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A new gap-graded particle size distribution and resulting consequences on properties of blended cement

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ABSTRACT

To improve the properties of blended cement and utilize cement clinker and supplementary cementitious materials (SCM) more efficiently, a new gap-graded particle size distribution (PSD) based on close packing theory was proposed, then blended cements with the gap-graded PSD were prepared by mixing cement clinker and SCM fractions homogeneously. The experimental results show gap-graded blended cement pastes present a lower water requirement, a higher packing density, and a more homogeneous, denser microstructure than reference cement (prepared by co-grinding). As a result, both early and late properties of the gap-graded blended cements with only 25% clinker content can be comparable with those of Portland cement. This investigation supports that a high performance blended cement with low clinker content can be prepared using the gap-graded PSD and arranging a high activity SCM, clinker, and a low activity SCM (or inert filler) in the fine, middle and coarse fractions, respectively.

1. Introduction

There is an increasing worldwide trend toward utilization of pozzolanic (or cementitious) by-products either as supplementary cementitious materials (SCMs) in manufacture of blended Portland cement or as mineral admixtures in concrete making for engineering, ecological and economic benefits [1]. It is also a countermeasure to reduce CO_2 emissions and produce substantial energy and cost saving, due to a reduction in cement clinker content as it is partially replaced by SCMs. However, one shortcoming has not been solved perfectly; that is relatively low early strength of blended cements, which also limits the substitution level of SCMs. Many attempts, such as chemical activation [2,3] and ultrafine grinding [4], have been made to improve the early properties of blended cements. Most of these methods are focused on enhancement of the pozzolanic activity of the SCMs, which leads to cost increases or difficulties in operation. Studies on the size distribution of SCMs particles in blended cements are very scarce in the technical literature.

Inventions of ultra-high strength cement-based materials, such as hot pressing cement, macro-defect-free cement (MDF) and densified systems containing homogeneously arranged ultra-fine particles (DSP), prove that a large amount of hydration products or a high hydration degree does not mean high compressive strength; the key lies in the porosity and the pore size distribution of the hardened paste, which are largely affected by the packing density of cement paste [5]. It is reported that fine cement clinker particles mainly contribute to early strength, and may cause undesirable volume changes and deterioration in rheological properties of cement paste due to rapid hydration [6]. Coarse cement clinker particles largely play a "filling effect" and don't make much contribution to strength development [7–9]. In contrast, cement clinker particles in the range of 3–32 μm have a low water requirement and a high hydration rate. Thus these particles make a dominant contribution to the strength of pure Portland and blended cements [10].

Based on analyses of particle size distributions (PSDs) used in cement-based materials, a new gap-graded PSD is proposed according to a close packing theory, in which cement particles are divided into three fractions. A high activity SCM (such as GGBFS, and high calcium fly ash), cement clinker, and a low activity SCM (or inert filler) are arranged in fine (<8 μm), middle (8–32 μm) and coarse (>32 μm) fractions, respectively. It is found that both early and late properties of the so-obtained gap-graded blended cements can be comparable with those of Portland cement. The authors believe that the results will be very useful for the preparation of a high performance blended cement with low clinker content and a more efficient utilization of Portland cement clinker and SCMs in blended cement manufacturing and concrete making.

2. A new gap-graded particle size distribution

PSDs used in cement-based materials can be classified into two broad categories. One is a wide PSD, the other one is narrower. The

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Fuller distribution curve is a typical wide PSD that was originally applied to concrete aggregate gradations to achieve maximum density. After being modified by Kuhlmanm [11], it can also be applied to no or relatively low hydraulic activity powders. The purpose of the Fuller distribution curve is only to achieve a maximum original packing density, regardless of the hydration behaviors of fine particles, which may lead to a high water requirement, fast setting or deterioration in rheological properties. To avoid those shortcomings, a narrow PSD is recommended in high hydraulic activity powders (such as Portland cement). For instance, a distribution advocated by Tsivilis is widely used in Portland cement, with its performance being characterized by improved workability and high ultimate strength, while the early strengths are relatively low due to the low packing density of cement particles in the initial paste [10]. Different from Portland cement, blended cement consists of cement clinker and one or more SCMs. That is to say, depending on SCMs, blended cements contain both high activity particles and low activity particles (perhaps even inert particles). Thus, in the case of co-grinding, the above-mentioned PSDs are often not suitable to apply in blended cements.

A new gap-graded PSD will be proposed based on a close packing theory; details are given as follows: Since the typical maximum particle size of cement is about 80 μm, the amount of particles coarser than 80 μm can be neglected. Particles larger than 45 μm exist in a certain measurable amount, thus 45 μm is selected as the diameter of first grade particles. According to diameter ratio of each filling grade of Horsfield packing, the diameters of particles of each filling grade are 18.63 μm, 10.13 μm, 7.97 μm, and 5.22 μm, respectively [12]. Taking traditional practices (cement particles are usually divided by 4 μm, 8 μm, 16 μm, 32 μm, 45 μm, and 80 μm) into account, 18.63 μm and 10.13 μm are combined as 16 μm, 7.97 μm and 5.22 μm are also combined as 6 μm for easy operation. Thus the diameters of the three filling grades are 45 μm, 16 μm, and 6 μm, then cement particles are divided into three fractions as <8 μm, 8–32 μm and >32 μm accordingly.

The PSD of each fraction should be as narrow as possible and concentrated to the diameter of the corresponding filling grade (Fig. 1 and Table 1). To achieve the maximum packing density without a fineness increase, the PSD of the blended cement should be as close as possible to the Fuller distribution curve. In that case, both a relaxation effect caused by large fillers and an empty void effect due to small fillers can be avoided, thus a high density can easily be achieved as voids are filled in grade by grade. The volume percentage of particles in each fraction can be calculated according to a modified Fuller distribution curve (a water film covering the particle surfaces is taken into account). Parameters of the new gap-graded PSD are summarized in Table 1 and Fig. 1.

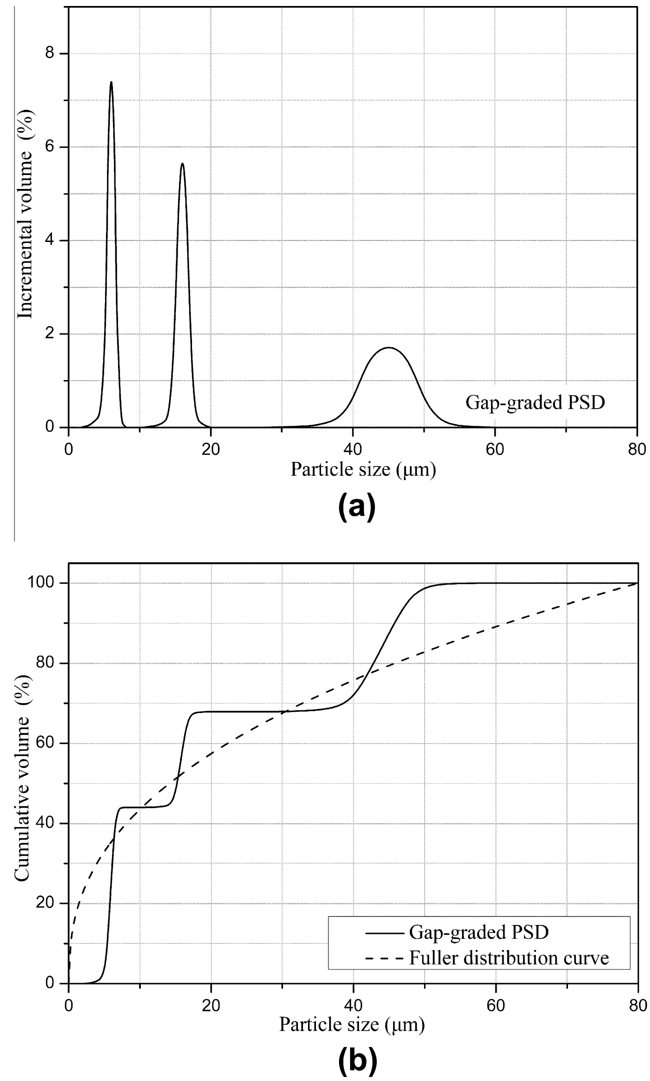

Fig. 1. Schematic outline of the gap-graded PSD. (a) Incremental volume vs. particle size. (b) Cumulative volume vs. particle size.

Table 1
Parameters of the gap-graded PSD.

Filling grade	Third	Second	First
Mean size (μm)	6	16	45
Size range (μm)	<8	8–32	>32
Incremental volume (%)	36	25	39
Cumulative volume (%)	36	61	100

3. Experimental procedures

3.1. Raw materials and classification of cementitious materials

To obtain different cementitious materials fractions, a Portland cement clinker, blast furnace slag (BFS), limestone, low calcium fly ash (a Class F fly ash according to ASTM C 618 [13]) and steel slag (a by-product of a steel converter that has been piled up outdoors for years) were ground and then classified by an air classifier, which is based on gravitational/sedimentation principles. By changing operational parameters, such as air flow rate, feed rate and rotor speed of the classifier, size fractions of cementitious materials required by the gap-graded particle size distribution were obtained. The chemical compositions of raw materials used and classified fractions are given in Table 2. It should be noted that deviation in chemical composition occurs during classification for Portland cement clinker, fly ash and steel slag, while no obvious difference in chemical composition is found for BFS.

The PSDs of the three cement clinker fractions measured by a laser diffraction method are provided in Fig. 2 and Table 3. PSDs of the SCM fractions are similar to that of the corresponding cement clinker fractions. From this, it can be seen that all fractions prepared have a narrow PSD and that the mean size of each fraction is nominally consistent with that of each filling grade, which are 6 μm, 16 μm and 45 μm, respectively.

3.2. Testing methods

3.2.1. Preparation of gap-graded blended cement with low clinker content

According to hydration behavior of different cement clinker and SCMs fractions [5,7,14], gap-graded blended cements with low

Table 2
Chemical compositions of Portland cement clinker, BFS, limestone, low calcium fly ash and steel slag used.

Material		Chemical composition (%)								
		SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	LOI
Limestone	Original	2.34	2.47	0.71	52.35	1.03	–	–	–	40.56
Portland cement clinker	Original	21.60	4.35	2.95	63.81	1.76	0.51	0.16	2.06	1.19
	<4 μm	19.20	4.20	2.77	61.6	1.84	0.91	0.15	4.41	3.23
	4–8 μm	20.75	4.37	2.71	62.92	1.84	0.52	0.16	2.75	1.95
	8–24 μm	21.26	4.35	2.75	63.61	1.80	0.58	0.21	2.51	1.59
	24–45 μm	21.84	4.42	2.96	64.04	1.75	0.49	0.14	1.80	1.05
	45–80 μm	22.29	4.35	3.08	64.26	1.70	0.47	0.16	1.35	0.57
Blast furnace slag	Original	35.22	12.15	0.25	37.08	11.25	0.49	0.25	1.19	−0.36
	<4 μm	34.98	12.00	0.24	36.54	11.42	0.51	0.25	1.48	1.37
	4–8 μm	35.72	12.26	0.26	36.56	11.28	0.48	0.25	1.21	−0.77
	24–45 μm	34.91	12.06	0.34	37.25	11.23	0.49	0.25	1.17	−1.19
	45–80 μm	35.04	12.12	0.42	37.43	11.25	0.49	0.24	1.18	−1.29
Low calcium fly ash	Original	45.43	24.36	6.70	7.53	1.51	1.23	0.36	1.03	7.88
	<4 μm	41.62	23.09	5.03	12.34	1.42	1.85	0.73	1.71	11.10
	4–8 μm	44.41	24.04	6.21	10.23	1.53	1.23	0.41	1.28	8.42
	24–45 μm	46.50	24.46	6.68	7.35	1.55	1.08	0.32	0.93	6.72
	45–80 μm	46.74	25.31	6.74	6.96	1.56	0.97	0.31	0.87	6.57
Steel slag	Original	14.84	3.59	24.14	39.14	9.33	0.05	0.05	0.16	5.91
	<4 μm	18.09	5.53	8.64	44.07	7.36	0.09	0.13	0.36	11.97
	4–8 μm	16.61	4.86	17.72	42.21	9.16	0.06	0.06	0.23	2.49
	24–45 μm	14.45	3.31	26.70	39.12	9.62	0.04	0.04	0.15	−1.35
	45–80 μm	14.03	3.18	28.48	38.85	9.53	0.05	0.04	0.14	−1.67

Note: LOI, loss on ignition; –, undetected.

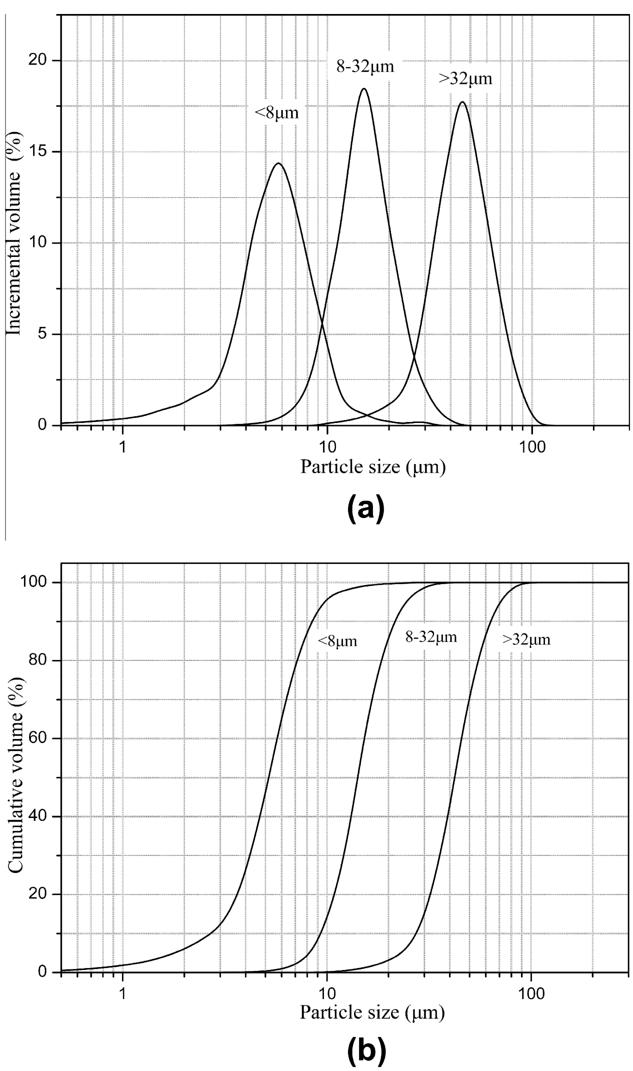

Fig. 2. Particle size distribution of each fraction of ground Portland cement clinker. (a) Incremental volume vs. particle size. (b) Cumulative volume vs. particle size.

Table 3
PSD of each fraction of ground cement clinker.

Fraction (μm)	<8 μm	8–32 μm	>32 μm
D_{10}	2.63	9.28	28.33
D_{50}	5.21	15.08	44.21
D_{90}	8.47	21.54	75.46

Note: D_{10}, D_{50} and D_{90} are the maximum particle diameters when cumulative volume reaches 10%, 50%, and 90%, respectively.

clinker content were prepared by mixing fine (<8 μm), middle (8–32 μm) and coarse (>32 μm) fractions homogeneously, in which a BFS, cement clinker, and a low activity SCM (or inert fillers) were arranged in fine, middle and coarse fractions, respectively. The mixture proportions of gap-graded blended cements (calculated according to modified Fuller distribution curve, Table 1) are listed in Table 4. A Portland cement and a reference cement consisting of 36% BFS, 25% cement clinker, and 39% fly ash prepared by co-grinding were also considered. 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 that of the gap-graded blended cements.

3.2.2. Packing density of cement pastes measurements

The maximum volume concentration of solids is used to characterize the packing density of cement pastes, namely as the maximum density of cement pastes [15]. This method is based on the fact that when the cement paste is at the prescribed consistency and the water content is just enough to fill up the voids between the cementitious materials grains, then the maximum density of cement paste is obtained. Specific densities of blended cements were measured firstly, then blended cements were mixed with water at different w/c ratios and the density of the paste was measured. The maximum volume concentration of solids φ of cement paste obeys Eq. (1):

$$\rho_c \cdot \varphi + \rho_w \cdot (1 - \varphi) = \rho_{wet} \rightarrow \varphi = (\rho_{wet} - \rho_w)/(\rho_c - \rho_w) \quad (1)$$

where ρ_{wet} is the maximum density of cement paste, and ρ_w and ρ_c are the densities of water and cement, respectively.

Table 4
Mixture proportions of gap-graded blended cements.

Fraction (μm)		<8	8–32	>32
Content (%)		36	25	39
Cement Id.	BCB	B (BFS)	C (cement clinker)	B (BFS)
	BCF	B (BFS)		F (fly ash)
	BCS	B (BFS)		S (steel slag)
	BCL	B (BFS)		L (limestone)
	SCS	S (steel slag)		S (steel slag)
	Portland cement	100% cement clinker		
	Reference cement	36% BFS + 25% cement clinker + 39% fly ash		

Note: 5% of gypsum dihydrate by mass of cementitious material was added for all cements in Table 4.

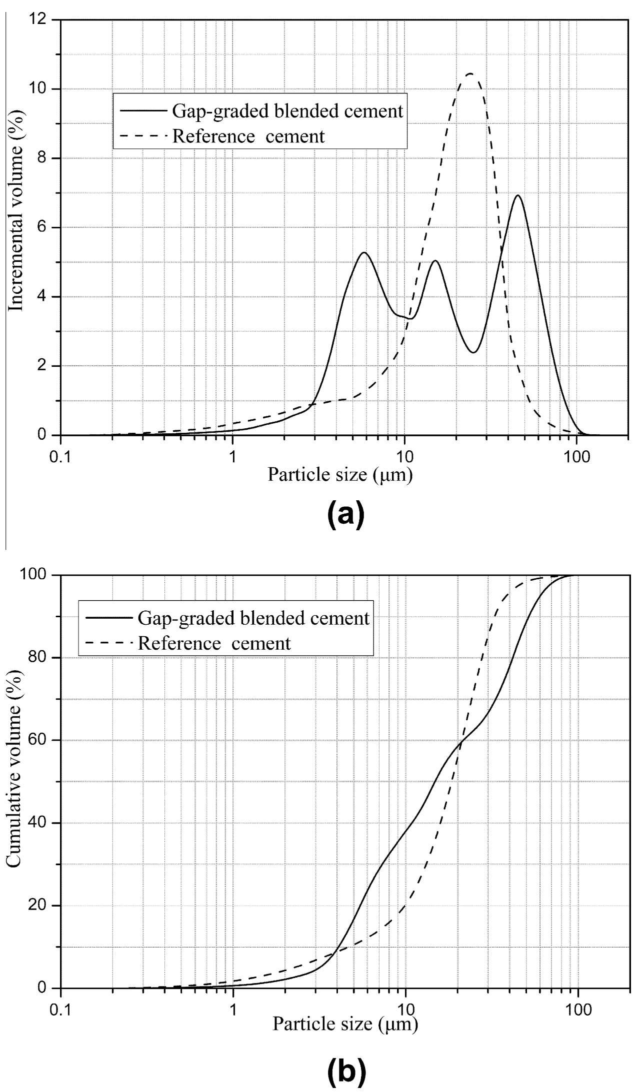

Fig. 3. Particle size distribution of gap-graded blended cement (BCF) and reference cement. (a) Incremental volume vs. particle size. (b) Cumulative volume vs. particle size.

At the same time, the water requirements of blended cements were determined as the necessary quantity of water to obtain a neat cement paste of normal consistency as specified in EN 196-3 [16].

3.2.3. Strength measurements

Cement mortars were prepared at water: obtained cement: river sand = 0.5:1:3 by mass and cast into 40 × 40 × 160 mm molds. After being cured at 20 ± 1 °C and a relative humidity (R.H.) of 90% for 24 h, the specimens were demoulded and cured in lime-saturated water at 20 ± 1 °C, followed by the strength tests according to EN 196-1 [17].

3.2.4. Heat evolution measurements

Heat evaluation of cement paste at a water to cementitious materials ratio (*w/c*) of 0.5 was measured with an isothermal calorimeter (TAM air) according to ASTM C 1702-09A [18], and the measurements were performed at a constant temperature of 25 °C for 72 h.

3.2.5. Microstructure of hardened pastes measurements

Cement pastes of normal consistency were cast into plastic bags and sealed before placing the pastes in a 20 ± 1 °C water bath. Small pieces taken from different parts of the hardened paste were put into ethyl alcohol to terminate their hydration after curing for 24 h, 3 d and 28 d, then vacuum-oven-dried at 65 °C for at least 48 h. The microstructure of these cement pastes was observed by scanning electric microscope (SEM, Nano 430, 10 kV, 245 μA) under a high vacuum condition and their pore size distributions were measured by mercury intrusion porosimetry (MIP, Poremaster-60, contact angle: 140.7°) with an operating pressure up to about 500 MPa. Then, the dried pieces were ground into a fine powder, followed by differential thermal analysis–thermogravimetry (DTA–TG) measurements at a heating rate of 10 °C/min in a nitrogen atmosphere.

4. Results and discussion

4.1. Particle size distribution of gap-graded blended cements

The incremental PSDs of the reference cement present a high peak as shown in Fig. 3, indicating that a cement prepared by

Table 5
Maximum volume concentration of solids of gap-graded blended cement pastes.

Cement Id.	BCB	BCF	BCS	BCL	SCS	Portland cement	Reference cement
Specific density (g/cm^3)	2.95	2.81	3.25	2.87	3.28	3.15	2.83
Maximum wet density (g/cm^3)	2.027	1.91	2.205	1.963	2.18	2.008	1.819
Maximum volume concentration of solids (%)	52.64	50.17	53.63	51.52	51.75	46.88	44.73

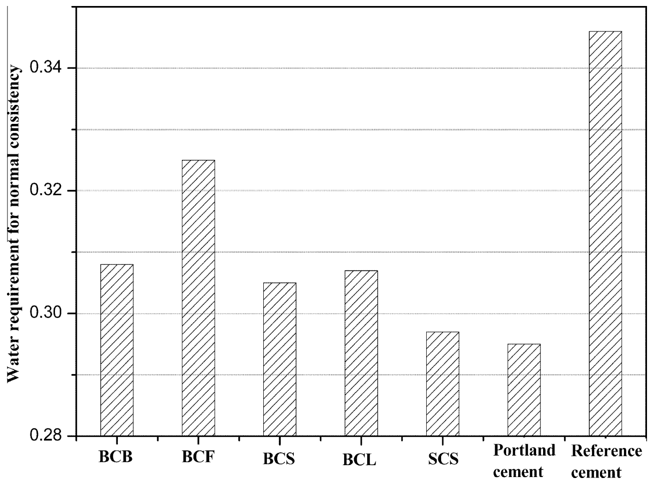

Fig. 4. Water requirement for normal consistency of gap-graded blended cements.

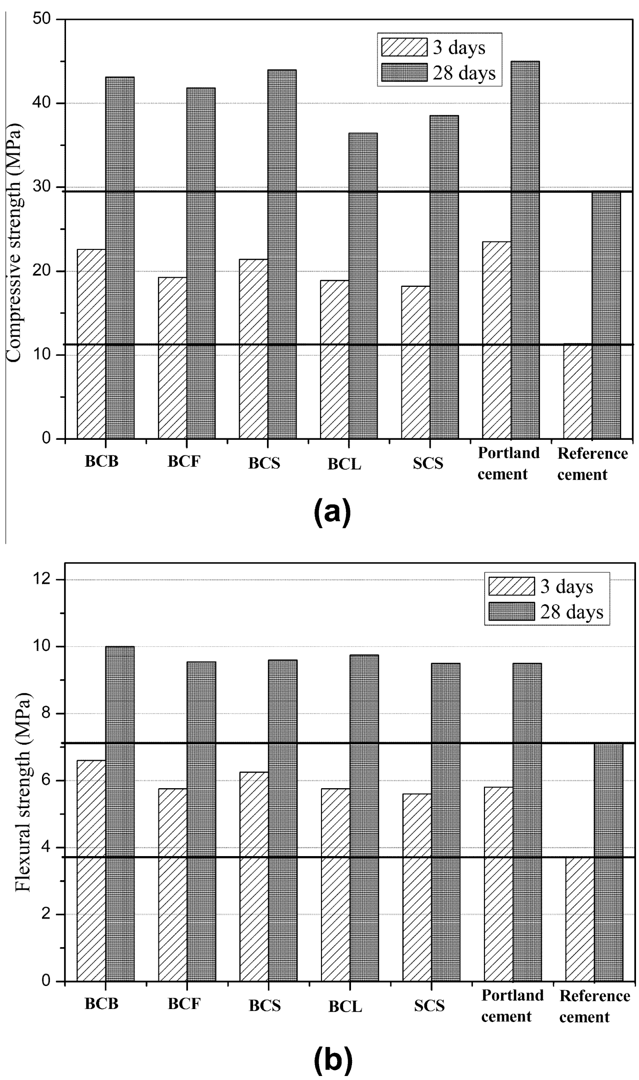

Fig. 5. Strength of mortar prisms with gap-graded blended cements. (a) Compressive strength. (b) Flexural strength.

co-grinding has a relatively narrow PSD. In contrast, the gap-graded blended cement (BCF) presents three peaks in its incremental PSD, with the peaks corresponding to about 6 μm, 16 μm and

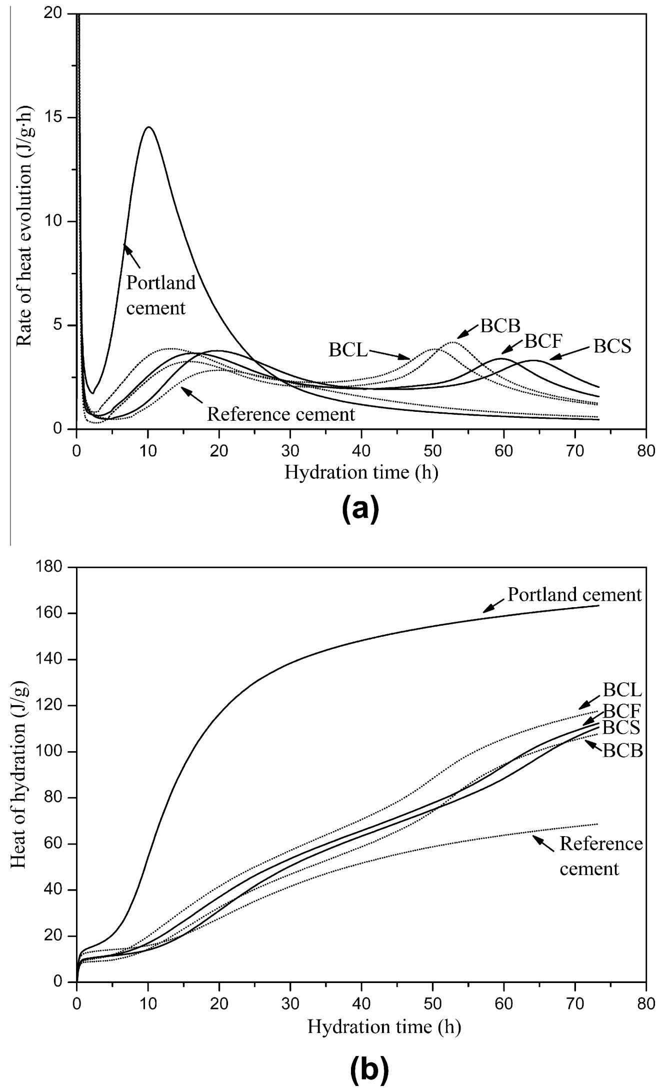

Fig. 6. Heat evolution of gap-graded blended cements. (a) Rate of heat evolution. (b) Cumulative heat of hydration.

45 μm. Although there is a certain overlap among each fraction due to the low efficiency of the classifier, the PSD of the gap-graded blended cement basically meets the requirements of the proposed gap-graded PSD.

4.2. Packing density of cement pastes

The maximum volume concentration of solids of the cement pastes as calculated by Eq. (1) is shown in Table 5. Gap-graded blended cements present much higher maximum volume concentrations of solids than the reference cement. For example, the maximum volume concentration of solids of the BCF cement paste can be as high as 50.17%, which is increased by 5.44% relative to that of the reference cement paste.

Fig. 4 demonstrates that gap-graded blended cements show a much lower water requirement than the reference cement. Due to coarse fly ash fractions that contain a high content of un-burnt carbon and a large amount of porous particles, gap-graded blended cements without fly ash show an even lower water requirement for normal consistency, which is only slightly higher than that of Portland cement. The results prove that the gap-graded blended cement pastes show a higher packing density than cements prepared by co-grinding, as the voids are filled in grade by grade.

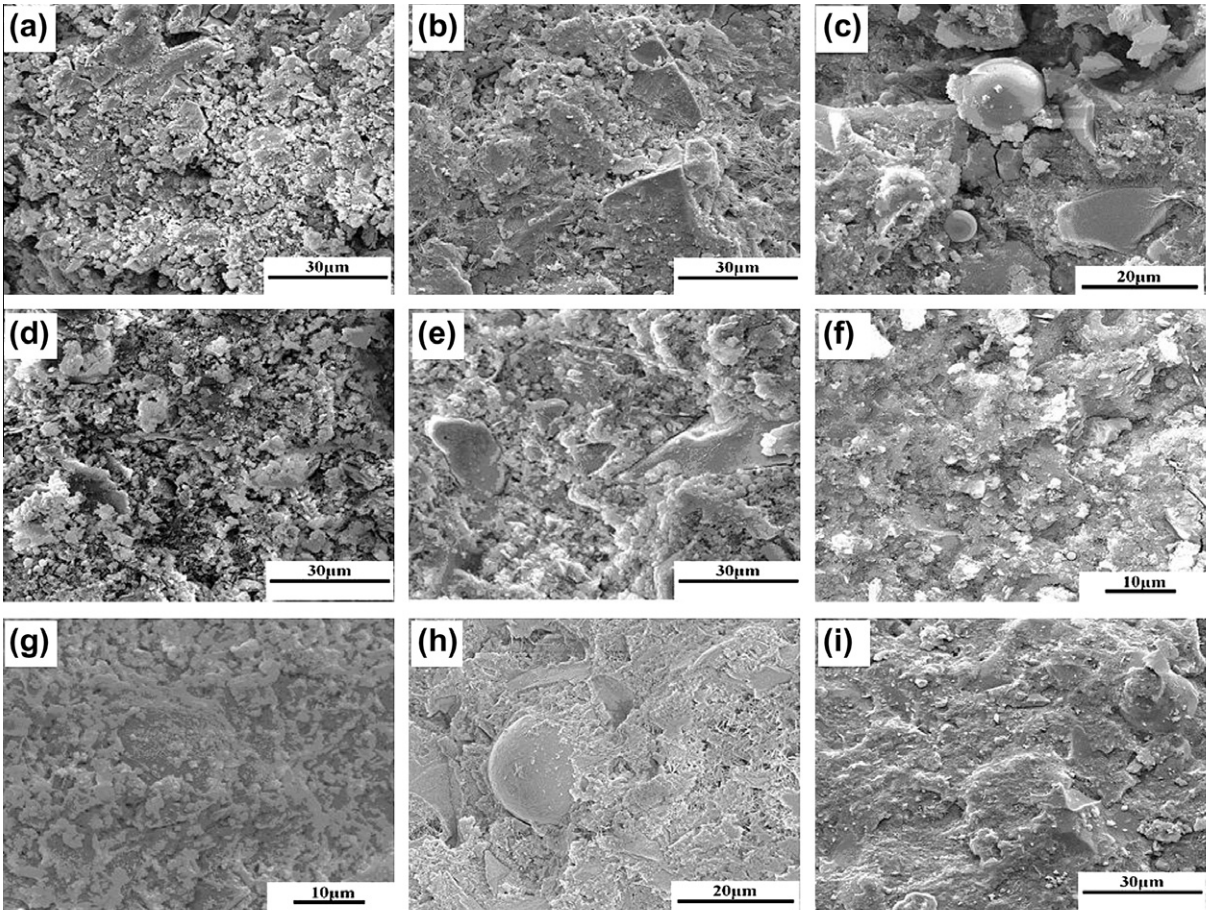

Fig. 7. SEM images of hardened cement pastes. (a) Reference cement paste cured for 24 h. (b) Reference cement paste cured for 3 d. (c) Reference cement paste cured for 28 d. (d) Portland cement paste cured for 24 h. (e) Portland cement paste cured for 3 d. (f) Portland cement paste cured for 28 d. (g) BCF cement paste cured for 24 h. (h) BCF cement paste cured for 3 d. (i) BCF cement paste cured for 28 d.

Table 6
Porosity and pore size distribution of hardened cement pastes.

Cement Id.	Curing age (day)	Porosity (%)	Most probable pore diameter (nm)	Pore size distribution (%)				
				<10 nm	10–50 nm	50–100 nm	100–1000 nm	>1000 nm
Portland cement	3	26.24	743.6	1.7	6.5	10.8	49.6	31.4
	28	19.09	72.5	7.4	25.1	49.4	13.8	4.3
Reference cement	3	34.16	1124.6	0.4	0.9	7.1	33.4	58.2
	28	28.74	216.3	2.2	7.3	24.9	42.2	23.4
BCF	3	27.29	816.4	1.9	6.7	14.2	49.3	27.9
	28	20.36	83.7	8.8	32.5	38.4	9.7	6.8
BCS	3	22.18	726.5	2.3	7.4	15.8	50.0	24.5
	28	15.43	59.3	10.8	41.2	36.1	10.4	4.7

4.3. Compressive and flexural strengths

Fig. 5A shows that the 3 d and 28 d compressive strengths of the reference cement are 11.3 MPa and 29.6 MPa, respectively. In contrast, both 3 d and 28 d compressive strengths of the gap-graded blended cements increase significantly and can be comparable with those of Portland cement. For instance, although using the same mixture proportions (25% cement clinker, 36% BFS and 39% fly ash), the 3 d and 28 d compressive strengths of the BCF cement are 19.3 MPa and 41.8 MPa, respectively, which are increased by 70.8% and 41.2% compared with those of the reference cement. Fig. 5B demonstrates that there is no obvious difference in flexural strength between gap-graded blended cements and Portland cement.

4.4. Heat evolution

Unlike the heat evolution of the Portland cement paste and the reference cement paste, the rate of heat evolution of the gap-graded blended cement presents three peaks as shown in Fig. 6. The first peak (around 0.1 h) and the second peak (in the range of 10–20 h) of heat evolution, which correspond to hydration of cement clinker particles, are much lower than those of Portland cement, due to the lower cement clinker content. The third peak in the range of 40–70 h is attributed to the pozzolanic and perhaps hydraulic reactions of fine BFS particles, suggesting that the pozzolanic reaction of the fine SCM particles in gap-graded blended cements mainly takes place after 2 d and is much more significant than that in the reference cement. In comparison with the heat

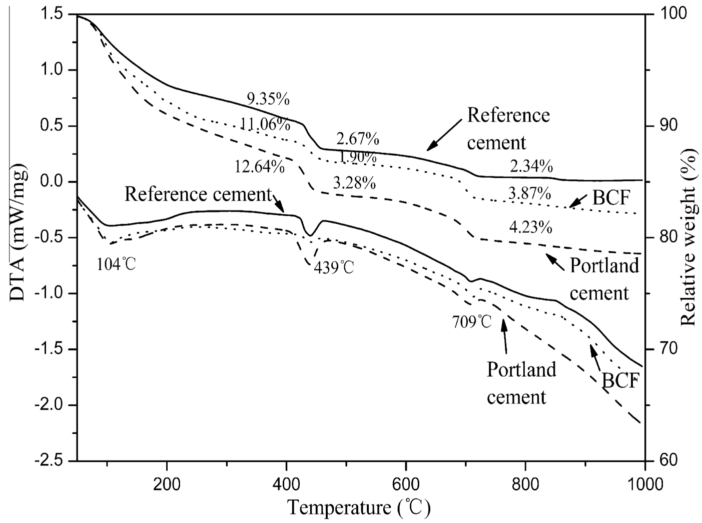

Fig. 8. DTA and TG curves of hardened cement pastes cured for 28 d.

evolution of Portland cement, the heat evolution of the gap-graded blended cement is much slower in the first 20 h, but continues to increase rapidly afterward.

4.5. Microstructure of hardened pastes

SEM images of hardened cement pastes are shown in Fig. 7. A small amount of hydration products and poor bonding among hydration products and coarse SCM particles are found in the reference cement paste up to 28 d curing (Fig. 7a–c). Due to rapid hydration of fine clinker particles, a large amount of hydration products with smaller capillary pores is found in the Portland cement paste cured for 24 h as shown in Fig. 7d, and clinker particles coarser than 30 μm have only surface hydrated (Fig. 7e), thus this part of costly clinker is in effect being wasted and can be replaced by less expensive SCMs. Fig. 7f demonstrates that a large amount of small-sized capillary pores still exist, although few large-sized pores are observed in Portland cement paste cured for 28 d. A large amount of hydration products together with its bonding particles produce a dense microstructure in the gap-graded blended cement (BCF) paste cured for 3 d (Fig. 7g and h). Hydration products increase steadily as hydration proceeds, with a new generation of hydration products filling in large-sized pores and bonding un-hydrated particles firmly together. The resulting consequence is the microstructure becomes denser and few capillary pores are found in the pastes cured for 28 d (Fig. 7i).

In comparison with the reference cement paste, the gap-graded blended cement pastes present lower porosity and the amount of pores larger than 100 nm is reduced significantly, as shown in Table 6. More important, for cement pastes cured for 28 d, the maximum concentration of pores of the reference cement paste lies in the range of 100–1000 nm, while that of the Portland cement paste lies in the range 50–100 nm, and changes to 10–50 nm for the gap-graded blended cement (except for BCF) paste. From the DTA curves in Fig. 8, the endothermal peak at 104 °C is associated with the evaporation of free water and dehydration of hydration products, those at 439 °C and 709 °C correspond to decomposition of $Ca(OH)_2$ and hydration products, respectively [19,20]. It can observed from these TGA curves that the gap-graded blended cement (BCF) paste presents a larger amount of hydration products and a smaller amount of $Ca(OH)_2$ relative to the reference cement paste. Although the amount of hydration products in the BCF cement paste is slightly lower than that in the Portland cement paste, the pore size distribution results prove that the BCF cement presents a denser microstructure than the reference cement or even than the Portland cement, due to grain size reinforcement and pore size reinfinement.

5. Conclusions

High performance blended cements can be prepared using the gap-graded PSD proposed and arranging the three components as a high activity SCM, cement clinker, and a low activity SCM (or inert filler) in the fine (<8 μm), middle (8–32 μm) and coarse (>32 μm) fractions, respectively. Gap-graded blended cement pastes present a low water requirement, a high packing density and a homogeneous, dense microstructure. As a result, both early and late properties of the gap-graded blended cements with 25% clinker content can be comparable with those of Portland cement. In addition, the heat of hydration of the gap-graded blended cement develops more slowly in the first 20 h but continues to increase rapidly afterward compared with that of Portland cement.

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References

[1] Malhotra VM, Metha PK. Pozzolanic and cementitious materials. London: Gordon & Breach; 1996.
[2] Zhang TS, Liu FT, Liu SQ. Factors influencing the properties of a steel slag composite cement. Adv Cem Res 2008;20(4):145–50.
[3] Fernánde JA, Palomo A. Composition and microstructure of alkali activated fly ash binder: effect of the activator. Cem Concr Res 2005;35(10):1984–92.
[4] Sanjay K, Kumar R, Bandopadhyay A. Mechanical activation of granulated blast furnace slag and its effect on the properties and structure of Portland slag cement. Cem Concr Compos 2008;30(8):679–85.
[5] Wang AQ, Zhang CZ, Zhang NS. The theoretic analysis of the influence of the particle size distribution of cement system on the property of cement. Cem Concr Res 1999;29(11):1721–6.
[6] Škvára F, Kolár K, Novotný J. The effect of cement particle size distribution upon properties of pastes and mortars with low water-to-cement ratio. Cem Concr Res 1981;11(2):247–55.
[7] Bentz DP, Conway JT. Computer modeling of the replacement of "coarse" cement particles by inert fillers in low w/c ratio concretes: hydration and strength. Cem Concr Res 2001;31(3):503–6.

[8] Bentz DP, Garboczi EJ, Haecker CJ, Jensen OM. Effects of cement particle size distribution on performance properties of Portland cement-based materials. Cem Concr Res 1999;29(10):1663–71.
[9] Binici H, Aksogan O, Cagatay IS, Tokyay M, Emsen E. The effect of particle size distribution on the properties of blended cements incorporating GGBFS and natural pozzolan (NP). Powder Technol 2007;177(3):140–7.
[10] Tsivilis S, Tsimas S, Benetatou A. Study on the contribution of the fineness on cement strength. ZKG 1990(1):26–9.
[11] Sprung S, Kuhlmanm K, Ellerbrock HG. Particle size distribution and properties of cement Part II: water demand of Portland cement. ZKG 1985(11):275–81.
[12] Lu HG. Introduction to powder technology. Shanghai: Tongji University Publisher; 1998.
[13] ASTM C 618-03. Standard specification for fly ash and raw or calcined natural pozzolan for use as a mineral admixture in portland cement concrete. New York: American Society for Testing and Materials; 2006.
[14] Celik IB. The effects of particle size distribution and surface area upon cement strength development. Powder Technol 2009;188(3):272–6.
[15] Kwan AKH, Fung WWS. Packing density measurement and modeling of fine aggregate and mortar. Cem Concr Compos 2009;31(6):349–57.
[16] EN 196-3. Methods of testing cement: determination of water requirement for normal consistency. London: British Standards Institution; 2005.
[17] EN 196-1. Methods of testing cement: determination of strength. London: British Standards Institution; 2005.
[18] ASTM C 1702-09A Standard test method for measurement of heat of hydration of hydraulic cementitious materials using isothermal conduction calorimetry. New York: American Society for Testing and Materials; 2009.
[19] Vedalakshmi R, Raj AS, Srinivasan S, Babu KG. Quantification of hydrated cement products of blended cements in low and medium strength concrete using TG and DTA technique. Thermochim Acta 2003;407(1):49–60.
[20] Badanoiu A, Georgescu M, Puri A. The study of 'DSP' binding systems by thermogravimetry and differential thermal analysis. J Therm Anal Cal 2003;74(1):65–75.