



Physicochemical characteristics of cementitious building materials derived from industrial solid wastes



S.A. Abo-El-Enein^a, F.S. Hashem^a, M.S. Amin^{a,b,*}, D.M. Sayed^a

^a Chemistry Department, Faculty of Science, Ain Shams University, Cairo, Egypt

^b Department of Basic Sciences and Technology, Community College, Taibah University, Saudi Arabia

HIGHLIGHTS

- Lime rich sludge (LRS) can act as an alkaline activator for ground granulated blast furnace slag (GGBFS).
- Addition of fine kaolinite sand (FKS) results in marked improvement in the hydraulic properties of GGBFS-LRS-FKS mixes.
- GGBFS, LRS and FKS wastes can be used for the production of building materials of strong hydraulic properties.
- The main hydration products are nearly amorphous and microcrystalline CSH.

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ABSTRACT

In this study the possibility of using alternative waste materials with cementitious properties was studied. Lime rich sludge (LRS) (solid waste of acetylene industry), ground granulated blastfurnace slag (GGBFS) and fine kaolinite sand (FKS) (by-product during kaolin mineralization) were used in the production of cementitious building materials. Different mixes were prepared using percentage weight ratios 80/20, 75/25, 70/30 of GGBFS and LRS, respectively, at water/cement ratio of 0.20 by weight. Fine kaolinite sand (5 wt%) was used as addition in these mixes. The mechanical and hydration characteristics of the prepared pastes were studied at various time intervals up to 90 days. The results showed that LRS acts as an alkaline activator for GGBFS and the optimum mix composition for activation was 75% GGBFS and 25% LRS. Addition of fine kaolinite sand (FKS) to these mixes resulted in a marked improvement in the hydraulic properties especially in the early hydration ages; this is related to the higher rate of pazzolanic interaction between the lime in LRS and the aluminosilicate constituents in fine kaolinite sand leading to formation of excessive amounts of calcium silicate hydrates (CSH) which act as binding centers between the remaining unhydrated parts of GGBFS and FKS. XRD patterns and DSC thermograms obtained for all pastes showed that the main hydration products are nearly amorphous and microcrystalline calcium silicate hydrates as well as minor amounts of calcium aluminosilicate hydrates.

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1. Introduction

Manufacturing of Portland cement (PC) is a resource exhausting, energy intensive process that releases large amounts of greenhouse gas (CO₂) into the atmosphere. Many researchers from the world are working on this serious issue created by cement and one of the solutions is the introduction of new building materials which have a positive impact on the environment. The utilization of industrial solid wastes in the production of such building materials represents another goal for economically and healthy aspects.

Ground granulated blastfurnaceslag, GGBFS, is a by-product of the manufacture of pig iron from limestone, iron ore and coke. The main constituents of GGBFS are CaO, SiO₂, Al₂O₃ and MgO. GGBFS has been used as a secondary cementing material for more than 100 years and there is a broad knowledge regarding its applications. Despite the fact that the amount of available slag is limited, there is an increasing demand for slag cement to reduce the CO₂ emission due to the production of cement and concretes [1]. Replacement of clinker by slag, not only offers energy savings and cost reduction compared to ordinary Portland cement (OPC), but also other advantages such as a lower heat of hydration, high sulfate and acid resistance, better workability, good ultimate strength and durability [2,3].

* Corresponding author at: Chemistry Department, Faculty of Science, Ain Shams University, Cairo, Egypt.

E-mail address: mohamedsamin@hotmail.com (M.S. Amin).

The cementitious properties of GGBFS is weak but it can achieve high compressive strength when an alkaline activator is used [4,5]. Commonly used alkaline activators are sodium hydroxide and sodium silicate solutions [6,7]. The use of alkali activated slag (AAS) has been reported to exhibit mechanical and durability characteristics similar or superior to those of ordinary Portland cement (OPC) binder [8–10]. Consequently, AAS has been established as a method for producing sustainable binders for construction. Lime has been found to be a suitable retarder to control the setting time of AAS concrete [11]. Collins and Sanjayan [5] studied the effects of lime on the strength development of AAS pastes and found that the presence of lime could significantly increase the strength of AAS pastes. In a recent study, Yang et al. [12] even attempted to develop an AAS system using lime as the main activator. Lime rich sludge (LRS) is a by-product produced by large quantities as a solid waste of acetylene gas industry. The main composition of LRS is hydrated lime ($\text{Ca}(\text{OH})_2$) and its accumulation represents an environmental and economic problem. Many attempts of sludge disposal alternatives such as agricultural use, land filling [13,14], marine disposal and incineration, have adverse environmental impacts. There is a resulting increase of interest in reuse of sludge by incorporation into construction materials [15–17]. The addition of aggregates to a binding system has proved to confer technical advantages as they contribute to volume stability, durability and structural performance [18,19]. Apart from the different available aggregate types, as far as their mineralogy is concerned, their volume content in the mixture, as well as their maximum size and gradation, influence the structure of a binder–aggregate mixture. Sands of different origins have been used in mortars and different flow ability, strength and stiffness have been recorded [20]. The objective of this study is to investigate the use of three by-products; mainly, ground granulated blastfurnace slag (GGBFS), lime rich sludge (LRS) and fine kaolinite sand (FKS) in the production of new cementitious materials that can be used in mortar and concrete applications. The production of these materials represents economical and environmental challenges. The hydration and mechanical characteristics of the prepared pastes were studied. The phase compositions of the formed hydrates were investigated using X-ray diffraction analysis (XRD) and differential scanning calorimetry (DSC) studies.

2. Materials and experimental techniques

2.1. Materials

The starting materials used in this investigation are:

- (i) Ground granulated blast-furnace slag (GGBFS) was provided from Egyptian Tourah Portland Cement Company, Tourah,

Table 1
Chemical oxide composition of the starting materials.

Oxide (%)	GGBFS	LRS	FkS
Al_2O_3	8.22	1.45	18.60
CaO	42.59	71.00	1.00
SiO_2	35.38	2.14	74.6
Fe_2O_3	1.79	–	0.34
MgO	6.17	0.12	–
K_2O	0.49	–	0.05
Na_2O	0.58	–	0.26
SO_3	2.74	1.03	0.29
TiO_2	0.43	0.02	1.38
P_2O_5	0.01	–	0.13
MnO	0.76	–	–
Cr_2O_3	0.001	–	–
Cl^-	–	0.22	0.22
ZrO_2	–	–	0.26
L.O.I	0.84	23.90	2.78

Egypt; its chemical oxide composition is given in Table 1 and its Blaine surface area is about $3400 \text{ cm}^2/\text{g}$.

- (ii) Lime-rich sludge (LRS) was obtained as a waste product from acetylene gas industry, Egypt. The constituents of LRS are given in Table 1. LRS was burnt at temperature up to $1000 \text{ }^\circ\text{C}$ in an adjustable muffle furnace for 3 h. This process removes CO_2 and water leaving CaO (burnt lime). Hydrated lime ($\text{Ca}(\text{OH})_2$) was prepared by regulated addition of water to burnt lime, followed by drying at $120 \text{ }^\circ\text{C}$ for 3 h.
- (iii) Fine kaolinite Sand (FKS), sand contaminated with minor amounts of kaolin, was obtained (as a by-product during mineralization of kaolinite clay from Middle East Mining Investment Company (MEMCO). The particle size of FKS was $<125 \mu\text{m}$ with percentage moisture 5–7%. The chemical oxide composition is also given in Table 1.

2.2. Experimental techniques

Six dry mixes were prepared using different weight composition ratios of GGBFS, lime-rich sludge (after conversion to hydrated lime) and fine kaolinite sand as shown in Table 2. Each dry mixture was first mixed using ethanol for 2 h in order to ascertain a complete homogeneity of the mixture. After evaporation of ethanol, each dry mixture was mixed with water with a water/solid ratio in the range of 0.20 by weight and then cylindrical specimens having 2 cm diameter and about 2 cm height were molded under hydraulic pressure of 5.0 MPa. The molded specimens were cured at about 100% relative humidity at room temperature for the first 24 h in order to attain the final setting of the specimens. The hardened cement pastes were then cured under tap water for 3, 7, 28 and 90 days. At each time interval, the hydration of the hardened cement pastes was stopped using the method described in an earlier publication [21]. The samples were then dried at $100 \text{ }^\circ\text{C}$ for 3 h in a carbon dioxide-free atmosphere and kept into a desiccators containing soda lime and calcium chloride (CaCl_2) until the time of testing was reached.

Compressive strength tests were performed on the hardened cement pastes after 1, 3, 7, 28 and 90 days. At each curing time, three cylindrical specimens were subjected to the compressive strength test and the average value was recorded. This was accomplished using a Ton-industrial machine with a maximum load of 60 tons.

Hydration kinetics was studied by the determination of chemically combined water and free lime contents at different ages of hydration. Chemically combined water contents (W_n , %) were determined as follow [21].

Two representative samples of the dried specimens, exact about 1 g each, were weighted in porcelain crucibles and ignited for one hour at $1000 \text{ }^\circ\text{C}$ in an adjustable muffle furnace, cooled in a desiccator and then weighted. The chemically-combined water content (i.e., the amount of water retained after drying) was calculated as W_n (%) using the following equation:

Table 2
Mixes notation and their composition.

Mix	Composition (wt, %)
I	80% GGBFS + 20% LRS
II	75% GGBFS + 25% LRS
III	70% GGBFS + 30% LRS
IV	80% GGBFS + 20% LRS + 5% FKS
V	75% GGBFS + 25% LRS + 5% FKS
VI	70% GGBFS + 30% LRS + 5% FKS

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