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Characteristics and applications of fly ash as a sustainable construction material: A state-of-the-art review

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ABSTRACT

Due to their good performance and environmental friendliness, fly ash-based construction materials have great potential as alternatives to ordinary Portland cement. To realize sustainable development and beneficial use of fly ash in the construction industry, this paper presents a comprehensive review of relevant literature to evaluate the properties and performance of fly ash, with a particular focus on recent advances in characterization, compositional understanding, hydration mechanism, activation approaches, durability and sustainability of fly ash as a construction material. Several key aspects governing the performance of fly ash, including chemical composition, activator type and hydrates evolution in concrete, are highlighted. Finally, the important needs, pertinent to the optimal and broad utilization of fly ash as an integral part of sustainable construction materials, are identified for further research and development, where large-scale application studies, further classification of fly ash, advanced characterization tools and technology transfer to biomass fly ash are recommended.

1. Introduction

Over the past few decades, the development of green construction materials has been promoted significantly by the higher sustainability standards of the construction industry. So far, two major trends of finding sustainable solutions for construction materials have been: (1) replacing nonrenewable aggregates with recycled materials, and (2) using SCM (fly ash, blast furnace slag, etc.) to partially or completely replace Portland cement (Marinković et al., 2017). These promote cleaner production by reducing emissions, air pollutants and wastes related to mining and manufacturing of materials. The general trend of replacing OPC with fly ash in concrete has become popular today. Fly ash is a byproduct of coal combustion primarily from coal-fired power plants, captured at the top of boilers (Provis et al., 2015).

As illustrated in Fig. 1, during/after combustion, excluded mineral particles or mineral matters within the coal will liquify, vaporize, condense or agglomerate. Due to surface tension force, spherical, amorphous fly ash particles are formed by rapid cooling in the post-combustion zone. At high temperature, the trapped volatile matter can expand inside to form a hollow cenosphere. Some of the residuals may become glassy particles, but some may crystallize, depending on the residual composition and the conditions of heating and cooling (Kutchko and Kim, 2006).

In recent years, many scientific advances have been made in characterization and up-cycling technologies of fly ash, which in turn significantly promote the value-added applications of fly ash, such as fly ash-based geopolymer, SCM and zeolite synthesis. Other application cases include, but are not limited to flowable fill, embankment, road base, blasting grit, catalysis, mining application, waste stabilization, agriculture and oil field service (Zhuang et al., 2016).

The main purpose of this work is to provide a comprehensive review of fly ash as a construction material. To achieve this goal, this literature review uses the following five steps: (1) Selecting review topics as follows: characterization, compositional understanding, activation approaches, nanotechnology applications, durability and sustainability evaluations of fly ash or its composites; (2) Systematic literature search of published domains and fly ash up-cycling communities, including: peer-reviewed research papers and books, existing relevant literature reviews, original research reports, case studies and anecdotal evidences; (3) 180 publications published since 2000 were included in this work

Abbreviations: AAFA, alkali-activated fly ash; AAR, alkali aggregate reaction; ACAA, American Coal Ash Association; C_3A, tricalcium aluminate; C–A–S–H, calcium aluminum silicate hydrate; CBA, cost-benefit analysis; CKD, cement kiln dust; CNT, carbon nanotubes; C–S–H, calcium silicate hydrate; FA, fly ash; FBC, fluidized bed combustion; FC, fly ash + cement blend; FGD, flue gas desulphurization; FTIR, Fourier transform infrared spectrometry; GNP, graphene nanoplatelet; HVFA, high volume fly ash; LCA, life-cycle assessment; MAS-NMR, magic-angle spinning nuclear magnetic resonance; N–A–S–H, sodium aluminosilicate hydrate; NPV, net present value; OPC, ordinary Portland cement; RCA, recycled concrete aggregate; rGO, reduced graphene oxide; SCM, supplementary cementitious material; SEM/EDS, scanning electron microscopy/energy-dispersive X-ray spectroscopy; TEM, transmission electron microscopy; XRD, X-ray diffraction; XRF, X-ray fluorescence

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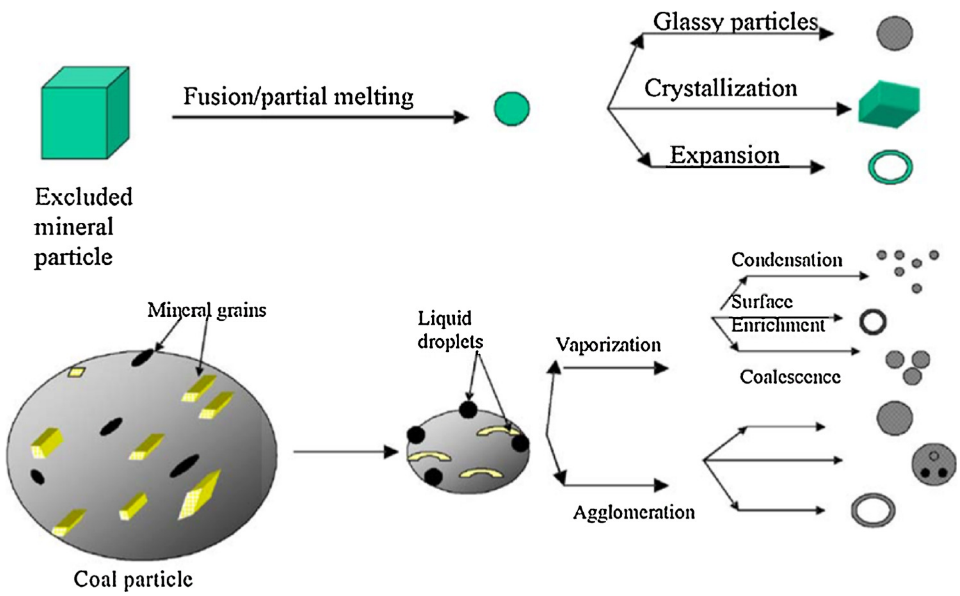

Fig. 1. General transformation of mineral matter in coal during combustion [Reprinted from (Kutchko and Kim, 2006), with permission from Elsevier.].

by using the following criteria: relevance to the review topics, quality and credibility, impact on the fly ash research, representing state-of-the-art fly ash research, and indicating the future trends of fly ash studies; (4) Literature analysis and synthesis by following the PQRS (preview, question, read, summarize) method (Roth, 1990), the literature was classified and summarized based on the topics or categories; (5) Identifying future research needs to facilitate the optimal and broad utilization of fly ash. The findings and rationale of this work will promote the beneficial use of fly ash as an integral part of sustainable construction.

2. Fly ash characterization

Fly ash is a man-made volcanic material. The definition of volcanic fly ash is "silicate or aluminosilicate material, which possesses weak or non-self-cementing ability, but in the finely divided state and damp environments at room temperature, it reacts with $Ca(OH)_2$ to form gel products" (Dunstan, 1989). There are many factors affecting the physical and chemical properties of fly ash, including coal type, boiler type, operating conditions and post-combustion conditions, etc. (Kutchko and Kim, 2006). XRD, XRF, FTIR, SEM/EDS and MAS-NMR spectroscopy are often used to characterize the fly ash. The following sections provide further discussion of fly ash in terms of physical, chemical and mineralogical properties (Fig. 2).

2.1. Morphology and physical properties

Fly ash particles are mostly spherical, including solid spheres (density = 2300–2600 kg/m^3) and cenospheres (0.2–1.1% of the total fly ash weight, density < 1400 kg/m^3) (Brouwers and Van Eijk, 2002) (Fig. 3a & d). Fly ash also has some irregular-shaped minerals and unburnt carbon (Fig. 3e & f). The size of particles varies depending on the combustion method, coal source, etc., ranging from less than 1*um* to greater than 200 *um*, but the hollow cenospheres and irregularly unburned carbon contents tend to have large sizes in the size distribution (Brouwers and Van Eijk, 2002; Ramezanianpour, 2014). High-Ca fly ashes are usually finer than low-Ca ashes, owing to the larger amounts of alkali sulphate present in high-Ca ashes (Mehta et al., 1984).

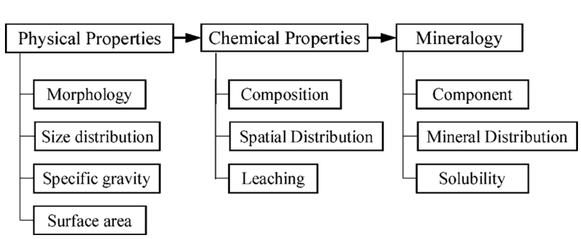

Fig. 2. Schematic overview of fly ash characterization.

The morphology of fly ash particles is mainly controlled by combustion temperature, cooling rate and composition of particles. For instance, spherical particles are rarely observed in FBC ash, and most of the particles are irregularly shaped (Fig. 3b). Seo et al. (2010) and Stutzxnan and Centeno (1995) believed that most of the minerals in FBC ash do not melt but only soften instead, due to the lower boiler temperature of 850–900 °C in the FBC process. Most high calcium ashes are spheres owing to the low melting point of Ca-modified ash. Brunauer-Emmett-Teller analysis and Blaine air permeability test are often adopted to measure specific surface area of fly ash, which varies from 150 m^2/kg for mechanically collected fly ashes to 1200 m^2/kg for ones collected by electrostatic precipitators (Mehta et al., 1984). The specific gravity of fly ashes also varies from 1.90 for a subbituminous ash to 2.96 for an iron-rich bituminous ash (Mehta et al., 1984).

2.2. Chemical compositions

The main chemical composition of fly ash is aluminosilicate compounds (Iribarne et al., 2001), and it also contains some metallic and calcium oxides (Brouwers and Eijk, 2003). Enders (1995) found the ratio of $A1_2O_3/(A1_2O_3 + SiO_2)$ in fly ash spheres can be constant, indicating the origin of glassy spheres from Kaolinite in coal. Fly ash also contains many trace elements, such as Cr, Ba, Ni, Pb, Sr, V and Zn (Yao et al., 2015), which are typically enriched in magnetospheres (Yang et al., 2014). Vassilev et al. (2004b) showed that water-soluble contents (0.2–0.6 wt%) of fly ash were rich in Ca and S, moderate in Al, Cl, Fe, K, Mg, Na, P, Si, and Ti, and also contained trace amounts of Cs, Li, Mn, Ni, Sn and Sr at ppm level, and As, Ba, Cr, Cu, Ge, Mo, Pb, Rb, Sb, Se, V, Zn and Zr at ppb level. They also reported that 2–29 wt% of total Ca, Cl, Na and S, and 0.1-1 wt% of total Al, Cs, K, Mg, P, Si, Sn and Ti were able to leach from the fly ash. Sulfate concentrations in the pore solution of fly ash pastes can rise significantly between 7 and 90 days, but this increase may be a short-term phenomenon (Tishmack et al., 2001). As fly ash hydrates can induce the fixation of heavy metals, the concentration of leaching heavy metals decreases with the development of fly ash