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The engineering properties of alkali-activated slag pastes exposed to high temperatures

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HIGHLIGHTS

- The workability increases relative to an increase in the alkali-activated when the liquid-to-solid ratio is fixed.
- The increase in alkali-activated significantly influences the setting time.
- The same trend is observed at high temperature, but the ultrasonic pulse velocity decreases as the liquid-solid ratio increases.
- The shear waves are reflected when they encounter defects in the objects or at the boundary of the objects.
- The infrared energy radiated from the absolute zero of the thermal image analysis.

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ABSTRACT

Alkali cementations material is a recent and new type of environmentally friendly and economical material that is produced from industrial waste (e.g., fly ash and slag). This material possesses many excellent engineering properties, including a high compressive strength, light weight and low thermal conductivity.

This study used different liquid–solid ratios, alkaline solutions and slag to produce pastes. The findings showed that the slump and slump flow of the alkali-activated slag pastes increased with the alkaline solutions and liquid–solid ratio. Without any slow setting additive, the setting rate could be reduced by reducing the alkaline solutions. After different curing ages at high temperatures, residual compressive strength, ultrasonic pulse velocity and thermal imaging tests. The findings showed that the ultrasonic pulse velocity and compressive strength of the alkali-activated slag pastes increased with the increase in the alkali-activated solution. The engineering properties declined as the liquid–solid ratio increased, but the workability improved. The increase in the alkaline solutions could enhance the compressive strength at high temperatures; the compressive strength of 0.5% alkali-activated at 500 °C was 30–50% of that of 1% alkali-activated. The ultrasonic pulse velocity at the high temperature of 500 °C was 2171–3322 m/s; the ultrasonic pulse velocities of 0.75% and 1% alkali-activated at 800 °C were 2605 m/s and 2812 m/s, respectively, but the ultrasonic pulse velocity of 0.5% alkali-activated 0.5% was only 2211 m/s. The alkaline solutions of 0.75% alkali-activated and 1% alkali-activated were sufficient to finish the polyreaction within a short period of time to afford a material that possessed low porosity and high strength material. The results show that research on alkali-activated slag significantly contributes to energy saving and carbon reduction.

1. Introduction

With the rapid growth of metropolitan populations and the rapid development of metropolitan areas observed in recent years, residential buildings have become more integrated, more densely packed and more composite based, and fire events are likely to happen due to carelessness [1]. The main concepts behind the current fire performance of the buildings and the development of fireproof construction are to suppress the damage to enhance the safety of the persons occupying the space and to improve the

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reusability of the buildings [2]. Therefore, the high temperatures experienced in fires can damage, to different extents, the primary structural members, such as beams, columns, boards and walls, in the reinforced concrete structures. The more severely damaged structures collapse in the fire, whereas the slightly damaged structural elements are mostly reusable after repair with appropriate reinforcement. Therefore, to determine whether the building structures after the fire should be demolished or repaired appropriately before reuse, there should be a rapid evaluation method with appropriate reliability [3].

Concretes based upon Portland cement exhibit weak performance when subjected to thermal treatment, and when the temperature increases above 300 °C, they begin to disintegrate. Alkali-activated binders show a high degree of stability when submitted to high temperatures of even approximately 1000 °C [4]. Other authors [5] have studied the activation of metakaolin and shale wastes and have reported a high mechanical performance after a thermal treatment. Those specimens show some slight strength loss between 600 °C and 1000 °C; however, they show a strength increase at 1200 °C in some cases. Kong et al. [6] studied alkali-activated metakaolin binders and observed that the residual strength after a thermal treatment, up to 800 °C, was influenced by the Si/Al ratio. Higher residual strengths were obtained using the mixtures with a Si/Al ratio between 1.5 and 1.7. Krivenko and Guziy [7] found that the alkali-activated binders exhibited high fire-resistance performance, thus suggesting that this material is suitable for use in works with high fire risks, such as tunnels and tall buildings. Perna et al. [8] confirmed that alkali-activated binders can be used as a 120 min anti-fire material in accordance with the related standards of the Czech Republic. The anti-fire material must show a temperature lower than 120 °C on the opposite side of the fire. Temuujin et al. [9] used alkali-activated binders as steel coatings, stating that they maintained high structural integrity even after being submitted to a heat treatment with a gas torch. Zhao and Sanjayan [10] compared the performance of OPC concrete and alkali-activated concrete under the standard curve of the fire test, mentioning that only the former exhibited spalling behavior. The internal pore structure of the latter allows for the rapid escape of water vapor, resulting in lower internal pore pressures [11].

Due to Taiwan's small area, dense population and minimal natural resources, the construction industry universally uses traditional reinforced concrete structures; the main cementitious material for reinforced concrete structures is Portland cement. The cement sintering temperature is as high as 1300–1400 °C, and the CO_2 emissions of the global cement manufacturing industry account for 5–7% of global greenhouse gas emissions [12]. At present, with the increase in environmental considerations, various countries have started to focus waste pollution. Therefore, searching for alternative energy and materials is currently an important topic. Actively developing an inorganic cementing material with low energy consumption and low CO_2 emissions has become an urgent issue for the civil engineering community, and an alkali-activated cementing material is one of the potential possibilities [13].

The strongly alkaline solution activates the slag activity for a polyreaction and an alkali resistance reaction, as well as for low shrink, low thermal conductivity, freeze–thaw resistance and a significant duration [14–18]. The hardened slag possesses good compressive strength, rapid hardening, resistance to chemical attack, low degree of permeability and better fire resistance, and it can solidify toxic heavy metals [19–20]. The importance of the hydration process is well known when the replacement ratio is low because of the impermeability, enhanced flowability and higher strength at high temperature [21]; findings have shown that as the hydration of modeling cement increases, the overall reaction of slag is usually influenced by the glass chemical content and size distribution, and the production conditions determine the reactivity [22–24]. Therefore, if this material's excellent characteristics are discussed in depth, it can become a new generation of environmentally friendly, green energy materials that can replace cement in the future.

2. Materials and experimental details

2.1. Materials

This study uses ground granulated blast furnace slag produced by the China Steel Corp. and pulverized by the China Hi-Ment Corporation; the properties of this slag conform to the specifications of CNS12549: the specific gravity is 2.89, and the fineness is 4000 cm^2/g. The chemical properties of this slag are shown in Table 1. The alkali silicate solution is a No. 3 sodium silicate solution produced by Rong Xiang Industrial Co., Ltd. The sodium silicate solution is also known as water glass, and it is a viscous, colorless and tasteless liquid; the chemical properties of this solution are shown in Table 2. A commercially available piece of alkali with a purity of 98% is used, and it is mixed with deionizer water into a 5 N NaOH in the laboratory and then sealed in a clean acid- and alkali-resistant barrel. The chemical properties of this material are shown in Table 3.

2.2. Test variables and mix proportions

The liquid–solid ratios of the sodium silicate solution were 0.50, 0.55 and 0.60, and the variation in the 5 N alkali-activated was 0.5%, 0.75% and 1% the recycled slag material was used to test the fresh properties and engineering properties. Were added sequentially slag, alkali-activated, sodium silicate solution is added last, the mixing time is set to 12 min. The residual properties at 200 °C, 500 °C and 800 °C were tested at the curing age of 28 days. The high-temperature flow chart is shown in Fig. 1. The unit weights in the mix design proportion are shown in Table 4.

2.3. Test methods

The test items in this study include slump (ASTM C143), slump flow (ASTM C230M-03), setting time (ASTM C756), compressive strength (ASTM C39), ultrasonic pulse velocity (ASTM C597), shear wave velocity (ASTM D6429) and thermal image (ASTM C1153) tests.

3. Results and analysis

3.1. Fresh properties

Table 5 shows that when the water glass addition increases with the liquid–solid ratio, the slump also increases, and when the alkali-activated is fixed at 0.5% and the liquid–solid ratio is 0.50, the slump (70 mm) is 30 mm smaller than the slump (100 mm) at the liquid–solid ratio of 0.60. The slump flow also increases with a corresponding increase in the alkali-activated; when the liquid–solid ratio is 0.60, the slump flow (143 mm) when the alkali-activated is 0.5% is improved by 50 mm when compared with an alkali-activated of 1.0%. The results show that the workability increases relative to an increase in the alkali-activated when the liquid-to-solid ratio is fixed. The increase in alkali-activated significantly influences the setting time. When the liquid–solid ratio is 0.55 and the alkali-activated is increased from 0.5% to 1.0%, the initial setting time is shortened by 70 min and the final setting time is shortened by 116 min. If the alkali-activated

Table 1
The chemical properties of slag.

Oxide	Results (%)
L.O.I.	0.58
SiO_2	33.47
Al_2O_3	14.79
Fe_2O_3	0.40
CaO	41.61
MgO	6.11
SO_3	0.65
Sulfide sulfur	0.65