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Performance evaluation of steam cured HPC pipe piles produced with metakaolin based mineral additives

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HIGHLIGHTS

- The effect of MK based materials on the steam cured high performance concrete is investigated.
- The XRD and TG analysis were applied to quantify the content of CH and AFt after curing.
- The MK based admixtures remarkably refines the ITZ and optimize the pore structure of concrete after heat treatment.

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ABSTRACT

High performance pipe piles are widely used in precast industry. In order to improve the production efficiency and performances of the products, steam curing and mineral admixtures are usually applied. This paper evaluates the performances of HPC pipe piles produced with metakaolin-based admixtures. Quantitative phase composition analysis shows that the addition of 10 wt% metakaolin reduces the portlandite content by up to 57.1%, while increases the content of ettringite to some extent. The addition of metakaolin or metakaolin-slag/limestone blends improves the mechanical properties, especially the hybrid usage of metakaolin and limestone filler. Pore structure and microscope analyze confirm the remarkably-refined pore characteristics caused by the addition of metakaolin-based admixtures, in which case the gel pores accounts up to 85% of the total pores. Those remarkably improved properties caused by the addition of metakaolin-based admixtures indicate a promising future for their applications in producing high performance pipe piles with further modified properties.

1. Introduction

Pre-stressed high performance concrete (HPC) pipe pile is widely used in various engineering projects such as building, highway and railway, port and wharf constructions, because of its advantages in mechanical properties, density, bearing capacity and convenience of construction [1,2]. Due to its increasing demand, the effective utilization of the molds is required in order to improve the economic efficiency of the production of HPC pipe piles. In order to shorten the cycle of the mold, the HPC pipe pile is usually required to gain a high strength at early age.

Among the approaches of achieving high early strength, accelerating the hardening process of cementitious materials by heat treatment such as steam curing, is an efficient manner of providing the desired early strength. Elevated temperature is known to improve the early stage hydration rate of the cement clinkers [3–8], and the relations between temperature/energy and hydration kinetics was also well established by the Arrhenius equation [9]:

$$\left(\frac{d\alpha}{dt}\right)\begin{matrix} T=T_2 \\ \alpha=\alpha_0 \end{matrix} = \left(\frac{d\alpha}{dt}\right)\begin{matrix} T=T_1 \\ \alpha=\alpha_0 \end{matrix} \times exp\left\{-\frac{E_a}{R}\times\left(\frac{1}{T_2}-\frac{1}{T_1}\right)\right\}$$

where α is the degree of hydration, Ea is the apparent activation energy (J/mol), R is the gas constant (8.31243 $J{\cdot}mol^{-1}{\cdot}K^{-1}$) and T is the absolute temperature. The acceleration mechanism includes both physical and chemical procedures that speeding up the dissolution, precipitation and diffusion of the hydrates [10,11]. However, one negative effect of elevated temperature curing on the hydrated matrix is the increased capillary porosity and reduced gel porosity [5,12], which will further results in the corresponding performance degradations. Kim [10] showed that concrete specimens subjected to a high early temperature (40 °C) attain higher early-age strength but eventually attain a lower later-age strength than cured at 20 °C.

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The heterogeneous structuration of the matrix with a dense hydrated phase develops rapidly around the remaining cement grain and involves a slow-down of the diffusion process, which would result in a majority of less dense hydrated phase surrounding the denser one and weakening the whole matrix, therefore a reduced strength is shown at later stages [13–15]. These influences should be carefully considered and handled when applying accelerated treatment in achieving high early strength, otherwise cracks due to inadequate later strength and the resulting poor anti-permeability may limit its applications in industries.

Meanwhile, supplementary cementitious materials (SCMs), such as fly ash (FA) [16–20], silica fume (SF) [16,17], ground granulated blast furnace slag (GGBFS) [21] and calcined calys [21] are widely used in cement products. Utilization of suitable SCMs is another common manner of achieving early strength [16–19]. The addition of finely ground slag and amorphous silica are capable of improving the early strength because of their high pozzolanic activity and high specific surface areas [22–24]. Attentions were also paid to another highly active mineral admixture, metakaolin (MK). Different from other SCMs as secondary products, metakaolin is usually produced by calcination of kaolin [25]. The secondary pozzolanic reaction of matakaolin results in reduced portlandite content and additional C–S–H gels with lower C/S ratio, also extra C–A–S–H phases are formed [26–29]. Owing to the high reactivity and high aluminate content of metakaolin, it was widely applied in order to improve the mechanical properties, sorptivity, pore structure, chloride resistance and durability of concrete due to the modification of pozzolanic reactions [28–35].

The application of elevated temperature curing together with supplementary cementitious materials has shown promising results in obtaining high early strength and inhibiting the disadvantages of high temperature curing. The hybrid usage of slag and fly ash in steam cured HPC was reported to show similar level of ultimate mechanical properties compared to the ones after 28 d of standard curing [36]. It was also found that pozzolanic materials help to improve the corrosion resistance of steam cured concrete. For instance, the addition of 20% FA in steam cured concrete shows an improved deicer-scaling resistance compared to the plain concrete [37], and the application of high volume fly ash (70 wt%) reduces the mass loss by around 86% in the acid resistance test [38]. The significantly improved sorptivity is an indication of the modified microstructure, especially when silica fume was applied. It was reported that the water absorbed values of steam cured mixes incorporating 10% SF was only about a third of those for OPC, owning to the pore refinement of silica fume [39]. Besides, limestone filler was also known to improve the early age strength under accelerated curing, while presents no negative impacts on the 28 d strength and durability [40,41]. In addition, the application of high efficient mineral admixtures such as silica fume and metakaolin showed remarkable modifications on the water sorptivity, chloride transportation and strength stability [42,43]. It can be seen that previous investigations showed the potential of using SCMs under steam curing conditions to achieve both high early strength and modified pore structure, while relatively limited attentions was paid to the effect of aluminate enriched metakaolin and its based hybrid mineral admixtures. A further understanding of their influencing mechanisms under steam curing would provide an additional option for the production of HPC pipe piles.

Based on the concerns above, it is of significance to characterize the performances of steam cured HPC pipe piles that produced with metakaolin based mineral admixtures. In this study, the hydration products are identified and quantified by using X-ray diffraction (XRD) and thermal gravity and Differential Scanning Calorimeter (TG-DSC). Important hardened properties including mechanical properties, pore structures, shrinkage and microstructure are also characterized and their relations are discussed in detail.

2. Experimental procedure

2.1. Materials

The cement used in this study was Type I Portland Cement 52.5 complying with the Chinese National standard GB175-2007. Blast furnace slag (GGBS), metakaolin (MK) and limestone filler (LS) were used as supplementary cementitious materials. The chemical composition and physical properties of the raw material were listed in Table 1. Natural sand with a fineness modulus of 2.8 was used as fine aggregates; crushed gravel with nominal maximum size of 25 mm was used as coarse aggregates. A polycarboxylate type high-range water reducing admixture (HRWRA) with a solid content of 40% was used to adjust the concrete slump between 50 and 60 mm.

2.2. Specimen preparation and curing regimes

The detailed mix proportions are given in Table 2. The binder content was fixed at 450 kg/m^3 based on the previous researches. The metakaolin replacement (of cement) was fixed at 10 wt%, blast furnace slag and limestone filler were also used together with metakaolin as binary blends. The water to binder ratio was kept constant at 0.25 in all mixtures. The molding period should be controlled within 10 min, then both paste and concrete mixtures with moulds were applied to a steam curing cycle (Fig. 1) with a total duration of 17 h. Then samples were removed from the molds and stored at 20 ± 2 °C until testing until testing time at 1 and 7 days after molding.

2.3. Testing methods

2.3.1. Phase composition

The X-ray diffraction (XRD) analysis was carried out with Co-Kα radiation ($\lambda_{K\alpha}$ = 1789) at 40 kV and 30 mA. The measured 2θ value ranges from 0° to 60° and were recorded in 0.04° steps with a counting time of 10 s per step. The thermo-gravimetric and differential scanning calorimeter (TG/DTG) analysis was conducted to analyze the hydration products. Finely ground powder samples

Table 1
Chemical composition of the binding materials (wt%).

Binding materials	Chemical composition (%)									Fineness (m^2/kg)
	SiO_2	Al_2O_3	CaO	Fe_2O_3	SO_3	MgO	Na_2O	K_2O	LOI	
PC	19.37	3.92	68.3	3.69	0.81	1.61	0.13	0.59	1.09	420[a]
MK	53.15	44.43	0.02	0.7	0.21	0.13	0.34	0.53	0.12	15 000[b]
GGBS	33.64	15.27	35.46	0.45	2.05	10.2	0.51	0.52	0.15	400[a]
LS	8.27	2.64	45.11	0.9	2.01	0.11	–	4.29	35.43	590[a]

[a] Blaine surface area.
[b] BET method measurements.