Construction and Building Materials 154 (2017) 791–803

Contents lists available at ScienceDirect

Construction and Building Materials

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

Comparative studies on the effects of sewage sludge ash and fly ash on cement hydration and properties of cement mortars

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HIGHLIGHTS

- Cement hydration can be accelerated with the addition of sewage sludge ash (SSA).
- Mechanisms behind the effects of SSA on the strength of cement mortars are given.
- Changes to the pore structures of the pastes are insignificant at low SSA contents.
- Brushite formed in SSA cement mortar makes contribution to the strength.
- Increased mesopores in SSA-containing mortars aggravate their drying shrinkage.

ARTICLE INFO

Article history:
Received 2 March 2017
Received in revised form 31 July 2017
Accepted 1 August 2017
Available online 10 August 2017

Keywords:
Sewage sludge ash
Hydration heat
Pore structure
Phase composition
Drying shrinkage

ABSTRACT

Sewage sludge ash (SSA) is the byproduct obtained from incinerating mechanically dewatered sewage sludge. Some published literature mentions that mortars of comparable strength can be produced using a small amount of SSA to replace cement. However, information on how SSA affects the properties of cement mortars is limited given the pozzolanic activities of most SSA being modest. This study identified the mechanisms behind some beneficial effects of the SSA on the strength development of mortars through a comparison study with fine sewage sludge ash (FSSA) and pulverized fly ash (PFA). The findings of this study indicated that the presence of SSA accelerates the rate of heat evolution from cement hydration while PFA does not produce this effect. A higher content of SSA or FSSA produces a greater effect. Replacing cement by SSA or FSSA up to 10% did not induce significant changes to the pore structure of the pastes. The formation of brushite in SSA or FSSA cement mortars contributes to the long-term strength of the mortars. PFA reduces the drying shrinkage of the mortars, but SSA causes greater drying shrinkage due to increasing content of mesopores with sizes less than 0.025 μm. This harmful effect is greater with FSSA.

1. Introduction

Hong Kong faces growing pressure in waste management due to its limited landfilling capacity and strong objections to its extension by the public [1]. Dumping wastes in landfills is not a sustainable means of managing waste. Sewage sludge is generated from the treatment of wastewater. In Hong Kong about 1000 tonnes of dewatered sewage sludge were produced every day in 2014 [2]. Sewage sludge was disposed of in landfills in the past. In 2015, the Hong Kong government commissioned a mega-sized sewage sludge incinerator to treat sludge. The incinerator can burn 2000 tonnes of dewatered sewage sludge a day [3]. Two types of ash are generated in this process; one is incinerated sewage sludge ash, i.e., SSA, and the other is air pollution control residues. Despite its smaller volume after incineration, SSA still needs to be managed properly and the current method in Hong Kong is disposal in landfills. For sustainable waste management, various means of recycling SSA to reduce the burden on landfills are needed.

1.1. Literature review and knowledge gap

The vast majority of published research about SSA focuses on the potential to use it in construction materials such as cement pastes, mortars, concretes [4–6], fired bricks, tiles [7–9], glass ceramics [10–12], etc. Many of these applications simply use SSA as a direct substitute for raw materials such as clay or sand. Another potential application of SSA is using it as a supplementary cementitious material (SCM) in view of the significant environmental benefits gained from substituting cement. From previous

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http://dx.doi.org/10.1016/j.conbuildmat.2017.08.003
0950-0618/

Table 1
Oxide compositions and physical properties of the tested materials.

Oxide (wt%)	OPC	PFA	SSA	FSSA	Method/Instrument
MgO	1.47	3.97	3.15	3.16	Rigaku Supermini200-type X-ray fluorescence spectrometer
Al_2O_3	3.77	18.91	12.20	12.26	
SiO_2	19.37	44.20	27.78	27.91	
CaO	63.85	11.87	10.42	10.47	
TiO_2	0.26	1.05	0.52	0.52	
Fe_2O_3	3.08	11.34	18.23	18.32	
SO_3	5.38	1.76	6.10	6.13	
MnO	0.06	0.24	0.24	0.24	
K_2O	0.69	1.65	1.88	1.89	
Na_2O		1.32	7.28	7.32	
P_2O_5		0.41	9.72	9.77	
Loss on ignition	2.08	3.28	1.97	2.01	
Specific gravity	3.09	2.51	2.33	2.74	BS EN 196-6:2010
Mean diameter (μm)	19	38	60	6	Malvern Instrument's Spraytec
BET (m^2/kg)	533	559	13293	17366	Micromeritics ASAP2020

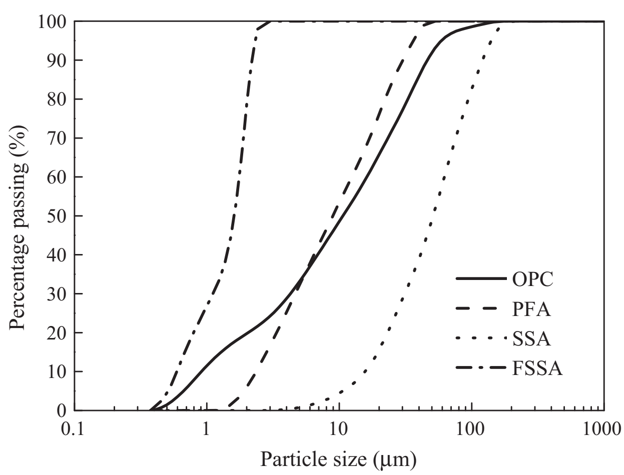

Fig. 1. Particle size distributions of the tested materials.

limited studies, it is widely accepted that blending a small amount of SSA does not affect the compressive strength of mortar monoliths and that SSA is only mildly pozzolanic. Monzó et al. [13] found that replacing cement with SSA up to 30% does not reduce the strength of mortars cured with 40 °C water and suggested that this is due to the pozzolanic properties of SSA. Cyr et al. [14] tested the compressive and flexural strength of mortars with 25% and 50% of cement replaced by SSA and found that SSA causes reduction in strength compared to control mortars, but such reduction becomes less over time. Lin et al. [15] found that smaller SSA particles possess greater pozzolanic activity resulting in higher compressive strength of mortars. Chen et al. [16] reported satisfactory compressive strength of concrete prepared by using SSA to substitute 10% of cement and 2% of sand simultaneously. Pinarli and Kaymal [17] and Ing et al. [18] also reported similar or greater strength values in mortars containing up to 10% SSA in the binder.

While many studies have been conducted on the physical properties of SSA blended cement products, relatively little attention has been paid to the effect of SSA on cement hydration. The effect on early hydration of cement needs to be evaluated when part of cement is substituted by SCM. The limited calorimetric data published so far by Cyr et al. [14] and Dyer et al. [19] are interesting but the tests can be expanded. Simple studies using pure SSA and blended with cement pastes may help explain better some of the results observed. Other factors can also affect strength development in mortars, including porosity, which will vary due to changes in water/cement (w/c) ratio caused by the presence of SCM. However, although high porosity is a primary characteristic of SSA as reported in many studies [20–24], the relationship between the pore structure and mechanical properties of the paste has not been reported. Dhir et al. [25] also expressed in their book that most studies on porosity of SSA-containing mortar or concrete actually involved different types of water absorption tests but not in-depth microstructure analysis. Additionally, as reported by Lynn et al. [26], although drying shrinkage is a controlling parameter on the durability of plain concrete, very few studies have been performed to assess the effect of SSA on the volume stability of mortars due to drying shrinkage and the associated mechanisms. Furthermore, inconsistent results on the workability of fresh mortars containing SSA were obtained. One study investigated the workability of fresh mortars containing SSA using the flow table spread (FTS) method [20] and reported that finer SSA reduces the mortar workability more than coarser SSA does. However, another study found contrary results with the same method [21]. It is hoped that this study will provide more information on using SSA for partial replacement of cement for producing cement mortars with emphasis on filling the above knowledge gaps.

1.2. Aim and objectives

There are clear and well-established environmental, economic and technical advantages to using SCMs. The main SCMs include coal fly ash, blast furnace slag, silica fume, natural pozzolan (e.g., volcanic ash) and natural calcined pozzolan (e.g., metakaolin). From a technical perspective, different SCMs exhibit different advantages and disadvantages. For example, pulverized fly ash (PFA) requires less water than cement and can improve concrete's workability, pumpability, finish and ultimate strength, but the curing process may take much longer due to its moderate pozzolanic activity [27,28]. Granulated slag provides superior resistance to salt corrosion which is a particular advantage in marine concrete structures. However, concrete made with granulated slag carbonates faster at early ages which may have an impact on reinforcing bars [29,30]. Silica fume and metakaolin, due to their fineness and high reactivity, can enhance concrete strength but they increase the water demands of the mixes [31,32]. As one may expect, comparative studies of SSA and other SCM using the same equipment and applying the same conditions would help evaluate the effectiveness of SSA used in blending with cement and identify any unusual effects from SSA. As the size of SSA particles may also affect its properties, tests have been repeated on fine sewage sludge ash (FSSA) of corresponding amounts for comparison. FSSA was obtained from grinding the SSA in a ball mill for 3 h.

In all, the aim of this study was to evaluate the potential factors governing the effects of SSA on mortar strength and how SSA may