Cement & Concrete Composites 52 (2014) 18–26

Contents lists available at ScienceDirect

Cement & Concrete Composites

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

Influence of preparation method on the performance of ternary blended cements

Tongsheng Zhang, Xiangyang Liu, Jiangxiong Wei, Qijun Yu *

School of Materials Science and Engineering, South China University of Technology, 510640 Guangzhou, People's Republic of China

ARTICLE INFO

Article history:
Received 30 November 2013
Received in revised form 23 March 2014
Accepted 22 April 2014
Available online 2 May 2014

Keywords:
Gap-graded blended cement
Interground blended cement
Particle size distribution
Supplementary cementitious material
Efficiency

ABSTRACT

This paper examined the feasibility of preparing high performance gap-graded blended cements by adding fine and coarse supplementary cementitious material (SCM) fractions into commercial Portland cement, and the efficiency of SCMs in gap-graded blended cements and interground blended cements were comparatively evaluated. The results show that the particle size distribution of gap-graded blended cements was much closer to a Fuller distribution, due to the intentional addition of fine and coarse SCMs, resulting in a higher initial packing density. As granulated blast furnace slag (GBFS) was mainly arranged in the fine fraction of the gap-graded blended cements, its efficiency was increased dramatically, contributing to 43.5% of the total measured hydration products. As a result, gap-graded blended cement pastes presented a homogeneous and dense microstructure due to "grain size refinement" and "pore size refinement", therefore their setting times were decreased significantly, and both early and late strengths were increased remarkably in comparison to the interground blended cements investigated in this study.

1. Introduction

Energy savings, emission reductions, resource conservation and environmental protection are the main ways for humans to achieve sustainable development. However, the current production of Portland cement seems unsustainable due to the consumption of large volumes of natural resources and energy and significant CO_2 emissions. For instance, China, the largest cement producing country, produces more than 2 billion tons of cement each year, and the output is continually increasing, as a large number of new infrastructures are being built. Meanwhile, nearly 2 billion tons of industrial solid wastes are generated annually in China, and about 1 billion tons of industrial wastes are not reused, which occupy a lot of potential farmland and cause serious environmental problems (such as water, air, and soil pollution) [1]. A large proportion of industrial wastes, mainly metallurgical slags and coal combustion ashes, can be used as supplementary cementitious materials (SCMs) to produce blended cement for concrete, which is considered as one of the development directions of the cement industry.

Due to the low hydraulic activity of SCMs, blended cements usually present delayed setting times and low early strengths, which also limit the substitution ratio of SCMs and application of prepared blended cements [2]. In the past decades, chemical activation [3] and ultrafine grinding [4,5] were applied to increase the hydraulic or pozzolanic activity of SCMs and, consequently, to improve the mechanical properties of blended cements at early ages. However, these methods usually lead to cost increases or pose difficulties in industrial operation (scale up).

Numerous researchers have shown that the properties of hardened cement pastes were significantly influenced by the initial particle packing density [6,7] and the subsequent hydration process [8,9]. To increase the initial packing density of blended cement paste, Zhang et al. proposed a gap-graded (discontinuous) particle size distribution (PSD) based on the close packing theory [10,11]. Cement particles were divided into three or five fractions according to the Horsfield model; therefore, a higher packing density can be easily achieved as voids are filled in, grade by grade [10]. Meanwhile, to optimize the hydration process of blended cement paste, SCMs with high activity, cement clinker and SCMs with low activity or inert fillers were suggested to be arranged in the fine, middle size, and coarse fractions of the gap-graded blended cements, respectively [12]. As a result, the properties of gap-graded blended cements with only 25% cement clinker met the requirements of a 42.5 grade blended cement. Therefore, the energy and resource consumption and CO_2 emissions during the preparation of blended cement could be decreased significantly [12]. In summary, the key of gap-graded blended cements lies in two points, one is enhancement of the contribution of solid particle packing (physical effect) to the properties of hardened cement paste, the

* Corresponding author. Tel./fax: +86 020 87114233.
E-mail address: concyuq@scut.edu.cn (Q. Yu).

http://dx.doi.org/10.1016/j.cemconcomp.2014.04.005
0958-9465/

other is densification of the microstructure of blended cement paste by increasing the hydration degree of cement clinker and SCMs with high activity (efficient utilization). As a result, gap-graded blended cement presented comparable early and late age properties with Portland cement, although the addition of cement clinker was significantly reduced and a significantly larger amount of SCMs was added (especially for SCMs with low activity).

However, the preparation procedures of the gap-graded blended cements are conventionally viewed as being too complex for industrial practice. Without changing the manufacturing procedures of blended cement significantly, how can one improve the efficiency of cement clinker and SCMs to produce high performance blended cement?

Commercial Portland cements usually present a relatively narrow PSD, especially for those manufactured by a vertical mill [13]. That is to say, the amounts of both fine and coarse particles in commercial Portland cements were much lower compared with those of a Fuller distribution as shown in Fig. 1, and the latter is regarded as classical PSD to achieve maximum packing density. Therefore, gap-graded blended cements can be produced by adding fine and coarse SCMs fractions into commercial Portland cement, which will increase the initial packing density of cement paste and promote efficient utilization of cementitious materials (both Portland cement clinker and SCMs). As a reference, in the present study, blended cements were also prepared by intergrinding the mixture of cement clinker, SCMs, and gypsum. By comparing the fundamental properties of gap-graded blended cements and interground blended cements, the feasibility of this method and the efficiency of SCMs in blended cements were evaluated in the present study. The results will be very useful for preparation of high performance blended cement with a larger amount of SCMs and more efficient utilization of cementitious materials in cement manufacture and concrete making.

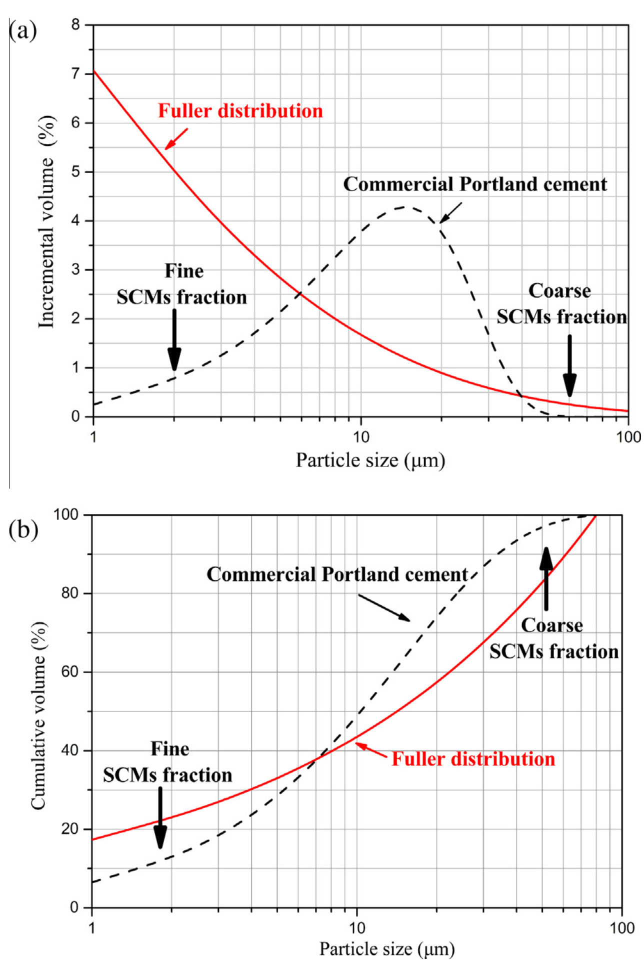

Fig. 1. Comparison of particle size distribution of commercial cement and Fuller distribution. (a) Incremental volume vs. particle size. (b) Cumulative volume vs. particle size.

2. Raw materials and experimental procedures

2.1. Raw materials

Granulated blast furnace slag (GBFS), low calcium fly ash (Class F fly ash according to ASTM C 618 [14]), and basic oxygen furnace slag (BOFS) were used as SCMs, Portland cement clinker produced by a rotary kiln was selected, limestone and flue gas desulfurization (FGD) gypsum were used as inert filler and set controlling material, respectively. Their chemical compositions are detailed in Table 1, and the mineral composition of the cement clinker is given in Table 2. Portland cement was prepared by grinding a mixture of 95% cement clinker and 5% FGD gypsum, and the Blaine specific surface area was controlled to be in the range of $350 \pm 10\ m^2/kg$. The fundamental properties of the produced Portland cement are given in Table 3.

2.2. Preparation of interground blended cements

According to the mixture proportions listed in Table 4, interground blended cements were prepared by intergrinding the mixture of cement clinker, SCMs and FGD gypsum as industrial practice. The Blaine specific surface areas of the blended cements were controlled to be in the range of $350 \pm 10\ m^2/kg$ as industrial practice.

2.3. Preparation of gap-graded blended cements

Firstly, Portland cement was prepared by grinding the mixture of 95% cement clinker and 5% FGD gypsum, and the Blaine specific surface area was also controlled to be in the range of $350 \pm 10\ m^2/kg$. Then GBFS, fly ash, BOFS and limestone were ground and classified by an air classifier, respectively. By changing operational parameters of the air classifier, fine (<8 μm) and coarse (>32 μm) SCMs fractions were obtained, the PSDs of typical SCMs fractions and the Portland cement are given in Fig. 2. Gap-graded blended cements were prepared by mixing the Portland cement and corresponding SCMs fractions homogeneously, the Blaine specific surface area was about 410 m^2/kg.

The gap-graded blended cements had the same mixture proportions as the corresponding interground blended cements, however, it should be noted that the GBFS was placed in the fine fraction (<8 μm) to increase its hydration degree, and SCMs with low activity or inert filler (such as fly ash, limestone) were arranged in the coarse fraction (>32 μm), as coarse cementitious materials largely played a "filling effect" regardless of their hydraulic activity [15–17]. Therefore, it is expected that the efficiency of cement clinker and SCMs in gap-graded blended cements will be improved significantly.

2.4. Testing methods

The PSDs of blended cements were determined by a laser diffraction method (Malvern Mastersizer 2000, refractive index of dispersant (ethyl alcohol): 1.32 and obscuration: 12.4%). The specific gravity of cements was measured by Le Chatelier flask, and then the maximum volume concentration of solids of cement paste was