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Effects of different surface modification and contents on municipal solid waste incineration fly ash/epoxy composites

C.K. Goh *, S.E. Valavan, T.K. Low, L.H. Tang

Republic Polytechnic, 9 Woodlands Ave 9, Singapore 738964, Singapore

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Incineration fly ash, a waste from municipal solid waste incineration plant can be used to replace conventional filler as reinforcing filler to enhance the mechanical strength of a composite. Surface modification was performed on the incineration fly ash before mixing into the soft polymer matrix so as to improve interfacial bond of the filler and epoxy resin. In this study, detailed characterisation of mechanical, morphological and leaching behaviours of municipal solid waste incineration (MSWI) fly ash infused composite has been carried out. Flexural and tensile test was conducted to determine the effect on mechanical properties of the composite by varying the concentration of incineration fly ash filler added into polymer matrix and surface modification of incineration fly ash filler using silane coupling agent and colloidal mesoporous silica (CMS). The results indicated that composite infused with incineration fly ash filler surface treated with CMS shown improvement on the tensile and flexural strengths. In addition, SEM images showed that surface modification of incineration fly ash with colloidal mesoporous silica enhanced the interfacial bonding with polymer resin which explained the improvement of mechanical strength. Leaching test showed result of toxic metals such as Pb, Zn, Fe, Cu, Cr, Cd and Rb immobilised in the polymer matrix of the composite. Hence, the use of MSWI fly ash as reinforcing filler in the composite appears green and sustainable because this approach is a promising opportunity to substitute valuable raw material with MSWI fly ash.

1. Introduction

Singapore has generated a total amount of about 7.5 million tonnes of solid waste in year 2014 ('Singapore Waste Statistics and Overall Recycling', 2015), which translates to per capita MSW generation of 1.37 tonnes per year. This is comparable to 1.4 tonnes of waste generated per capita each year in the United States (Municipal Solid Waste Generation, Recycling, and Disposal in the United States, 2012). Singapore's waste management solution is to incinerate all combustible waste that is not reused or recycled. Municipal solid waste incineration (MSWI) is an efficient method for waste management because it allows a reduction of waste volume and weight together with the benefit of thermal energy production (Lang, 2005). However, it may cause environmental problems, related to the disposal of MSWI fly ash produced after incineration process. This is because the MSWI fly ash contains toxic metals such as lead (Pb) and zinc (Zn). Hence it is classified as hazardous waste (Lang, 2005). It has been estimated that approximately 650 thousand tonnes of incineration ash were produced in Singapore and currently most of these are landfilled ('Singapore Waste Statistics and Overall Recycling', 2015). This disposal management option is not sustainable because Singapore has only one offshore landfill (Lang, 2005). Therefore, being able to convert incineration ash into useful materials could reduce landfilling and extend the lifespan of the landfill. Most of the current efforts are focused on utilisation of MSWI fly ash for cement and concrete production, road pavement, glasses and ceramics, agriculture, stabilizing agent, adsorbents and zeolite production (Lam et al., 2010). So, this paper will explore an alternative application, *i.e.* fabrication of high quality composites because incineration fly ash is potentially used as reinforce fillers for polymer materials (Sreekanth et al., 2009). Composites based on organic polymers consume non-renewable fossil oil resources. Therefore, this work is potentially to reduce the consumption of organic polymers by substitution of these with inorganic incineration fly ash. There are few reports in the literature (Sreekanth et al., 2009; Satheesh et al., 2013) of incineration ash being used as fillers for polymeric materials with promising results, as the ash is able to integrate with and disperse homogenously into the polymer matrix. However, these reports were mainly focused on the coal fly ash (Ahmaruzzaman, 2010) or a mixture of coal fly ash, flue

* Corresponding author.
E-mail address: goh_chee_keong@rp.edu.sg (C.K. Goh).

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gas desulfurization (FGD) fly ash and MSWI fly ash (Besco et al., 2013, 2014). To date, the use of solely MSWI fly ash into polymer composites has not been reported because it contains more harmful toxic metals, which can be released into the environment through weathering and leaching (Lam et al., 2010).

Commercially available epoxy resin is taken as a model for this study because epoxy based polymer composites have a wide range of engineering and structural applications such as aerospace, defence, automobile, electrical and other manufacturing industries. In general, particulate composite materials are consisting of polymer resins as matrix and particles as reinforcement fillers. These particles are normally obtained from natural minerals such as talc, calcium carbonate or synthetic fillers such as carbon black. The purpose of use of fillers can be divided into two basic categories, first, to improve the properties of the material and second, to reduce the cost of composite. MSWI fly ash can be used as a potential filler material in polymer matrix composites because it is abundantly available from waste incineration plants. In addition, fly ash contains mineral and amorphous phases that are able improve the physical and mechanical properties of the composites (Zacco et al., 2014). It is reported that composites between hydrophobic polymeric materials and hydrophilic fly ash particles are incompatible and led to poor interfacial bonding and inferior mechanical properties (Alkadasi et al., 2003). For the purpose of improving the adhesion properties of fly ash to polymer matrix, the surface treatment of fly ash could be done before incorporating it into polymer matrix in order to enhance the mechanical strength of composites, which has been reported in many literatures (Thongsang and Sombatsompop, 2006; Shubham and Tiwari, 2012). For instance, Shubham and Tiwari (2013) indicated that the tensile and impact properties of glass fibre reinforced epoxy composites loaded with silanization of fly ash were improved in strength when compared to unmodified fly ash at same concentration. Kishore et al. (2002) suggested that the epoxy composites containing 10% by volume of fly ash treated with silane coupling agent and acetone showed greater absorption of impact energy and maximum load compared to untreated fly ash particles. Thongsang and Sombatsompop (2006) showed that the fly ash particles could become a reinforcing filler to improve the mechanical properties of fly ash/natural rubber composites, after surface treatment by silane coupling agent at 2–4 wt%. The works done by Chaowasakoo and Sombatsompop (2007) suggested that the improved mechanical properties of the epoxy-based composites could be obtained by addition of 0.5 wt% silane coupling agent for surface modification of fly ash using thermal and microwave curing methods. Besco et al. (2013, 2014) reported the results on the use of mesoporous silica nanoparticles (MSNs) to stabilise and treat fly ash from a mixture of coal fly ash, flue gas desulfurization (FGD) fly ash and municipal solid waste incineration (MSWI) fly ash as fillers for polypropylene (PP). They found that the polypropylene (PP)-filler composites containing different stabilised fly ash amounts up to 30 wt% showed a significantly enhancement in tensile and flexural elastic moduli together with improvement of flexural resistance and deflection temperature under load. They also indicated that the starting material of fly ash, which contains large quantities of leachable toxic metals such as Pb and Zn, was stabilised by a chemical process using mesoporous silica nanoparticles (MSNs), making it a promising strategy to use raw-materials from waste incineration plant, preserve natural resources avoiding the exploitation of traditional natural fillers and reduce the cost of fillers in manufacturing of composites (Bontempi et al., 2010; Bosio et al., 2014).

In this paper, the fabrication and extensive physical (mechanical tests and analysis) and structural (scanning electron microscopy) characterisations as well as leaching behaviour of epoxy/fly ash-based composites formulated with two different surface modifications using silane coupling agent and colloidal silica nanoparticles (MSNs) are reported. The aims of this work are the study of the effectiveness of different surface treatment of MSWI fly ash as reinforcing filler for thermosetting composites.

2. Materials and methods

2.1. Materials

Epoxy resin of Epicote 1006 (Bisphenol-A, mono functional reactive diluents) was used as matrix phase with viscosity of 1100–13,000 mPa s and density of 1.11 g/cm^3. It's compatible Epicote 1006 Hardener was mixed with ratio of 10:6 by weight as recommended by the supplier. The epoxy resin and the hardener were supplied by Wee Tee Tong Chemicals Pte Ltd, Singapore. The municipal solid waste incineration (MSWI) fly ash was collected from Tuas Incineration Plant, Singapore. The grate furnace incinerator operates at temperatures between 850 and 1000 °C with a capacity of 800 tonnes per day. Table 1 shows the elemental composition of the MSWI fly ash, which was measured by Energy Dispersive X-ray Fluorescence (EDXF) Spectrometer (Shimadzu). The gammaaminopropyltriethoxysilane (Silquest A1100), supplied by Momentive Specialty Chemicals Singapore Pte. Ltd. was used as a silane coupling agent for surface modification of MSWI fly ash. The colloidal mesoporous silica (CMS) was supplied by Sigma-Aldrich, Singapore and it was an aqueous colloidal dispersion of SiO_2 (30 wt%) with high specific surface area (320–400 m^2/g) for surface treatment of MSWI fly ash.

2.2. Surface modification of the municipal solid waste incineration (MSWI) fly ash

Firstly, the municipal solid waste incineration (MSWI) fly ash were carefully dried before use in an oven at 80 °C overnight. The surface modification by silane coupling agent (Silquest A1100) was done using a wet method with 5 v/v% of silane coupling agent in deionised water. In general, the raw fly ash were stirred in the solution of silane coupling agent for 15 min in order to ensure a uniform distribution of the coupling agent on the FA surface before dried at 100 °C for 24 h in an oven. For the MSWI fly ash treated by colloidal mesoporous silica (CMS), the raw fly ash were added to an aqueous solution of CMS at 30 wt% and stirred well for an hour. A liquid-to-solid ratio of about 0.2–0.3 was generally reached. Then, the samples were washed with deionised water to remove soluble salts. Finally, the samples were centrifuged and dried at 100 °C for 24 h in an oven.

Table 1
Chemical composition of MSWI raw fly ash (wt%).

	MSWI raw fly ash
CaO	58.79
SiO_2	4.71
K_2O	4.66
Fe_2O_3	2.63
ZnO	1.82
TiO_2	1.30
PbO	0.25
CuO	0.18
MnO	0.12
SnO_2	0.12
Cr_2O_3	0.08
ZrO_2	0.06
SrO	0.06
CdO	0.02
Rb_2O	0.02
SO_3	3.96
Cl	20.94
Br	0.28

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