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Properties, microstructure and hydration products of lightweight aggregate concrete with metakaolin and slag addition

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HIGHLIGHTS

- MK is more efficient than slag on improvement of properties and durability of LWAC.
- Synergetic reaction of MK and slag improved properties and microstructure further.
- ITZ was improved through internal curing by pre-wetting of LWA.
- There is a linear correlation between strength and chloride diffusion coefficient.

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ABSTRACT

The effects of metakaolin (MK) and slag on the strength, shrinkage, chloride resistance and interfacial transition zone microstructure of lightweight aggregate concrete were characterized by a range of analytical techniques. Slag decreased early age strength while MK increased late age strength, which was further increased by the combination of MK and slag. MK was more effective on reducing chloride diffusion coefficient and shrinkage than slag. These properties were further improved by the combination of MK and slag. Linear correlation was observed between strength and chloride diffusion coefficient with higher strength presenting lower diffusion coefficient. Portlandite, ettringite, hemicarboaluminate and monocarboaluminate were identified as hydration products. MK promoted the formation of hemicarboaluminate and monocarboaluminate. Portlandite content decreased at 28 days in concrete with MK and slag, resulting in an interfacial transition zone with denser microstructure and lower Ca/Si ratio, due to the pozzolanic reaction.

1. Introduction

High strength and high performance concrete has been under extensive study during the last century, which has high bulk density and excellent performance but also consumes significant amount of natural resources and produces considerable quantities of CO_2 [1]. To reduce the carbon footprint of cement industry and reserve the resources, lightweight aggregate concrete (LAC), which has low density, low thermal conductivity, higher fire resistance and strength/weight ratio, recently attracted widely attention from researcher and engineers [2–4]. High performance LAC has lower density, usually in 1500–1950 kg/m^3, which can reduce over 20% bulk density of concrete and the consumption of materials such as steel, resulting in cost savings and economic benefit [5,6].

Utilization of mineral admixtures such as silica fume, fly ash and slag promoted the development of high strength and high performance LAC [7–12]. The mineral admixtures are introduced into concrete to improve the performance and reduce the consumption of natural resources and greenhouse gas emissions. High performance LAC (HPLAC) with compressive strength of 55.8 MPa and density of 1836 kg/m^3 can be prepared with excellent impermeability and resistance to chloride ion penetration by addition of 10 wt% silica fume and fly ash [13]. By introducing 10 wt% of fly ash, slag and silica fume, high performance LAC with density of 1624 kg/m^3 and compressive strength of 60.5 MPa was successfully produced [14]. However, there are some engineering problems with these mineral admixtures. For example, low water cement ratio leads to a high shrinkage of HPLAC, silica fume are quite expensive and difficult to achieve even distribution due to the fine particle size, the early age activity of fly ash is poor and the large addition quantity will seriously affect mechanical

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performance, and the performance of slag is improved through grinding technology which increases the cost.

In recent years, metakaolin (MK) has been widely used in the cement and concrete industries. MK is produced by heating kaolin at 650–800 °C where water and OH was removed from the interlayer structure, together with structure deformation to lose long-range order of silicon-aluminium layer structure, resulting in high reactivity in favourable conditions such as alkaline activation and hydrothermal process [15,16]. Studies on the rate of the pozzolanic reaction of metakaolin and improvement of compressive strength in metakaolin blended cement reported that the rate of pozzolanic reaction of metakaolin blended cement was higher than those of silica fume blended cement at early ages [17,18], indicating that metakaolin is more effective than silica fume. Another study on the effect of metakaolin on the shrinkage of concrete indicated that metakaolin significantly reduced the total shrinkage and creep of high strength concrete with compressive strength of 90–100 MPa [18].

Although MK has been used as an admixture to improve the strength and durability of structural concrete [17–22], there was little study on the effect of MK on lightweight aggregate concrete. In this study, the effects of MK and slag on the mechanical properties, durability and microstructure of LAC were evaluated by a range of analytical techniques. LAC containing two MK replacement levels (5 and 10 wt%) and three slag replacement levels (5, 10 and 15 wt%) were used to characterize the compressive strength, chloride penetration resistance, shrinkage and interfacial transition zone of LAC, comparing to those of the control concrete. The aim of the study is to obtain the mechanism of the effects of MK and slag on LAC.

2. Experimental details

2.1. Materials

Ordinary Portland cement (OPC) (CEM I 42.5) with a density of 3130 kg/m^3 and specific surface area of 339 m^2/kg was used for all concrete mixtures with mineral admixtures of slag (density of 2960 kg/m^3 and specific surface area of 339 m^2/kg) and metakaolin (specific surface area of 2800 m^2/kg) which was produced by calcination of kaolin at 750 °C. The chemical composition of materials used in this research is given in Table 1. River sand with a fineness modulus of 2.38, apparent density of 2604 kg/m^3 and bulk density of 1534 kg/m^3 was used as fine aggregate. Artificial shale ceramsite was used as coarse aggregate, whose specific gravity and water absorption were determined according to ASTM C127 [23] and presented in Table 2 and Fig. 1. The particle size of coarse aggregate is 5–20 mm. A polycarboxylicether type superplasticizer (SP) with a specific gravity of 1.07 was employed to achieve the desired workability in all concrete mixtures.

2.2. Mix design

A w/c ratio of 0.3 was chosen for all mixes. To develop the metakaolin and slag modified lightweight concrete, Portland cement was partially replaced by 5 and 10 wt% MK, and 5, 10 and 15 wt% slag respectively. The porous aggregate was generally pre-wetted for 24 h and then mixed with river sand. Concrete moulding was under artificial vibrating mode. A total of eleven mixes was proposed in this study (Table 3). Different dosages of SP were selected in order to achieve similar workability between mixes.

Table 2
Physical properties of lightweight aggregate.

Unit weight (kg/m^3)	Bulk density (kg/m^3)	Cylinder strength (MPa)	Water absorption (%)
680	1600	5.0	6.42

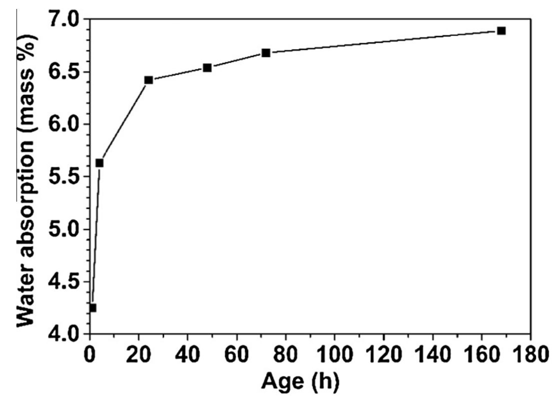

Fig. 1. Water absorption of lightweight aggregate.

All mixes were performed in accordance with ASTM C192 in a power-driven revolving pan mixer [24]. Cubes of 100 × 100 × 100 mm^3, rectangular specimens of 100 × 100 × 400 mm and cylinders of 100 mm in diameter and 200 mm in height were cast in steel moulds and compacted on a vibrating table. The cube and cylinder specimens were removed from the moulds at 24 h after casting, and then allowed to cure under standard conditions (25 ± 2 °C and relative humidity of 98%), for compressive strength and rapid chloride migration test, respectively. The rectangular specimens were cured at 20 °C and relative humidity of 60% for shrinkage test.

2.3. Test method

2.3.1. Compressive strength test

To evaluate the strength of the control, MK, and slag LAC, the compressive strength test was conducted on the cube specimens by means of a 3000 kN capacity machine according to ASTM C39 [25]. The test was performed on the concretes at the ages of 3, 7, and 28 days. Three specimens were used for each batch.

2.3.2. Rapid chloride migration (RCM) test

RCM test was performed according to NT Build 492 at 28 days for all mixes [26]. Three vacuum-saturated specimens of 100 mm in diameter and 30 mm in thickness were used for each batch. The distance of chloride ingress in the specimen was determined and the chloride diffusion coefficient was calculated accordingly.

2.3.3. X-ray diffraction (XRD) and thermal analysis

Pastes with the same mix design as concretes were prepared and cured under the same conditions for XRD and thermal analysis. The samples were immersed in ethanol to avoid rehydration

Table 1
Chemical composition of OPC, MK and slag (wt%).

	SiO_2	Al_2O_3	CaO	Fe_2O_3	SO_3	MgO	Na_2O	K_2O	TiO_2	P_2O_5	LOI
OPC	21.50	5.86	59.81	2.85	2.06	2.23	0.20	0.67	–	–	3.70
MK	38.63	57.37	0.03	0.77	0.15	0.07	0.39	0.49	0.40	0.61	1.04
Slag	33.82	15.02	38.83	0.44	2.34	7.14	0.29	0.57	0.91	0.02	0.73