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Properties of high-volume limestone powder concrete under standard curing and steam-curing conditions

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ABSTRACT

A comparative study of the mechanical properties, volume stability and durability of high-volume limestone powder concrete (HVLPC) and high-volume fly ash concrete (HVFAC) was conducted by testing pore structures of the paste and determining the adiabatic temperature rise, porosity, compressive strength, chloride ion permeability, 1 year's natural carbonation depth and dry shrinkage strains of the concrete. The test results illustrate that the reductive influence of high-volume limestone powder on the temperature rise of the massive concrete is identical to that of the high-volume fly ash. Compared with high-volume fly ash concrete, high-volume limestone powder concrete with the same water/binder ratio has relatively high interconnected porosity, low compressive strength, and low resistance to carbonation and chloride ion penetration, especially at the steam-curing conditions. The volume stability of concrete containing a high volume of limestone powder is almost identical to that of concrete containing fly ash with the same water/binder ratio. Reducing the water/binder ratio and replacing part of the limestone powder by ground granulated blast furnace slag can reduce the negative effects of limestone powder on the macro-properties of concrete.

1. Introduction

Limestone powder has been recognized as one of the common mineral admixtures with low reactivity [1,2]. The primary constituent of limestone powder is calcium carbonate ($CaCO_3$), whose content is usually more than 95%. It also contains SiO_2, Fe_3O_4, MgO and Al_2O_3 as minor constituents [3–5]. Because limestone has low strength and good grindability [6], the energy consumption of limestone powder production is relatively small. Limestone powder can be produced and used in many places because limestone is easily available and inexpensive [7]. The average particle size of limestone powder is usually smaller than that of Portland cement [8,9]. Zhang et al. [10] found that a gap-graded particle size distribution led to a decrease of water demand, increased the packing density of composite paste, excellent volume stability and increased mechanical properties of concrete. Xu et al. [11] attempt to present a particle random sequential packing model to characterize the mesostructure of cementitious composites. Limestone powder is primarily used as a filler material in the production of the gap-graded composite binder. The apparent density of limestone powder is usually approximately 2700 kg/m^3, which is between those of fly ash and Portland cement [9]. Limestone powder tends to influence the cement hydration [12]. Limestone powder promotes the early hydration of cement [13,14] and provides nucleation sites for the formation of C-S-H gel [15–17]. Limestone powder can also produce calcium carbosilicate hydrates and calcium carboaluminates by reacting with tricalcium silicates and calcium aluminates [18–20]. The early-age mechanical properties of concrete are improved owing to the promoting influence of limestone powder on cement hydration, and the later strength is reduced because of the dilution effect [16,21]. Tsivilis et al. [22] found that composite cement with 20% limestone, showed optimal resistance to rebar corrosion, and the addition of limestone decreased both the porosity and carbonation depth of the mortar. Liu et al. [23] reported that the filling function of limestone powder could increase the density of the hardened paste and the interfacial transition zone between hardened paste and aggregates, improving the performance of concrete. It is reported [24] that the magnesium sulphate resistance of the mortars could be improved by the addition of limestone powder.

Fly ash from the combustion of coal is a by-product that has been commonly used as mineral admixture in the preparation of high-performance concrete [25,26]. The particles of fly ash are normally spherical in shape, have dimensions of micrometres to millimetres, and can react with the hydration products of cement [27]. The use of fly ash saves cement, reduces heat of hydration in mass concrete [28–30], increases flow ability [31], decreases shrinkage of concrete [32,33], improves resistance to chloride-ion penetration [34,35] and reduces risk of steel corrosion [36]. Jin et al. [37] reported that a suitable addition of fly ash could promote the resistance to chloride penetration and sulphate corrosion.

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The significant temperature rise at early ages tends to increase the cracking risk of massive concrete structures. The large replacement of cement by mineral admixture decreases the hydration heat of concrete, which is benefit to the massive concrete [38,39]. The utilization of high-volume fly ash in massive concrete has been widely investigated [40, 41]. Some research studies [42–44] have reported that the addition of high-volume fly ash can improve the workability of fresh concrete and the durability of hardened mass concrete. Wang et al. [45] designed high-volume fly ash concrete for a concrete foundation slab, and the temperature variation of the mock-up illustrated that the temperature inside the massive concrete is reduced by adding a high amount (45%) of fly ash. Ground granulated blast furnace slag (GGBS) is also widely used as a mineral admixture in the preparation of concrete. The improving effect of GGBS on the properties of concrete is more evident than that of fly ash because of the higher pozzolanic reactivity [30]. Thus, the addition of GGBS can partly compensate for the negative effect of mineral admixture with low activity on the properties of concrete [46].

Based on a review of the literature, research on the dosage of limestone powder is very rare in the current studies. The properties of concrete with a large adding amount of limestone powder have not been sufficiently studied. The relatively higher temperature inside the massive concrete due to the hydration heat of cementitious materials tends to influence the hydration kinetics of the binders. So the influence of elevated temperature curing at early ages on the properties of the high-volume limestone powder concrete is worth researching. In this research, high-volume fly ash concrete was selected as the control sample (sample F). Three mix proportions of high-volume limestone powder concrete were prepared: with the same water/binder ratio as the control sample (sample L1); with a relatively lower water/binder ratio compared with the control sample (sample L2); replacing 25% of the limestone powder with GGBS (sample L3). The properties of the high-volume limestone powder concretes were studied by testing the pore structures of paste and the porosities of concrete and measuring the adiabatic temperature rise, carbonation depth, chloride ion permeability, compressive strength and dry shrinkage of concrete with different initial curing temperatures.

2. Experimental

2.1. Raw materials

Portland cement with the grade of P.I 42.5 which conforms to Chinese National Standard GB 175 (equivalent to European CEM I 42.5) was utilized in this study. The particle size distribution curves of the raw materials are shown in Fig. 1. The chemical compositions of the raw materials determined by XRF are shown in Table 1.

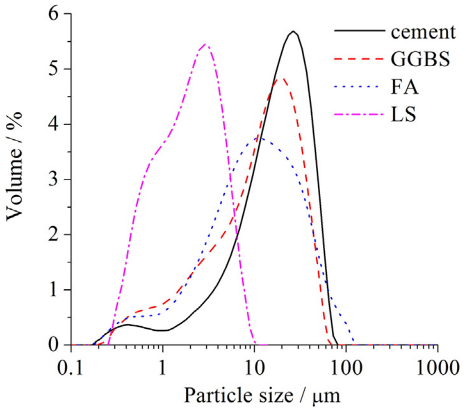

Fig. 1. Particle size distributions of raw materials.

Table 1
Chemical compositions of cement, fly ash, GGBS and limestone powder *w*/%.

Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	$CaCO_3$	MgO	SO_3	Na_2O_{eq}	LOI
Cement	21.18	4.73	3.41	62.48	–	2.53	2.83	0.56	0.72
Fly ash	53.33	27.65	6.04	2.86	–	1.35	0.45	0.64	4.71
GGBS	31.76	14.84	0.6	36.44	–	9.08	1.94	0.56	0.86
Limestone powder	8.43	2.39	1.41	–	82.85	3.28	0.10	0.80	–

Note: $Na_2O_{eq} = Na_2O + 0.658K_2O$; *w*-mass fraction.

2.2. Mix proportions

The mix proportions of pastes are shown in Table 2. The mix proportions of concretes are shown in Table 3. Four series of mixes were prepared. The mineral admixture replacement ratio is 40% (mass ratio). The paste or concrete containing a high volume of fly ash with a water/binder ratio of 0.4 is selected as the control sample, which is marked as sample F. The paste and concrete containing a high volume of limestone powder with water/binder ratios of 0.4 and 0.33 are marked as Samples L1 and L2, respectively. The paste and concrete containing 30% limestone powder and 10% GGBS are marked as sample L3. The fluidity of mixtures was adjusted by a polycarboxylate superplasticizer.

2.3. Test methods

Concrete cubes of 10 cm × 10 cm × 10 cm were prepared. After casting, some specimens were cured in a standard curing room with constant temperature and humidity (20 ± 1 °C, 95% RH). The other specimens were cured with standard curing conditions for the first 12 h after casting and then moved to a steam room with a constant temperature of 45 °C. After steam-curing for 7 days, the specimens were moved back to the standard curing room with the conditions of 20 °C and 95% RH. At the ages of 3, 28, 90 and 360 days, the compressive strengths of the concretes were tested. The chloride ion permeability test was conducted at 28, 90 and 360 days to determine the resistance of the concretes to chloride ions penetration according to ASTM C 1202 “Standard Test Method for Electrical Indication of Concretes Ability to Resist Chloride Ion Penetration”. The porosity and pore size distribution of the hardened pastes were measured using a mercury intrusion porosimeter.

The open porosity of concrete was determined by the displacement method. This method employs the use of 24 h of vacuum saturation to remove all entrapped air within the sample mass and force water into the effective pores of the concrete. The total volume V_{total} and the saturated weight m_{sat} were measured. All samples were moved to an electric dry oven with 60 °C for 14 days, and then the dry weight m_d of the samples were measured. The porosity of the concrete was calculated as

$$p_o = V_{water}/V_{total} \times 100\% \tag{1}$$

$$V_{water} = (m_{sat} - m_d)/\rho_w \tag{2}$$

The adiabatic temperature rise test was performed on a 60 L specimen with an electrical thermometer embedded in its centre. During the testing procedure, the air temperature within the chamber and

Table 2
Mix proportions of pastes.

Samples	Composition of binder (by mass%)				Water to binder ratio
	Cement	Fly ash	Limestone powder	GGBS	
F	60	40	0	0	0.4
L1	60	0	40	0	0.4
L2	60	0	40	0	0.33
L3	60	0	30	10	0.4