



Study on engineering properties of alkali-activated ladle furnace slag geopolymer



Wei-Chien Wang^a, Her-Yung Wang^{b,*}, Hsin-Chieh Tsai^b

^a Department of Civil Engineering, Chung Yuan Christian University, Chung Li, 32023, Taiwan, ROC

^b Department of Civil Engineering, National Kaohsiung University of Applied Sciences, 807, Taiwan, ROC

HIGHLIGHTS

- The increased L/S dilutes the concentration of the alkali agent, which effects the engineering properties.
- A higher amount of alkali agent yielded greater engineering properties.
- Curing in saturated limewater promotes the polymerization reaction.

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ABSTRACT

Geopolymers, a new form of aluminosilicates, are environmentally friendly materials. These materials are produced from industrial wastes. This study, based on the industrial waste, Ladle furnace slag (LFS), employed an alkali-activated technology to activate LFS. The fixed alkali modulus ratio ($\text{SiO}_2/\text{Na}_2\text{O}$) was 1. LFS Geopolymer was prepared at different liquid/solid ratios (L/S) of 0.35, 0.40 and 0.45 and with different alkali agents of 4%, 6% and 8%. The LFS Geopolymer was cured under various conditions (air and saturated limewater) to evaluate the mixture and engineering properties of LFS Geopolymer at different ages. The results show that the workability of the LFS geopolymer increased with an increasing L/S and alkali agent. Moreover, the compressive strength and ultrasonic velocity increased with an increase in the alkali agent and a decrease in L/S, but the weight loss was reduced. Therefore, the appropriate use of alkali-activated technology can activate LFS, thereby enhancing its engineering properties. Curing in saturated limewater can greatly improve the engineering properties of the geopolymer compared to air curing. Specifically, the compressive strength of LFS increases by 5.4–58.9%, and the ultrasonic velocity of LFS increases by 0.84–22.9%. The thermal conductivity increases by 0.166–0.443 W/m-K, and the overall shrinkage of LFS cured in the saturated limewater ranges between 0.0017% and 0.0342%, which is far lower than samples cured in air, thus indicating that curing in saturated limewater can effectively prevent LFS shrinkage.

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1. Introduction

With the increasing severity of natural disasters caused by global warming and environmental problems, great importance is attached to energy conservation, carbon reduction and environmental protection. Civil engineering materials are turning to green renewable resources and sustainable development [1]. Due to rapid economic development and improvement in people's living standards, the use of cement is escalating, with the promotion of public construction and high-rise buildings. In the cement production process, tons of energy is consumed, and large amounts of car-

bon dioxide are emitted. The production of 1 ton of cement produces 0.85 ton of carbon dioxide, exerting an immense impact on the environment [2]. The total CO_2 emission from the cement manufacturing industries worldwide accounts for 5–7% of all global greenhouse gas emissions [3]. In an effort to tackle these environmental problems, alternative materials must be found.

The iron and steel industry is thriving, and the product grades are gradually improving. Steel slag is a waste material, or by-product, of the steel-making process. An enormous amount of steel slag is generated worldwide; for example, Europe alone generates nearly 20 million tons of steel slag every year [4,5]. This ladle furnace slag can effectively fill the voids of concrete because LFS has a composition similar to that of water quenching blast furnace powder (which consists mainly of CaO and SiO_2), a pozzolanic and

* Corresponding author.

E-mail address: wangho@cc.kuas.edu.tw (H.-Y. Wang).

cementaceous material that has the cementing properties of cement and a pozzolanic reaction, thus rendering the entire system more compact [6]. Therefore, using LFS resources as a cementing material can convert this industrial waste into a reusable resource and attain the goal of carbon reduction.

Geopolymers are three-dimensional aluminum silicate inorganic polymers composed of $[AlO_4]$ and $[SiO_4]$ tetrahedral that are typically prepared from aluminum silicates or industrial wastes and mixed with an alkali silicate solution under highly alkaline conditions [7,8]. Unlike cement, which is bonded by hydration, geopolymers utilize chemical bonding [9]. The production of alkali-activated cements allows the use of a wide range of materials (both minerals and byproducts) with compositions within the systems of $SiO_2-Al_2O_3$ or $SiO_2-Al_2O_3-CaO$, such as blast furnace slag [10].

The reaction mechanism and strength development of the geopolymer are influenced by the type and concentration of the alkaline solution, curing temperature, curing conditions and specific surface area. The alkali activator is designed to activate multiple calcium aluminum silicate minerals and is the most important factor in the hydration of these aluminum silicate minerals. Currently, the commonly used alkali activators include sodium silicate, sodium carbonate and NaOH. NaOH has a significant effect on the structure and the compressive strength of geopolymers during geopolymerization. Concentrated NaOH ensures the better coupling of the solid particles both in the aqueous phase and in the final structure of the geopolymeric system [11]. Additionally, the concentration of the alkali activator is the second most important factor for the hydration process and structural strength development. The structural strength effect of the alkali activator increases with the increase of its concentration. A low-concentration alkali activator has a low structural strength and a low hydration rate. Under highly alkaline conditions, polymerization occurs when reactive alum inosilicates dissolve rapidly, releasing free $[SiO_4]^-$ and $[AlO_4]^-$ tetrahedral units into the solution. The tetrahedral units are alternatively linked into a polymeric precursor by sharing an oxygen atom, thereby forming polymeric Si–O–Al–O bonds [12,13], but these materials are easily weathered and fragile. These problems can be addressed by adding different minerals and non-shrinkage agents, curing in water or in other ways [14]. Because water content and forming pressure has a significant effect on the mechanical strength and sorptivity performance of geopolymer, particularly in the fabrication of geopolymer pressed block [15]. This is because both water content and forming pressure have a direct influence on the total porosity of the geopolymer matrix [16].

This study focused on LFS, which contains silicon and aluminum oxide. Steel slag was processed in a polymerization reaction using alkali-activation to prepare a ladle furnace slag geopolymer paste. Then, the engineering properties of LFS were evaluated.

2. Experimental

2.1. Experimental materials

This study used LFS provided by Walsin Lihwa. The NaOH used in this study was in the form of a white sheet and was used to prepare a 10 M activator solution with laboratory deionized water. The solution was packaged and stored in acid and alkali bucket. Sodium silicate was sticky, colorless and tasteless liquid.

2.2. Experimental mixture and variables

This test included a total of 9 proportion groupings. The fixed alkali modulus ratio (SiO_2/Na_2O) was 1. LFS Geopolymer was prepared using L/S of 0.35, 0.40 and 0.45 and alkali agents of 4%, 6% and 8%. The test curing was carried out in air (D) saturated limewater (W). The curing in saturated limewater was conducted according to the ASTM C511 specification [17]. Ratios of material in mixture are shown in Table 3.

First, NaOH, sodium silicate and water were mixed well prior to use. The LFS was poured into a mixer for dry mixing and mixed again with the alkaline solution. After completing the mixing, the paste was poured into a cubic specimens of 50 mm × 50 mm × 50 mm and a long specimens of 25 mm × 25 mm × 285 mm. The molds were removed after 1 day. The samples were placed in air ($25 \pm 5^\circ C$) and saturated limewater curing grooves for curing. Mechanical properties tested were at 3, 7 and 28 days. The shrinkage of the LFS was tested at 1, 3, 7, 14, 21 and 28 days, and anti-sulfate attacks were tested at 28 days.

2.3. Experimental methods

The slump flow was measured according to ASTM C230 [18]. The ultrasonic velocity was tested in according to ASTM C597 [19]. The compressive strength was tested in according to ASTM C109 [20]. The thermal conductivity was measured with a portable heat transfer meter, and the thermal conductivity of the tested alkali-activated cementing materials was measured using a probe. Shrinking was carried out according to ASTM C157 [21]. Anti-sulfate attack was conducted according to ASTM C1012 [22]. Drying and soaking cycles in sulfate were performed, and a total of 5 cycles were conducted after 28 days to observe weight loss.

3. Results and discussion

3.1. Analysis of the physical and chemical properties of these materials

The physical and chemical properties of the materials used in this study are detailed in Table 1. The LFS mainly composed of CaO (48.6%) and SiO_2 (23.7%). Its chemical composition is similar to that of cement, and it has cementation and pozzolanic reactions. Due to insufficient polymerization, sodium silicate was added to supplement the Si ions and thereby enhance colloidal polymerization. Additionally, 10 M NaOH (98% purity) was used to activate the LFS in the geopolymer preparation. The TCLP poison dissolution results are shown in Table 2. The TCLP result for LFS was mainly composed of Ba (0.80421%), followed by Pb (0.024897%), whereas the remaining compositions are low or not detected. This indicates the raw materials leached less amounts of heavy metals.

3.2. Slump flow

Fig. 1 shows that when the L/S increased from 0.35 to 0.45, the slump flow values increased by 9.3–86.1%, suggesting that increasing the L/S can effectively enhance the workability of the geopolymer. When the L/S was 0.45 and the alkali agent increased from 4% to 8%, the slump flow increased from 155% to 183%. These results show that the slump flow value increases with increasing alkali agent, primarily because the alkali metal silicate solution is relatively sticky, improving the workability.

Table 1
The physical chemistry properties of Materials.

Chemical analysis (%)						
Ladle furnace slag	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Cr_2O_3
	23.7	4.2	1.21	48.6	8.1	0.01
Silicate solution	SiO_2	Na_2O	Fe	Water insoluble matter	SiO_2/Na_2O	
	28–30	9–10	0.02	0.2	2.8–3.3	
NaOH	NaOH	$NaCO_3$	NaCl	Fe		
	98.2	0.165	0.0135	0.0004		
	Specific gravity		Fineness(cm^2/g)		°Bé	
Ladle furnace slag	2.85		5500		–	
Silicate solution	1.38		–		37	

Note: Baume degrees (°Bé) was a method of solution concentration.

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