Construction and Building Materials 140 (2017) 248–256

Contents lists available at ScienceDirect

Construction and Building Materials

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

Design and experimental study of a ternary blended cement containing high volume steel slag and blast-furnace slag based on Fuller distribution model

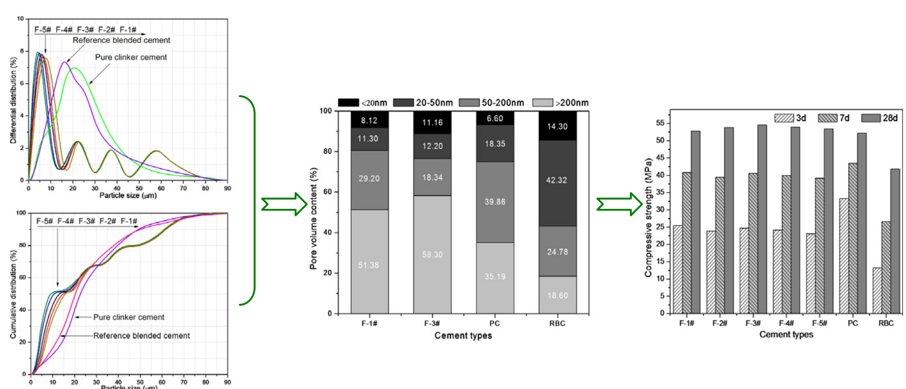
Jihui Zhao [a,b,*], Dongmin Wang [b], Peiyu Yan [a]

[a] Department of Civil Engineering, Tsinghua University, Beijing 100084, China
[b] School of Chemical & Environmental Engineering, China University of Mining & Technology, Beijing 100083, China

HIGHLIGHTS

- A ternary blended cement containing high volume steel slag and GBFS is designed.
- Blended cement has four particles ranges that are composed of different materials.
- Blended cement property can be adjusted by changing materials ratio of 0–15 μm range.
- Blended cement designed has good physical and mechanical properties and low porosity.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 25 October 2016
Received in revised form 25 January 2017
Accepted 21 February 2017

Keywords:
Blended cement
Fuller distribution model
Steel slag
Granulated blast-furnace slag
Compressive strength
Microstructure

ABSTRACT

To improve the utilization efficiency and application property of smelting solid waste in blended cement, a ternary blended cement (Fuller-SS-S-C binder) containing high volume steel slag (SS) and granulated blast-furnace slag (GBFS or S) was designed and prepared based on Fuller distribution model. The results show that the cumulative distribution of Fuller-SS-S-C binder particles is close to Fuller distribution as a whole, but the particles of 0–15 μm, 15–30 μm, 30–45 μm and 45–80 μm fractions are SS-S-C (composite powder containing SS, S and cement), C (cement), SS-S (composite powder containing SS and S) and SS, respectively. The properties of Fuller-SS-S-C binder can be adjusted by changing compositions of SS-S-C in the range of 0–15 μm. Fuller-SS-S-C binders prepared have higher strength than reference blended cement, and their hydration heat contain three exothermic peaks and concentrate on after 15 hours. Compared with pure cement, the non-evaporable water content of Fuller-SS-S-C binder has great gap, but the pore size distribution of Fuller-SS-S-C binder is dominated by innocuous pores of less than 20 nm, moreover, the porosity, total pore volume and medium pore diameter of Fuller-SS-S-C binder are lower than those of reference blended cement and pure cement, indicating that Fuller-SS-S-C binder has dense microstructure.

* Corresponding author at: Department of Civil Engineering, Tsinghua University, Beijing 100084, China.
E-mail address: zhaojihui324@163.com (J. Zhao).

http://dx.doi.org/10.1016/j.conbuildmat.2017.02.119
0950-0618/

1. Introduction

Steel slag (SS) is an industrial solid waste generated during the steelmaking process [1,2], the amount of which produced is huge, about 100 millions every year in China, but its utilization rate is very low [3,4]. For the past many years, most of SS as waste was in idle, which brings about some problems such as environmental pollution, occupation of land and waste of resources [5–7]. So it urgently needs to improve the utilization efficiency of SS, which has also been a most concern of the government and researchers at the present stage.

As the chemical and mineral compositions of SS are similar to those of portland cement clinker, so it has a great application potential as supplementary cementitious materials (SCM) in the cement and concrete industry [8–10]. However, SS has poor crystal type and compact structure of silicate minerals, such as γ-type dicalcium silicate (C_2S), and only a small amount of tricalcium silicate (C_3S), resulting in a low hydration activity and hardening strength of SS [11–13]. The early and later strength of cement-based materials would be obviously reduced after mixing with large amount of SS powder in cement or concrete, seriously restricting the utilization rate and application property of SS in cement-based materials, currently, the mixing amount of SS powder in cement is basically less than 10% of the total mass of cement [14,15]. From the perspective of improving the activity of SS, researchers from all over the world have carried out a lot of research works and concluded that mechanical grinding, chemical activation and thermally activation can improve the activity of SS and hydration-hardening properties of blended cement containing SS [16–21]. However, the improvement of the above three ways on the hydration activity of SS is limited and some ways also are not applicable to industrial applications due to high cost, which is insufficient to significantly improve the utilization rate of SS in cement-based materials.

For the blended cement containing high volume of SS, there are chemical match (hydration reaction effect) and physical match (physical filling effect) between components of blended cement [22,23]. The application effect of SS in cement alone is not ideal, but the composite powder of SS and granulated blast-furnace slag (GBFS or S) has a good effect, indicating that the two generate a chemical superimposition effect, i.e., there is a good chemical match between SS and S [24,25]. The physical match between components of blended cement is related to close packing of particles, which is also key way to improve the property of blended cement [26–28]. M.S. Tang [29] proposed that cement-based materials can also has high mechanical property without complete hydration, which depends on whether the interior of cementitious materials has the close packing state and good interface bonding. Many scholars' researches also indicate that the optimum match of SCM and portland cement can be obtained by improving the close packing and interface bonding of particles, thus achieve the purpose of improving application performance and utilization rate of S, fly ash, SS and other industrial waste in cement-based materials [30,31]. Some early studies on high-performance cementitious materials [32–38], such as HPC (Hot Pressing Cement), DSP (Densified System Containing Homogeneously Arranged Ultrafine Particles), FR-DSP (Fibre-Reinforced Densified Small Particle), MDF (Macro-Defect-Free Cement) and RPC (Reactive Powder Concrete), are the practical verification of this theory (i.e., the most close packing and good interface bonding theory).

In this paper, on the basis of the close packing theory of Fuller particle distribution, a ternary blended cement containing high volume SS and S (denoted by Fuller-SS-S-C binder) was proposed and the hydration-hardening properties of five kinds of Fuller-SS-S-C binders prepared were studied from physical and mechanical property, hydration heat, hydration degree and microstructure. The properties of Fuller-SS-S-C binders and pure cement and traditional blended cement containing high volume SS and S were also compared to evaluate the advantages of Fuller-SS-S-C binder.

2. Compositions design of ternary blended cement based on Fuller distribution model

2.1. Fuller distribution model

Fuller distribution model was firstly proposed by William B. Fuller and Sanford E. Thomson [39], and it was used to calculate the particle size distribution required for mortar and concrete aggregates to achieve the optimum packing density. Its mathematical expression is as follows:

$$P(x) = 100 \cdot \left(\frac{x}{D}\right)^n$$

where, *P(x)* is the cumulative volume of particles through x μm sieve pore (%); *x* is the size of sieve pore (μm); *D* is the maximum diameter of particles (μm); *n* is the distribution index of particles, for cement and SCM, the value of *n* is generally taken as 0.4.

As the 80 μm sieving residues of cement and SCM are generally required to be very small, almost zero, (i.e., the cumulative volume of particles through 80 μm sieve pore is 100%), so the value of *D* (maximum diameter of particles) in Fuller distribution equation can be approximately regarded as 80 μm. Thus, the cumulative volume of particles through sieve can be calculated by Fuller distribution equation when the maximum diameter of cement or SCM particles is 80 μm, the result is shown in Table 1.

Many research literatures [40–43] show that Fuller distribution is a wide particle size distribution and Portland cement with Fuller distribution (denoted by Fuller-cement) has a great specific surface area. Fuller-cement has a high early strength, but the high water requirement of normal consistency and relatively low later strength are its shortcomings. The high water requirement is caused by high content of fine cement particles, and low later strength is due to high porosity which is caused by high water requirement and large amount of unhydrated cement particles (more than 40% by mass) [31].

2.2. Compositions design of ternary blended cement

To improve the shortcomings of Fuller-cement, the key is to control the early hydration rate of Fuller-cement, not too fast, too fast early hydration rate would lead to the high water requirement of normal consistency for cement, causing high porosity; but also not too slow, too slow hydration rate would lead to low early strength. Therefore, some researchers propose that the fine particles of Fuller-cement can be replaced by some active SCM to control the early hydration rate of Fuller-cement [44–47]. In

Table 1
Cumulative volume of particles through 80 μm sieve according to Fuller distribution model.

Particle size (μm)	Cumulative volume (%)	Particle size (μm)	Cumulative volume (%)
1	17.33	30	67.55
3	26.89	35	71.84
5	32.99	40	75.79
8	39.81	45	79.44
10	43.53	50	82.86
15	51.19	60	89.13
20	57.43	70	94.80
25	62.80	80	100