Construction and Building Materials 54 (2014) 339–347

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Volumetric deformation of gap-graded blended cement pastes with large amount of supplementary cementitious materials

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HIGHLIGHTS

- Gap-graded blended cement pastes presented comparable chemical shrinkage with Portland cement paste.
- Most of chemical shrinkage occurred after the formation of skeleton structure, leading to reduced autogenous shrinkage.
- The microstructure of gap-graded blended cement paste was dense and homogeneous.
- Shrinkage stress was small and uniformly distributed in gap-graded blended cement paste.
- Gap-graded blended cement paste presented smaller volumetric deformation and superior resistance to cracking.

ARTICLE INFO

Article history:
Received 11 October 2013
Received in revised form 18 December 2013
Accepted 19 December 2013
Available online 19 January 2014

Keywords:
Gap-graded blended cement
Volumetric deformation
Chemical shrinkage
Hydration products

ABSTRACT

In this study, volumetric deformation of gap-graded blended cement pastes with large amount of supplementary cementitous materials was investigated and compared with those of Portland cement and reference blended cement pastes. The results show that the gap-graded blended cement pastes presented a higher initial packing density, therefore smaller amount of hydration products was needed to achieve dense microstructure, resulting in smaller chemical shrinkage. Notably, most of chemical shrinkage of gap-graded blended cements was occurred after the formation of skeleton structure, thus the autogenous shrinkage of gap-graded blended cements was reduced significantly due to restraint of the skeleton structure. Further, the microstructure of gap-graded blended cement pastes was dense and homogeneous due to grain size refinement and significant hydration of GBFS, and shrinkage stress was small and uniformly distributed. As a result, gap-graded blended cement pastes presented smaller volumetric deformation and superior resistance to cracking than Portland cement and reference cement pastes.

1. Introduction

The durability of concrete structures is increasing concerned during the past decades, and the early volumetric deformation of cement paste is generally considered as the key factor leading to early age cracking and, consequently, to the loss of durability of concrete structures. Tazawa and Bentz reported that finer cement usually resulted in larger autogenous shrinkage of cement-based materials, thus coarse cement was recommended in concrete manufacture if the mechanical properties of the concrete met the requirements [1,2]. Numerous literatures proved that the autogenous shrinkage of cement pastes with supplementary cementitious material (SCM) was significantly influenced by the hydraulic activity (or the type) and fineness of the incorporated SCMs [3–6]. For instance, the addition of silica fume increased the autogenous shrinkage of cement pastes remarkably [7]. When the specific surface area of granulated blast furnace slag (GBFS) was lower than 400 m^2/kg, the addition of GBFS decreased the autogenous shrinkage of cement pastes. In contrast, for GBFS with specific surface area higher than 400 m^2/kg, the autogenous shrinkage of cement pastes increased with the increase of GBFS replacement [8]. Low calcium fly ash presented low hydraulic activity, therefore the addition of low calcium fly ash generally reduced the autogenous shrinkage of cement pastes [9].

From the above literatures, it can be concluded that the volumetric deformation of cement-based materials mainly depends on the hydration process of cementitious materials and the composition of hydration products. Burrows and Ba proved that fast hydration of cementitious materials resulted in larger volumetric deformation, leading to a higher risk of cracking of cement-based materials [10,11]. Therefore optimization of hydration process of cementitious materials is an effective way to minimize the volumetric deformation of cement-based materials.

Particle size distribution (PSD) has a significant influence on initial packing density and hydration process of cement paste,

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http://dx.doi.org/10.1016/j.conbuildmat.2013.12.053

eventually affecting the amount and composition of hydration products in cement paste. If cement paste had a higher initial packing density, smaller the amount of hydration products were needed to fill-up the voids in cement paste, therefore the volumetric deformation of cement paste would be improved dramatically. In previous study, a gap-graded PSD was proposed based on close packing theory, the initial packing density of blended cement paste was increased significantly, as voids between large size particles were filled in by fine particles grade by grade [12]. And the hydration process of gap-graded blended cements was optimized by arranging SCMs with high activity, cement clinker, and SCMs with low activity (or inert fillers) in fine, middle size and coarse fractions, respectively. The microstructure of gap-graded blended cement pastes was densified gradually at later ages due to hydration of GBFS. As a result, gap-graded blended cements with only 25% clinker by mass presented comparable mechanical properties with pure Portland cement [13,14].

Although with superior mechanical properties, it is more important to clarify the volumetric deformation of gap-graded blended cement pastes before application, as the durability of concrete structures is largely depended on the volumetric deformation of cement paste incorporated. In the present study, the volumetric deformation of gap-graded blended cement pastes, Portland cement paste and reference blended cement paste were comparatively studied, and the volumetric deformation mechanism of gap-graded blended cement pastes was discussed from the viewpoint of composition of hydration products and microstructure of hardened paste. The results will be very useful to improve the volumetric deformation of cement-based materials by reasonable utilization of cement clinker and SCMs.

2. Experimental procedures

2.1. Raw materials

The chemical compositions of raw materials used in the experiment are given in Table 1. Cement clinker, GBFS, and low calcium fly ash (a Class F fly ash according to ASTM C 618 [15]) were ground and then classified by an air classifier. The PSDs of cementitious material fractions required by the gap-graded PSD are given in Fig. 1.

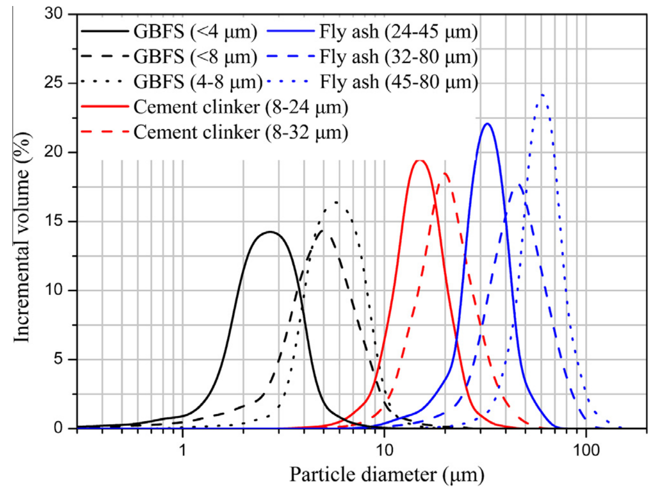

Fig. 1. Particle size distributions of cementitious material fractions used in the experiment.

2.2. Preparation of gap-graded blended cements

Gap-graded blended cements (BCF and BBCFF) were prepared by mixing cementitious material fractions homogeneously according to the mix proportions listed in Table 2, while reference cement and Portland cement were prepared by co-grinding the mixture. The Blaine specific surface areas of these two cements were controlled to be in the range of 350–360 m^2/kg, which is seen to be equal to those of the gap-graded blended cements approximately. Fig. 2 shows that gap-graded blended cements presented wider PSDs than cements prepared by co-grinding (reference cement and Portland cement), which will leads to a higher initial packing density of cement paste. Although gap-graded blended cements had same mix proportion with reference cement, however, it should be noted that GBFS, cement clinker and fly ash were placed in the fine, middle size, and coarse fractions of gap-graded blended cements, respectively.

2.3. Testing methods

2.3.1. Water requirement and packing density of cement pastes

The specific gravity of cements was measured by Le Chatelier flask, and then the maximum volume concentration of solids of cement paste was tested according the procedures specified in Zhang's research [13], to characterize the initial packing density of cement paste. In addition, water requirement for normal consistency of blended cements were determined according to EN 196-3 [16]. As the water requirements for normal consistency of Portland cement, reference cement and gap-graded blended cements were quite different from each other as shown in Table 3, therefore cement pastes and mortar with same fluidity were used for volumetric deformation measurements, in consideration that cement-based materials were mainly used under equal workability (fluidity).

2.3.2. Chemical shrinkage of blended cements

Chemical shrinkage of the blended cements prepared, typical Portland cement and GBFS fractions was measured by volumetric method at 20 ± 1 °C, details of the method were specified in the literature [17]. To simulate the hydration of GBFS in blended cement, a mixture of 90% GBFS and 10% CaO by mass were mixed, and 0.2 mol/L NaOH solution was used as a simulated pore solution in chemical shrinkage measurement of GBFS [18,19]. Along with chemical shrinkage measurement, the hydration degrees of Portland cement and GBFS fractions was also determined by non-evaporation water method [20] and ethylene diamine tetraacetic acid disodium salt (EDTA) preferential solving method [18], respectively.

2.3.3. Autogenous shrinkage of cement pastes

The autogenous shrinkage of blended cement pastes of normal consistency was measured using non-contact corrugated tube method at a 20 ± 1 °C environmental chamber [21]. Three parallel samples were performed and the average value of results was used as the autogenous shrinkage of cement pastes.

2.3.4. Restrained shrinkage cracking of gap-graded blended cement pastes

Cement paste of normal consistency was cast into an ellipse-ring shaped mold, and a stainless steel ellipse in the center of the mold was used to restrain the shrinkage of the surrounding cement paste [22]. After being cured at 20 ± 1 °C and 90% relative humidity (RH) for 24 h, the outer molds of ring specimen were demolded, the top surface of cement paste was sealed using epoxy resin without hardener, and then the specimens were placed in an environmental chamber with 20 ± 1 °C and 50% RH. The initial cracking time and the width of cracks of cement pastes were recorded to characterize their cracking resistance.

2.3.5. Drying shrinkage of cement mortars

Mortar prisms of 25 × 25 × 280 mm were prepared at cement to sand mass ratio of 0.5, and the fluidity of the mortars was controlled in the range of 130–140 mm by adjusting water addition. After being cured at 20 ± 1 °C and 90% RH

Table 1
Chemical compositions of Portland cement clinker, GBFS, and low calcium fly ash used in the experiment.

Material	Density (g/cm^3)	Chemical composition (%)								
		SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	LOI
Portland cement clinker	3.14	21.6	4.35	2.95	63.81	1.76	0.51	0.16	1.06	1.19
GBFS	2.90	35.22	12.15	0.25	37.08	11.25	0.49	0.25	1.19	−0.36
Low calcium fly ash	2.56	45.43	24.36	6.70	7.53	1.51	1.23	0.36	1.03	7.88

Note: LOI, loss on ignition.