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Hydration kinetics, freeze-thaw resistance, leaching behavior of blended cement containing co-combustion ash of sewage sludge and rice husk

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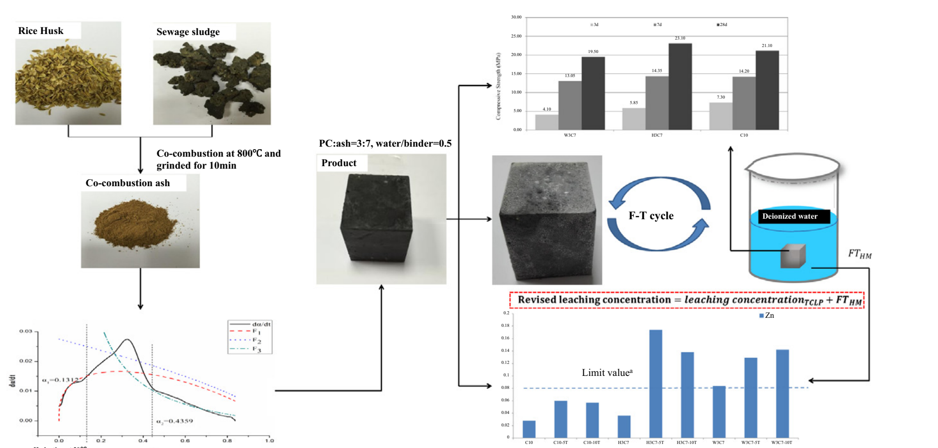
HIGHLIGHTS

- Co-combustion of rice husk and sewage sludge.
- The hydration is dominated by NG initially and then dominated by D.
- The novel cementitious material yields excellent mechanical properties.
- Leaching toxicity tests show the blended cement is environmentally acceptable.
- F-T action has negative impact on the leaching of HMs in the novel material systems.

GRAPHICAL ABSTRACT



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ABSTRACT

The application of co-combustion of sewage sludge together with rice husk is expected to increase in the coming years because of the economic and environmental benefits. Hence, resources of massive residues from co-combustion process deserve particular attention. In this study, cementitious materials that are composed of co-combustion ash, H (co-combustion of 20% sewage sludge + 80% rice husk) or W (co-combustion of 30% sewage sludge + 70% rice husk), were developed. Hydration characteristics, mechanical properties, freeze-thaw (F-T) durability, and environmental performance were investigated. Results show that the cumulative hydration heat increases along with the increase in the amount of amorphous SiO_2 in blended cement. The inclusion of H and W inhibits hydration at the early hydration stage and decreases the diffusion coefficient of paste at the later hydration stage. Moreover, the addition of H or W reduces the unconfined compressive strength (UCS) of sample at an early age. However, the UCS for 7-day and 28-day specimens even exceeds that of the reference. Blended cement containing co-combustion ash possesses leach resistance and poor frost resistance. Meanwhile, a significant increase

Abbreviations: HMs, represents heavy metals; RHA, represents rice husk ash; F-T, represents freezethaw; H, represents final ash from co-combustion of 20% sewage sludge + 80% rice husk; W, represents final ash from co-combustion of 30% sewage sludge + 70% rice husk; PC, represents pozzolanic cement; C10, represents pure pozzolanic cement pastes; W3C7, represents cement pastes composed of 30% W and 70% PC; H3C7, represents cement pastes composed of 30% H and 70% PC; C10-5T and C10-10T, represent pure pozzolanic cement pastes exposed to 5 and 10; F-T, cycles, respectively; W3C7-5T and W3C7-10T, represent blended cement pastes composed of 30% W and 70% PC, exposed to 5 and 10 F-T cycles respectively; H3C7-5T and H3C7-10T, represent blended cement pastes composed of 30% H and 70% PC exposed to 5 and 10 F-T cycles respectively; FT_{HM}, leaching concentration of HM during F-T cycle.

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of leached heavy metals is generated after F-T cycle. This phenomenon is a negative environmental impact of F-T action.

1. Introduction

Along with the significant increase of sewage sludge production, the final accumulation of sewage sludge has become a serious environmental problem. Therefore, the disposal of sludge in large amounts has to be urgently solved. In recent years, many researchers have focused on reusing sludge by incineration [1–4]. Sludge incineration has several advantages that are not found in other treatment alternatives. One of the advantages is that a large reduction of sludge volume to a small stabilized ash accounts for only 10% of the volume of mechanically dewatered sludge [5,6] and thermal destruction of toxic organic constituents [7].

With high moisture content, the heating value of primary sludge is not sufficient to evaporate the water inside of it. Co-combustion with biomass [8] overcomes this fault because the process generates sufficient heat energy without additional fossil fuel. However, the heavy metals (HMs) accumulate in the residue that is formed after co-combustion [9–11], and residues that are not well disposed cause environmental problems. HM elimination is possible if the characteristics of the residues are used, and this is compatible with environmental and economic requirements.

Various researchers who focus on the possible applications of incinerated ash have studied building and construction materials. Besides solving disposal problems, economic, ecological, and energy saving is another advantage of incinerated ash reuse in the construction industry. According to the other studies [12–14], incineration by-products that could potentially be used as pozzolanic materials in the construction industry includes paper sludge ash, rice husk ash (RHA), and sewage sludge ash. The use of these incinerated ashes as partial replacements for cement confers the environmental benefits of waste reuse and CO_2 savings by reducing the cement content and improvement of material mechanical properties. Among these by-products, RHA has attracted interest because of its high amorphous silica content. Several studies have used RHA as a low-cost and high-performance building material [15,16]. Although co-combustion of rice husk and sewage sludge provides promising application prospects, only few studies have been conducted.

According to previous research, the products of co-combustion of sewage sludge and rice husk ash contains high proportions of HMs, and their leaching potentially involves environmental problems, especially when large quantities of ashes are incorporated in cement matrices. Despite interferences and some negative effects, cement-ash paste, which is basically evaluated by strength and leach resistance, passes current quality and environmental acceptance criteria in most cases. However, evaluating and improving the hydration process, mechanical strength, and leachability are important in the application of green building materials. In addition, for ensuring long-term environmental safety, the durability tests of the specimens are required. Among these long-term experiments, the freeze-thaw (F-T) process negatively affects products [17]. The F-T durability of blended cements had been reported in many investigations [18–21]. The results indicate that F-T action reduces the strength because of strain generation, while it also changes the microstructure of the cement-based materials, which further affects the leaching behavior of HMs.

This study mainly aims to investigate the feasibility of the developed building materials that are composed of ash from the co-combustion of rice husk and sewage sludge. The hydration behavior, hydration kinetics, mechanical property, F-T durability, and environmental-friendly performance are also analyzed. This study is helpful for the promotion of rice husk and sewage sludge co-combustion technique in the industry.

2. Experimental

2.1. Materials

Rice husk and sewage sludge samples were collected from Wuhan, Hubei. The sludge and rice husk were dried in an oven at 105 °C for 3 h and for 3 days, respectively. Referring GB/T 212-2008 method for the proximate analysis of coal, the ash was prepared as follows: first, the muffle furnace with ventilation installation was heated at 815 ± 15 °C; the mixture of sludge and rice husk was placed at a certain percentage into the furnace to co-combust for 1 h, and finally the residue after co-combustion was collected and grinded in a ball mill (XQM-4L) for 10 min. The ashes were defined as H (co-combustion of 20% sewage sludge + 80% rice husk in wt%) and W (co-combustion of 30% sewage sludge + 70% rice husk in wt%). The ashes were mixed with CaF_2 (internal standard) on a 70:30 wt basis, and the mixture was subjected to XRD for the mineralogical composition study [22,23]. The qualitative and quantitative measurements of the samples were conducted by using the software Jade and Maud, and the results are shown in Fig. 1 and Table 1.

Fig. 1 descripts the similarities in mineral composition between W and H, which show that both ashes present bump of non-crystalline phases at 2θ = 23–27° region, indicating a siliceous glass structure [24]. Table 1 gives the results obtained from XRD quantification (XRDQ) of the different mineral phases present in the materials. W and H are composed of major amorphous contents (>75%) and minor contents of crystalline phases.

The pozzolanic cement (PC) that conforms to Chinese National Standard GB175-2007 was used to prepare the specimens. The chemical compositions of raw materials are shown in Table 2.

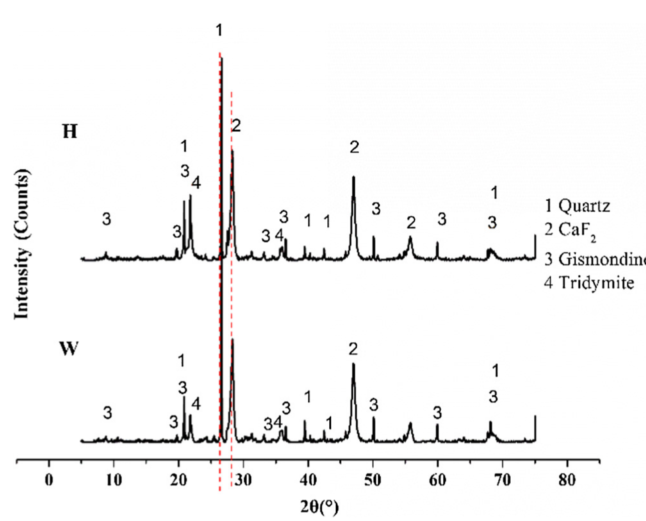

Fig. 1. XRD patterns of H and W.