Construction and Building Materials 146 (2017) 183–191

Contents lists available at ScienceDirect

Construction and Building Materials

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

Strain hardening cementitious composites incorporating high volumes of municipal solid waste incineration fly ash

Junxia Li [a,b], Zhili Dong [c], En-Hua Yang [d,*]

[a] Interdisciplinary Graduate School, Nanyang Technological University, Singapore 639798, Singapore
[b] Residues & Resource Reclamation Centre, Nanyang Environment and Water Research Institute, Nanyang Technological University, Singapore 637141, Singapore
[c] School of Materials Science and Engineering, Nanyang Technological University, Singapore 639798, Singapore
[d] School of Civil and Environmental Engineering, Nanyang Technological University, Singapore 639798, Singapore

HIGHLIGHTS

- MSW IFA was used as cement supplement for the production of SHCC.
- Mechanical properties of SHCCs can be maintained when up to 20% cement was replaced by IFA.
- Reduced compressive strength but enhanced tensile ductility of SHCCs at higher replacement dosage of up to 40%.
- SHCC binder can effectively immobilize heavy metals in IFA.

ARTICLE INFO

Article history:
Received 24 February 2016
Received in revised form 27 March 2017
Accepted 12 April 2017
Available online 19 April 2017

Keywords:
Incineration fly ash
IFA
Strain hardening cementitious composites
SHCC
Friedel's salt

ABSTRACT

This paper reports the potential use of municipal solid waste incineration fly ash (IFA) as cement supplement for the production of strain hardening cementitious composites (SHCC). Results showed that IFA is not a conventional pozzolan according to ASTM C618. Certain chemical reaction; however, occurred when IFA is used together with cement as evidenced by the formation of Friedel's salt in IFA-SHCCs. As a result, the compressive strength as well as tensile ductility of IFA-SHCCs can be maintained when up to 20% cement was replaced by IFA. At higher replacement level, however, excessive alkali metal chloride may leach out from the matrix leading to porous honeycomb microstructure of matrix which results in reduced compressive strength but enhanced tensile ductility of IFA-SHCCs. Leaching tests showed that almost all heavy metals concentration complied with the limits set in the Dutch Soil Quality Decree for construction materials. This suggests SHCC binder can effectively immobilize heavy metals in IFA potentially due to the low water-to-binder ratio of IFA-SHCCs matrix. Preliminary evaluation indicates that IFA may be used to replace cement in the production of SHCC. Further studies are necessary to investigate the long-term environmental impact of IFA-SHCCs.

1. Introduction

Municipal solid waste (MSW) management is a tough issue due to limited landfill space and stringent environmental constraint worldwide. Incineration is a commonly accepted solution to greatly reduce the mass and the volume of MSW by 70% and 90%, respectively. The remaining residues after incineration, however, still need to be disposed of by landfill. As of 2012, about 0.3 million tons of incineration ashes were landfilled in Singapore [1]. Being an island city-state with limited land space and natural resources, it is crucial for Singapore to develop strategies to prolong the lifespan of its only remaining landfill and to recover waste into resources. A viable solution is to use incineration ashes for civil engineering applications, which helps to alleviate the disposal cost, to preserve landfill capacity, to conserve dwindling resources of natural raw materials, and to mitigate potential environmental impacts.

The MSW incineration ash can be classified into the MSW incineration fly ash (IFA) and the MSW incineration bottom ash (IBA). Generally, MSW IFA has higher heavy metal concentration and is considered more hazardous than MSW IBA. From literature, the use of MSW IFA in construction materials is mainly prohibited by two factors summarized below.

* Corresponding author.
E-mail address: ehyang@ntu.edu.sg (E.-H. Yang).

http://dx.doi.org/10.1016/j.conbuildmat.2017.04.098
0950-0618/

- The high content of chloride (Cl). MSW IFA may be used as a supplementary material for the production of cement clinker. The high Cl content in MSW IFA, however, can lead to cycling in the cement kilns which causes rapid clogging and corrosion inside the heat exchangers [2]. High Cl content in the resulting cement may accelerate steel corrosion in reinforced concrete structure. Pretreatment such as washing or thermal treatment is proposed to remove and to minimize the influence of Cl [3–6].
- Heavy metal leaching. When the ashes are used directly, e.g. road base aggregates and fillers, heavy metal leaching into soil and underground water is of great concern. It has been reported that cement solidification/immobilization can effectively reduce the potential of heavy metal leaching [5,7,8].

Strain hardening cementitious composites (SHCC) is a new class of construction material. With exceptional mechanical properties such as high tensile ductility, high damage tolerance, and fine crack width, SHCC can be used in many applications where reinforcement is not necessary. For example, SHCC is an ideal material for retrofitting of unreinforced masonry walls [9], pavement overlays [10], and surface repair of dams and earth retaining walls [11]. Other potential applications of unreinforced SHCC include shotcrete for underground rock cavern and tunnel linings [11]. Thus, MSW IFA may be used in unreinforced SHCC where high chloride is not a concern. On the other hand, heavy metals in MSW IFA may be solidified by the strong cement-based binder system of SHCC where low water-to-binder ratio is often used.

Recent study has shown that pre-treated MSW IFA by washing could be a potential substitution of Portland cement in construction materials due to high amount of silicon oxide, calcium oxide and aluminum oxide in the ash [12]. Reusing MSW IFA as cement supplements or brick showed lower environmental impact than landfill after solidification according to a life cycle assessment reported by Huang and Chuieh [13]. The present study provides an alternative use of raw MSW IFA (untreated) as cement supplements for the synthesis of SHCC. Due to the absence of coarse aggregate in SHCC mix design, considerably high cement content was used in its production, typically two to three times higher than that of normal concrete. High cement usage causes environmental burden and economic impacts. The best identified alternative is to replace cement with industrial wastes, such as coal fly ash and slag. Yang and Li [14] succeeded in incorporating high volumes of coal fly ash into SHCC (referred to engineered cementitious composites, ECC). In current study, the use of untreated MSW IFA as cement supplements to produce SHCC was reported and effects of MSW IFA replacement ratio on the hydration production, microstructure, as well as mechanical properties of SHCC were investigated. The ability of heavy metal solidification/immobilization in IFA-SHCCs was also evaluated with monolithic and granular samples.

2. Experimental program

2.1. Materials

MSW IFA was collected from a local waste-to-energy (WTE) incineration plant. The incineration plant is a mass burn facility capable of treating 800 tons of solid waste daily and generates 22 MW of energy. An advanced grate burning system including a multi-stage grate furnace was designed and biofuel is used for waste incineration. Waste is burned consistently without pre-processing. The burning temperature is between 800 and 1000 °C. The facility mainly burns municipal solid wastes with small quantity of industrial waste. Ferrous metals are recovered after burning through magnetic separation. No other post combustion recoveries for nonferrous metals such as eddy current or wet/dry separation are used in the facility. As can be observed from Fig. 1, the majority of IFA particles sizes are in the range of 10–150 μm.

Ordinary Portland cement (OPC) conforming to the Singapore standards SS 26 was used in this study. The gradation of cement is shown in Fig. 1 and the average particle size of the cement is 15.4 μm. The chemical composition of the major elements in oxides form was determined in duplicate by X-ray Fluorescence (XRF) spectroscopy and results are shown in Table 1. Short polyvinyl alcohol (PVA) fibers of 8 mm long were used in producing SHCC. Properties of the PVA fiber are summarized in Table 2. The surface of PVA fibers was coated with hydrophobic oiling agent of 1.2% by weight to control the interface properties of the fiber and matrix.

2.2. Mix design and sample preparation

IFA was used as a partial replacement of cement in producing SHCC at replacement levels of 20%, 30%, and 40% by weight of the binder (cement + IFA), respectively. Table 3 gives the mix design of the four mixes. A water-to-binder ratio of 0.34 and a 2% of PVA fiber by volume were used in all mixtures. To prepare IFA-SHCC mixtures, cement and IFA were dry-mixed for 3 min. Superplasticizer was pre-mixed with water before adding it into the dry mixture and mixed for another several minutes until the fresh paste achieved a consistent and uniform state. Finally, fibers were added and mixed in high speed for 3 min to attain a homogeneous mix. Significant amount of heat was released during processing of mixture with high IFA content resulting in reduced setting time. This may be attributed to the presence of the chloride ion in IFA which accelerates hydration [15].

2.3. Testing methods

A scanning electron microscope (FESEM 6340F) was used to study the morphology of IFA and fracture surface of hardened IFA-SHCCs. All samples were oven-dried at 100 °C for 24 h prior to surface coating of a thin platinum layer with a thickness less than 20 nm. Energy-dispersive X-ray spectroscopy (EDS) is an analytical technique allowing for the elemental analysis of the sample associated with the morphology of different chemical compositions. X-ray powder diffraction (XRD) analysis was also carried out with diffractometer (Bruker D8 Powder) to understand the crystalline phases of IFA and IFA-SHCCs.

Compression test was performed according to ASTM C109. For each mix, at least three 50 mm cube specimens were tested in compression machine with 3000 kN capacity under load control

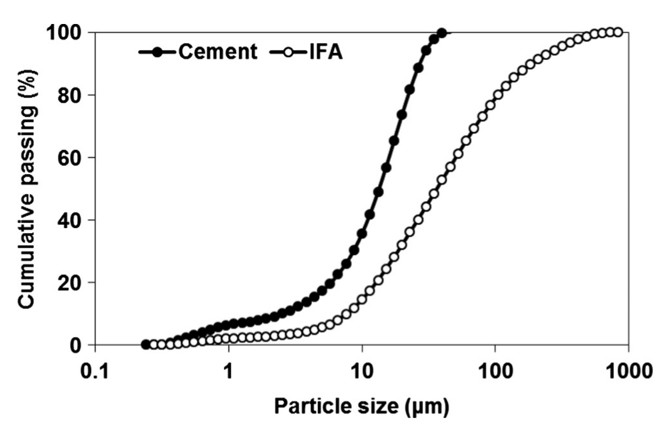

Fig. 1. Gradation curves of cement and IFA.