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Compressive strength of one-part alkali activated fly ash using red mud as alkali supplier

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HIGHLIGHTS

- One-part mix alkali activated materials were developed using only waste materials.
- Fly ash with high unburned carbon content was used as an aluminosilicate precursor.
- Red mud was used as a NaOH supplier in the geopolymerization of fly ash.
- UCS of inorganic polymers activated with red mud and NaOH were measured.
- The developed materials can be used as controlled low strength materials.

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ABSTRACT

Because both fly ash with high unburned carbon particles and red mud are waste materials with very low reuse rates, the reuse of these two waste materials is environmentally and economically beneficial. This experimental investigation aims at developing one-part mix alkali activated materials using only waste materials. Therefore, this study uses fly ash with high unburned carbon particles (or high loss on ignition) as an aluminosilicate precursor and uses red mud as a NaOH supplier in the geopolymerization of fly ash. The results of this study demonstrate that the unconfined compressive strength of the developed one-part fly ash inorganic polymers activated with red mud increases with an increase in red mud content because of the active dissolution of silica and aluminum with an increase in red mud and a consequent promotion of the polycondensation process. The comparison between the inorganic polymers activated with red mud and NaOH pellets reveals that the relation between compressive strength and the Na/Si ratio of the tested inorganic polymers activated with red mud is almost the same as that of the tested inorganic polymers activated with NaOH, reflecting that all solid NaOH (or Na_2O) in red mud can be dissolved to form highly alkaline solutions. Therefore, one-part alkali activated fly ash can be synthesized using red mud as a solid alkali activator.

1. Introduction

Fly ash is the fine residue generated from the combustion of pulverized coal. In Korea, around 60% of fly ash is beneficially reused, and the largest markets for the reuse of fly ash are the cement and concrete industries [9]. However, recent fly ashes in Korea contain relatively high content of unburned carbon particles; thus, it is expected that the amount of disposed fly ash in Korea is increasing due to the regulation of ASTM C618 [5]. Red mud is the alkaline residue generated from alumina extraction through the Bayer process. Because the Bayer process includes the digestion of bauxite ore in sodium hydroxide solutions, red mud has very high alkalinity, resulting in very limited reuse of red mud [11,34,35]. Therefore, the reuse of fly ash with high unburned carbon particles and red mud is environmentally and economically beneficial.

Due to the continuous increase in air emission regulations or environmental concerns, a number of attempts have been made to replace ordinary Portland cement with an environmentally friendly and economical substitute such as inorganic polymer binders, which is called alkali activated material or geopolymer. The geopolymerization or polycondensation reaction occurs when the amorphous alumina- or silica-rich materials such as metakaolin, fly ash, blast furnace slag, and others are mixed with highly alkaline solutions such as sodium (or potassium) hydroxide and/or

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sodium (or potassium) silicate [8,16,25,27,33]. Although inorganic polymer technology was developed around 40 years ago and has been studied by numerous researchers, the massive use (or bulk production) of alkali activated materials in industry has been very limited up to now because the alkaline activator solution in the traditional two-part mix inorganic polymers (mix of aluminosilicate precursors with alkaline activator solutions) are not cost effective, along with high carbon footprint compared to Portland cement [1,23,26]. Additionally, the alkaline activator solution is corrosive and viscous [2,13,14,17,22]. Therefore, these previous studies developed the concept of the one-part mix inorganic polymer (involving the idea of "just add water" to the dry mixture of aluminosilicate precursors and solid alkaline activator).

The aim of this experimental investigation is to develop one-part mix alkali activated products using only waste materials. Therefore, this study uses fly ash with high unburned carbon particles (or high loss on ignition) as an aluminosilicate precursor and uses red mud as a NaOH supplier in the geopolymerization of fly ash. Consequently, this study reports the variation of the unconfined compressive strength (UCS) of fly ash activated with red mud as a function of red mud content. Additionally, for a comparison with the results of developed alkali activated materials using only waste materials, the UCS values of one-part mix fly ash inorganic polymers activated with NaOH pellets are reported as a function of NaOH mass content (= mass of NaOH/total mass) in this study.

2. Experimental program

2.1. Materials

Five different fly ashes (FA 1, FA 2, FA 3, FA 4, and FA 5) were sampled from five different power plants in South Korea. Additionally, the red mud, which was used as an alkali activator for the geopolymerization of fly ashes, was supplied by the KC Corporation in Korea. Table 1 shows the major chemical compositions for fly ash samples and a red mud. Most notably, Table 1 indicates that the loss on ignition (LOI) of all tested fly ashes is greater than 6%, indicating that the reuse of the tested fly ashes in the concrete industry is very limited [5]. Additionally, it is notable that an inverse relation can occur between the mass contents of SiO_2 and LOI in Table 1, which might reflect that the reactive silica content decreases with an increase in LOI. Sodium hydroxide (NaOH) pellets (>98%) were obtained from Daechung Chemicals, Korea, and were used as received. Distilled water was used in all experiments.

Fig. 1 indicates the particle size distribution curves of the tested materials determined by laser diffraction method, and Table 2 shows the basic index properties of the tested materials, which were determined according to ASTM D854 for specific gravity (G_s); liquid nitrogen adsorption method using BET theory for specific surface (S_a); and fall cone method (British Standard 1377) for liquid limit (LL).

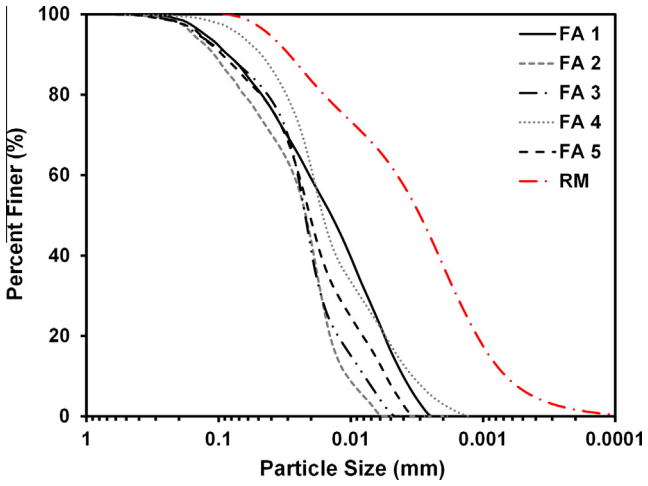

Fig. 1. Particle size distributions of 5 fly ashes and 1 red mud used in this study.

Table 2
Index properties of tested materials.

Type	D_{50} (μm)	C_u	G_s	S_a (m^2/g)	LL (%)
FA 1	12	5.00	2.25	5.35	37.0
FA 2	21	2.80	2.13	2.57	33.8
FA 3	22	2.75	2.28	3.31	36.5
FA 4	15	5.31	2.34	4.72	28.6
FA 5	20	4.55	2.22	2.00	35.4
RM	3	7.21	3.18	9.79	52.5

Note: FA = fly ash; RM = red mud; D_{50} = median particle size; C_u = uniformity coefficient; G_s = specific gravity; S_a = specific surface; LL = liquid limit.

2.2. Testing program and sample preparation

Five fly ash samples were mixed with the red mud in the dry state to obtain a varying red mud content (RM_C = mass of red mud/total mass), ranging from 0% to 60% (Table 3). Because each mixture of fly ash and red mud with different RM_C has different characteristics, around 1.2 times liquid limit water was added to each solid mixture with varying RM_C to obtain proper workability. Additionally, for the comparison of the developed inorganic polymers activated with red mud, the one-part mix fly ashes activated with NaOH pellets were prepared at varying NaOH contents (mass of NaOH / total mass) (Table 3). Note that all of the fly ashes were used for the synthesis of inorganic polymers activated with red mud, while three fly ashes (FA 1, FA 2, and FA 5) were used for the synthesis of inorganic polymers activated with NaOH.

After mixing of the fly ash-red mud (or fly ash-NaOH pellets) mixture and water for 15 min in a laboratory mixer, the inorganic polymer paste was poured into 50 mm cubic molds, and allowed to sit for 1 day at room temperature. The molds were then placed in a slightly elevated oven (~60 °C) for 3 days of curing. After removing the inorganic polymer blocks from the molds, the blocks were

Table 1
X-ray fluorescence analysis of tested fly ashes (FA) and red mud (RM).

Type	SiO_2	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	Na_2O	P_2O_5	TiO_2	LOI
FA 1	42.05	20.06	4.73	7.27	1.13	1.17	1.52	0.60	1.27	19.20
FA 2	48.39	20.33	1.41	5.19	1.56	0.48	0.38	0.50	1.18	19.70
FA 3	58.60	17.37	3.94	5.30	1.22	0.97	1.99	0.40	1.05	8.00
FA 4	50.61	22.37	3.78	6.37	1.66	1.28	0.98	1.44	1.02	9.60
FA 5	60.04	18.43	2.86	4.05	1.59	1.06	1.95	0.40	0.97	7.50
RM	18.30	21.60	2.76	29.45	0.03	–	12.02	0.13	6.26	9.10

Note: unit of numbers in table = weight%; LOI = loss on ignition.