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Influence of thermally activated alum sludge ash on the engineering properties of multiple-blended binders concretes

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HIGHLIGHTS

- Heat activated alum sludge ash (AASA) can be classified as a Class N pozzolan.
- The water demand of the ternary mix of OPC, AASA and GGBS is reduced.
- The binary mix of OPC with 15% AASA resulted in maximum compressive strength.
- The compressive strength of AASA ternary mix concrete is higher than the binary.
- The strength gain pattern of the splitting tensile and compressive are similar.

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ABSTRACT

This paper investigates the influence of thermally activated alum sludge ash (AASA) as partial cement replacement on the engineering properties of binary and ternary blended binders concretes that incorporate silica fume (SF), ground granulated blast furnace slag (GGBS) and palm oil fuel ash (POFA). The water/binder ratio for all the types of mixes is fixed at 0.30. The results show that AASA exhibits pozzolanic behaviour and can be classified as a Class N (natural) pozzolan. The binary blended binders with 15% AASA cement replacement increased the compressive and the tensile strength of concrete up to 85.3 MPa and 5.38 MPa at 28 days, respectively, and further increases in the AASA content gradually reduced these strengths. All the ternary combinations performed better than the binary mixes with AASA for the same replacement levels.

1. Introduction

Water treatment sludge is an important by-product from water treatment plants (WTPs) in the drinking water industry. Because aluminium sulphate ($Al_2(SO_4)3{\cdot}18H_2O$) is the most widely used coagulant worldwide for source-water purification, aluminium-coagulated water treatment sludge (alum sludge) is the most widely generated by-product from water treatment processes. The sludge dry mass primarily contains minerals; sandy particles; some small quantities of organic substances, such as humus and the remains of organisms or algae; and aluminium sulphate residues and polymers from the sludge-conditioning stage. There are no specific standards for WTP residues, but the Solid Waste and Public Cleansing Management Act, 2007 (Act 672) [1], classifies sludge that contains one or more metals, including chromium, copper, nickel, lead, cadmium, aluminium, tin, vanadium and beryllium, as scheduled waste (SW204), and alum sludge is classified as SW2040 107 Sludge that primarily contains aluminium. Under this act, the alum sludge is prohibited from direct discharged into the water courses downstream of the water intake points. The alum sludge is dewatered and it is either disposed within the WTP site or disposed to landfill. The cost of treating and disposing the sludge comprises a significant portion of the operating costs of a water treatment plant. Studies have shown that the amounts of heavy metals composition generated by some water treatment plants in Malaysia were within safe limits [2], although the accumulation of heavy metals composition in landfills remains a concern. The growing concern of environmental organisations with regards to health and environmental risks has led to stringent standards and the restriction or prohibition of discharging this residue into the environment (such as streams, landfills and soil).

In addition to disposal issues, the increasing amounts of alum sludge produced daily are triggering considerable environmental and economic concerns. However, the options for recovering/recycling alum sludge are generally not well developed as

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economically viable options for worldwide application. The search for cost-effective, eco-friendly (green) disposal options and the possibility of recycling the sludge have become an urgent priority. Some recent literature reviews have shown that alum sludge was being considered for use as a construction material by incorporating it in concretes and ceramics [3–5].

A reasonable number of pozzolanic materials have been proposed as cement replacement in concrete for decades. Recent studies have focused on thermally activated clays as potential sources of pozzolanic materials [6,7]. The use of pozzolanic materials from industrial by-products that can be utilised as replacements for cement has received considerable attention due to the benefits they bring to the engineering properties and durability of blended cement-based materials and because the use of these materials is environmentally and economically beneficial. According to the existing UNE-EN 197-1 standards [8], the pozzolanic materials that are generally incorporated in concrete are natural pozzolan from volcanic ashes, metakaolin (MK), and industrial by-products such as fly ash (FA), silica fume (SF), granulated ground blast furnace slag (GGBS) and palm oil fuel ash (POFA). Clay minerals that are mainly formed from siliceous and aluminous compounds become highly reactive when they are calcined at temperatures between 600 °C and 900 °C [7]. The loss of water due to thermal treatments destroys the crystalline structure of the compounds, thereby converting them into an unstable amorphous state. If they are then mixed with calcium hydroxide and water, they undergo a pozzolanic reaction and form compounds with enhanced strength and durability. Metakaolin, which acts as a highly reactive pozzolana, is one such material [9]. It is obtained through the thermal treatment of kaolin clays at temperatures from 600 to 800 °C [10] and then mixed with lime or cement. Additionally, the development of pozzolanic properties in fired clays depends mainly on the nature and abundance of clay minerals in the raw materials, the calcination conditions and the fineness of the final product [11].

Blended cements that incorporate these pozzolanic materials in either binary or ternary blends have been shown to possess improved fresh state and hardened properties. Extremely fine supplementary cementitious materials, such as MK, SF, and rice hush ash (RHA), are expected to significantly reduce the slump loss due to the increased water demand [12]. Li and Zhu [13] investigated the mechanical and physical properties of Portland cement (PC) in terms of the use of superplasticiser in the concrete by comparing a binary cement of PC/MK and a ternary blended cement of PC/MK/slag. Their findings indicated that a proportion of 20–30% ultra-fine slag and 10% MK and PC improved the fluidity of the ternary blended cements compared to the MK blended cement, which in turn improved the compressive strengths of the cements at 28 days. The strength properties of self-compacting concretes that incorporate multi-blended mineral admixtures containing FA, GGBFS, SF and MK were investigated by Guneyisi et al. [14]. The results indicated that there was a reduction in the compressive strengths of the concretes with increasing FA content, whereas the concretes containing GGBFS had comparable strength values to those of the control concrete. The SF and MK concretes, in contrast, had consistently higher compressive strengths than the control concrete.

The primary aim of this study is to propose the use of thermally activated alum sludge ash as an alternative cementing material in concrete. To date, there have been no detailed studies on the properties of concrete utilising binary and ternary blends of AASA and other pozzolanic materials (SF, GGBS and POFA). This study focuses on the engineering properties of AASA, not only as a binder but also as a replacement for Portland cement in multiple blended concretes. The investigated parameters include the physical, chemical and mechanical properties and leachates of AS and the physical and mechanical properties of multiple blended concretes. Comparisons with the parameters of the reference Portland cement concrete are performed. It is highly desirable to use AASA as a pozzolanic material to partly replace Portland cement to produce sustainable concretes as well as to reduce the negative environmental effects and the volume of waste disposed of in landfills.

2. Experimental program

2.1. Materials

2.1.1. Cement

Ordinary Portland cement type I (OPC), which conforms to ASTM C150-1992 [15], was used for all the concrete mixtures. Tables 1 and 2 show the chemical and physical characteristics of the cement, respectively.

2.1.2. Alum sludge

The raw material used in the present study was alum sludge that was obtained from a local drinking water treatment plant and then oven-dried at 105 °C for 24 h (see Fig. 1a for its physical appearance). The AS is light brown in colour and it has an inoffensive odour. The dried sludge was crushed and sieved through a 10 mm sieve to remove coarse and foreign particles (if any), and then the sample was ground using a Los Angeles (LA) machine until the required fineness was achieved (see Fig. 1b for its physical appearance). The obtained ashes were ground to meet the fineness specifications of ASTM C 618-2003 [16]. Its particle size distribution was determined using a Malvern Mastersizer 2000 laser diffraction particle size analyser. X-ray fluorescence (XRF) was used to analyse the chemical composition of the AS. Loss on ignition (LOI) was measured by oven drying the alum sludge at 105 °C for 24 h to obtain a constant mass before calcining it at 1000 °C for 1 h. The electrometric method according to BS 1377: Part 3: 1990: clause 9 [17], which is considered to be the most accurate method, was utilised to determine the pH value of the alum sludge suspension in water. The pH is the main indicator of hydrogen activity in the clay or soil. When the pH increases to greater than 7 (alkaline), the properties of the clay change because of the small hydrogen concentration. Then, X-ray diffraction (XRD) was used to perform a mineralogical analysis of AS to identify the main phases in the AS. Scanning electron microscopy (SEM) was also utilised to quantify the changes in the physical properties and compositions of the AS.

Thermally activated alum sludge ash (AASA) was obtained by controlling the incineration of dry alum sludge at 105 °C for 24 h. Then, the dried sludge was placed in a laboratory electric furnace at 800 °C for a period of 2 h, and the heating rate was 5 °C/min, taking into account costs and energy consumption. Then, the sludge was cooled gradually (see Fig. 1c for its physical appearance). Thereafter, the calcined product was ground using a LA machine until the required fineness was achieved for the purpose of improving its reactivity (see Fig. 1d for its physical appearance). The particle size distribution was determined using a laser diffraction particle size analyser. After the thermal activation processes, the chemical compositions and physical properties of AASA were determined to assess the efficiency of the processes. The mineralogical composition of the AASA was studied using XRD to identify the major phases in the AASA. SEM was also used to examine the surface characteristics of the AASA.

2.1.3. Pozzolanic materials

Three types of pozzolanic materials, namely silica fume (SF), ground granulated blast-furnace slag (GGBS) and palm oil fuel ash (POFA) were employed as partial replacements of OPC by weight in different combinations of binary and ternary cementitious blends. The name of the condensed silica fume (SF) is Force 10,000D microsilica. Tables 1 and 2 list the chemical and physical properties of these materials, respectively.

2.1.4. Aggregate

The fine and coarse aggregates obtained from local sources are in accordance with the ASTM standard. The local natural sand used as a fine aggregate has a maximum aggregate size of 4.75 mm and a fineness modulus of 2.89. Crushed granite was used as a coarse aggregate and has a maximum size of 10 mm. The fine aggregate has a specific gravity of 2.61 and water absorption of 0.72%, and the coarse aggregate has a specific gravity and water absorption of 2.64 and 0.48%, respectively.

2.1.5. Superplasticiser

The superplasticiser (SP) used in this study is an aqueous solution of modified polycarboxylate-based superplasticiser (Viscocrete-2044). The specific gravity of 1.08 was utilised to achieve the desired workability in all the mixtures.