effect [19]. At late ages, fly ash begins to make greater chemical effects and improve the properties of concrete. Hanehara et al. [20] reported that the pozzolanic reaction rate of fly ash is much lower than cement hydration rate and it mainly depends on the curing temperature. Wang et al. [21] also found that elevating the curing temperature can effectively promote the pozzolanic reaction of fly ash at early ages.

Nowadays fly ash is widely used in the concrete industry as a mineral admixture. A lot of studies are focused on the properties and development of concretes containing high-volume fly ash [22–25]. Considering that using fly ash to replace part of cement can substantially decrease the hydration temperature rise of concrete and reduce the cracking risk of concrete [2,13], high-volume fly ash (HVFA) concrete is increasingly adopted in massive concrete structures. Through a laboratory investigation Atiş [26] found that HVFA concrete could be used for road pavements and large industrial floors due to its high late strength and low shrinkage properties. Wang et al. [27] designed a HVFA concrete for a foundation slab of a 597-meter building, and the results of mock-up experiment and finite-element calculation showed that the cracking risk of concrete was very low and the strength of concrete could meet the design requirement.

Steel slag is a by-product from the industrial production of steel. The chemical components of steel slag, usually varying with the raw materials and producing process, mainly include CaO, SiO_2, Al_2O_3, Fe_2O_3, FeO, MgO, and P_2O_5 [28,29]. And the common mineral constituents in steel slag are olivine, merwinite, C_3S, C_2S, C_4AF, C_2F, RO phase and free-CaO [29–31], which are similar to those in cement. The existence of C_3S, C_2S, C_4AF and C_2F endows steel slag certain cementitious properties, making it a potential mineral admixture for concrete. However, due to the low cooling rate of steel slag, the activity of its cementitious minerals is much lower than that in Portland cement [30,32]. Wang and Yan [32] carried out a research on the hydration of cement and steel slag and revealed that the hydration rate of steel slag was much lower than that of cement, although their hydration processes were quite similar with each other.

Kourounis et al. [29] found that adding steel slag would slow down the hydration of the blended cements and decrease the strength, though the blended cements containing steel slag exhibited satisfactory properties. Wang et al. [33] indicated that using steel slag as a mineral admixture in concrete had negative effects on both the strength and durability of concrete, and increasing the steel slag replacement rate would make the negative effects stronger. Therefore, the utilization rate of steel slag in the cement and concrete industries is quite low in China at present. Most part of the steel slag is discharged as waste, which leads to a serious environment problem.

But on the other hand, it has been proved that steel slag could prolong the dormant period of cement-steel slag composite binder [34]. What's more, steel slag has an excellent effect on decreasing the early hydration heat of the binder [31], which is even better than that of fly ash. These properties of steel slag highly match the temperature requirements of massive concrete structures. If steel slag can be applied to massive concrete as a mineral admixture, it will not only make great economy benefit but also make a contribution to the sustainable development of environment.

In this paper, two different temperature curing conditions (standard curing condition and temperature match curing condition) were set. The aim is to compare the properties between HVFA concrete and high-volume steel slag (HVSS) concrete under different temperature curing conditions and investigate the feasibility of using HVSS concrete in massive concrete structures.

2. Experimental

2.1. Materials

The materials used in this study were Ordinary Portland cement with the strength grade of 42.5 complying with the Chinese National Standard GB 175-2007, low-calcium fly ash complying with the Chinese National Standard GB/T 1596-2005, ground basic oxygen furnace steel slag complying with the Chinese National Standard GB/T 20491-2006, crushed limestone of 5 to 25 mm and natural river sand smaller than 5 mm. The specific surface areas of cement, fly ash and steel slag are 376 m^2/kg, 358 m^2/kg and 461 m^2/kg, respectively. Besides, polycarboxylic superplasticizer was used to adjust the fluidity of concrete. The chemical compositions of the cement, fly ash, and steel slag were shown in Table 1.

2.2. Mix proportions

As shown in Table 2, two mix proportions were prepared with the same amount of binder (400 kg/m^3), water-to-binder ratio (0.42) and mineral admixture substitution rate (45% by mass). One mix proportion was for the HVFA concrete (denoted by 'F'), and the other was for the HVSS concrete (denoted by 'S').

2.3. Curing conditions and test methods

The concrete specimens were cast with appropriate compaction and demoulded after about 36 h of initial curing. In order to study the properties of concrete in actual structures, two different curing conditions were set:

(i) Standard curing condition (SC): Specimens were cured in a room at 20 ± 1 °C and more than 95% relative humidity.
(ii) Temperature match curing condition (TMC): Specimens were cured in a curing box whose temperature was adjusted according to the adiabatic temperature rise curve of concrete.

Thus, there are four groups of concrete. Group F-SC represents HVFA concrete under standard curing condition. Group S-SC represents HVSS concrete under standard curing condition. Group F-TMC represents HVFA concrete under temperature match curing condition. Group S-TMC represents HVSS concrete under temperature match curing condition.

A specific adiabatic temperature measuring instrument with accuracy of ±0.1 °C was used to measure the adiabatic temperature rise curves of concrete. The slumps of the steel slag concrete and fly ash concrete were 17.6 and 16.8 cm, respectively. Specimens of 100 × 100 × 100 mm were prepared for the compressive strength and splitting tensile strength tests. Specimens of 100 × 100 × 300 mm were prepared for the elastic modulus test. And specimens of 100 × 100 × 50 mm were cut for chloride ion penetration test. The compressive strength, splitting tensile strength and elastic modulus of concrete were tested at the ages of 2, 3, 5, 7, 14, 28, 56 and 90 days according to the Chinese National Standard GB/T 50081-2011. And the permeability of concrete was measured at the ages of 28, 56 and 90 days according to ASTM C1202 "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration".

Steel slag paste was prepared by mixing sodium hydroxide solution (initial pH = 13.5) and steel slag at the solution/steel slag ratio of 0.42 (mass ratio). One group was cured under the temperature of 65 °C for the initial 7 days and 20 °C for the remaining ages (denoted by 'S-65 °C'), and the other was cured under the temperature of 20 °C throughout the ages (denoted by 'S-20 °C'). Non-evaporable water (w_n) content of the steel slag paste was tested at the ages of 3 and 90 days to evaluate its degree of hydration.

Table 1
Chemical compositions of the cement, fly ash, and steel slag: %.

	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	MnO
Cement	54.86	21.10	6.33	4.22	2.60	2.66	0
Fly ash	2.86	53.33	27.65	6.04	1.35	0.45	0
Steel slag	45.38	14.38	7.19	20.34	3.46	0.34	5.13