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Flexural strength of notched concrete beam filled with alkali-activated binders under different types of alkali solutions

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HIGHLIGHTS

- Sustainable repair binding material using waste materials.
- Role of GBFS content and kinds of alkaline solutions on bonding strength.
- FA + GBFS activated with SHSS solution give highest flexural strength of notched PCC beam.
- SHSS provided high flexural strength of notched PCC beam than those of SH and SS.

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ABSTRACT

This article investigates the flexural strength of notched Portland cement concrete (PCC) beams filled with alkali-activated binders (AAB). The low calcium fly ash (LFA) and ground granulated blast furnace slag (GBFS) are used to develop AAB. The bond strength performance between notched PCC beam and AAB has been studied. A different mix of AABs were investigated: those are low calcium fly ash (LFA) paste, FA + GGBS paste and GGBS paste with three different types of alkaline solutions viz., 10 M sodium hydroxide solution (SH), sodium silicate solution (SS), and 10 M sodium hydroxide mixed with sodium silicate solution solutions (SHSS). The flexural strength of notched PCC beams filled with AABs at different influence factors are tested under three point bending. Test results evident that the flexural strength of PCC notched beams tends to slightly increase with increasing of GBFS content for all kinds of alkaline solutions. The fracture surface of specimens is reasonable to bond strength obtained. The notched PCC beams filled with FA + GBFS activated with SHSS solution provides the highest 28-day flexural strength of 3.57 MPa. This research attempts to use waste materials as a promoter in AAB as an alternative repair material, which is significant in addressing the sustainable use of waste materials in terms of engineering, economical and environmental perspectives.

1. Introduction

The applications of Portland cement are essential to the rapid urbanization in many developing countries. High mechanical performances with low cost are an advantage of Portland cement. However, the increasing of Portland cement manufacture corresponds to energy and environmental issues. Metz et al. [1] reported that high emission of carbon dioxide (CO_2) emission from Portland cement manufacture is approximately 7% of the total worldwide emissions to atmosphere, and causes of greenhouse effect. Attempts to reduce its carbon dioxide (CO_2) by reducing the use of Portland cement is one effective approach to solve the global warming issue. Logesh Kumar and Revanti [2] reported that Portland cement can be partially replaced by fly ash (FA), ground granulated blast furnace slag (GBFS), rice husk ash, and metakaolin. However, Portland cement cannot be fully replaced by any materials. To solve this problem, new binder is needed to use instead of Portland cement for enhancing environment which is having less CO_2 footprint than Portland cement as reported by McLellan et al. [3]. An environmental friendly binder material studied in this research is the Alkali-activated binders (AAB).

The development of AAB has been widely studied in recent years. This is because of its advantages over Portland cement in

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terms of CO_2 emission [4]. The AAB can be classified into two systems: (1) the activation of blast furnace slag with mild alkaline solution and (2) the activation of metakaolin or low calcium fly ash with medium to high alkaline solutions [5]. The main reaction products of alkali-activated blast furnace slag are calcium silicate hydrate (C-S-H) and/or calcium aluminosilicate hydrate (C-A-S-H) gels which is similar to those of Portland cement reaction products [6]. While the main product of alkali-activated metakaolin or low calcium fly ash is sodium aluminosilicate hydrate (N-A-S-H) gel [7]. Li et al. [8] also explained that the reaction products of alkali-activated blast furnace slag system is different to alkali-activated metakaolin or low calcium fly ash system. The reaction product of sodium aluminosilicate hydrate (N-A-S-H) gel provided the low strength development under ambient temperature curing [9], and thus temperatures between 40 and 85 °C is needed to accelerate the reaction [10]. Whereas the reaction products of calcium aluminosilicate hydrate (C-(A)-S-H) gel showed excellent in strength development cured at ambient temperature than sodium aluminosilicate hydrate (N-A-S-H) system [8]. Despite it has a complex between two systems but coexistence of calcium aluminosilicate hydrate (C-(A)-S-H) and sodium aluminosilicate hydrate (N-A-S-H) gels proved excellent mechanical properties cured at ambient temperature as reported by several researchers [9–12]. Recently, there is enabled AAB for using as sustainable binder in some application of construction work. For example, the AAB made from calcium carbide residue and fly ash was used to stabilize marginal lateritic soil as a sustainable pavement base material [13]. A sustainable non-bearing masonry units manufactured from calcium carbide residue and fly ash was investigated by Horpibulsuk et al. [14]. Also, a novel low-carbon masonry units made from recycled glass-fly ash geopolymer was conducted by Arulrajar et al. [15]. In addition, Phoo-ngernkham et al. [16] studied on compressive strength, bending and fracture characteristics of AAB mortar which made from high calcium fly ash and Portland cement cured at ambient temperature. It was found that the flexural strength and fracture characteristics of AAB were similar to Portland cement system, therefore, it can be used as an alternative binder.

Nowadays, high-performance repair material is essential to the concrete repair. Xiong et al. [17] reported that the repair materials can be classified into three kinds: those are cement-based materials, polymer modified cement-based materials and polymer or resin materials. Even though the resin-based repair material has an excellent mechanical properties, they are rather expensive. As mention, alternative low cost repair material with excellent mechanical properties should be considered. Current research works on this area have been focused for developing new kinds of repair materials as per the literature reviews [12,18,19]. The use of AAB where made from metakaolin and granulated blast furnace slag (GBFS) as precursors to protective coating for marine concrete and transportation infrastructures have been recently reported [20–22]. Most researches focused on a sustainable protection for marine concrete structures. Pacheco-Torgal et al. [23] studied on the potential of AAB for concrete infrastructure rehabilitation. One of the most important properties of alternative repair material is bond strength between concrete substrate and repair materials [24]. Many publications [12,18,19,25–27] have studied the bond strength between two materials by using slant shear test. Pacheco-Torgal et al. [26] also studied the bond strength between concrete substrate and repair materials. It is indicated that alkali-activated tungsten mine waste provided higher bond strength and more cost effective than the commercial repair materials. Also, Hawa et al. [25] attempted to develop a very high-early strength AAB which have high compressive and bonding strengths with low drying shrinkage. The excellent in bonding strength is found with failure modes occurred through concrete substrate use of alkali-activated high calcium-based cured at ambient temperature [12,18,19]. Moreover, some publication [28] has attempted to use alkali-activated metakaolin as a pavement repair materials by using splitting and slant shear tests. Duan et al. [29] has conducted on development of alkali-activated metakaolin as a repair material with waterproof properties, fast setting and high-early strength for enhancing the durability of concrete in the road concrete repair or as protection coatings for marine concrete. Other topics are referred to in the literatures such as Pacheco-Torgal et al. [23] and Phoo-ngernkham et al. [19]. They studied on the flexural strength of notched concrete beam filled with repair materials for evaluating the performance of alkali-activated tungsten mine waste and alkali-activated high calcium fly ash compared to commercial repair materials. Based on an extensively literature review on AAB, they can be used as repair material with low cost and excellent properties.

The objective of this research is, therefore, to investigate the flexural strength of notched PCC beams filled with AAB made from ground granulated blast furnace slag (GBFS) and low calcium fly ash (LFA) with different types of alkali solutions. The obtained knowledge would be very beneficial to the understanding and to the future application of alkali-activated binders as fundamental of alternative repair material.

2. Experiment procedure

2.1. Alkali-activated binders

Alkali-activated binders (AAB) was manufactured from low calcium fly ash (LFA) from Hekinan power plant and ground granulated blast furnace slag (GBFS) from Nippon Steel and Sumitomo Metal Corporation. 10 M sodium hydroxide (SH) and sodium silicate (SS) with 11.67% Na_2O, 28.66% SiO_2, and 59.67% H_2O were used as liquid activators with a constant liquid alkaline to binder ratio of 0.60. 10 M SH solution was used for this study because it provided high compressive strength as reported by previous studies [30,31]. For the preparation of 10 M SH, sodium hydroxide pellets of 400 g was dissolved by distilled water of 1 L and then allowed to cool down for 24 h before use [32]. The chemical compositions of LFA and GBFS are illustrated in Table 1. The sum of $SiO_2 + Al_2O_3$, and Fe_2O_3 of LFA is 86.20% and the CaO oxide is 3.32%. This LFA has been classified as class F Fly Ash as per ASTM C618 [33]. The GBFS consists of 30.53%SiO_2, 13.67%Al_2O_3, and high CaO oxide of 46.0% as the main chemical compositions. The LFA has specific gravity of 2.20, median particle sizes of 12.3 μm, and Blaine fineness of 3150 cm^2/g, while GBFS has specific gravity of 2.91, median particle sizes of 12.4 μm, and Blaine fineness of 4930 cm^2/g, respectively. They are used as precursors for making AAB. The microstructure of LFA and GBFS has discussed in previous study [12] that the LFA consists of spherical particles with smooth

Table 1
Chemical compositions of LFA and GBFS (by weight).

Materials	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	TiO_2	SO_3	Other oxides	LOI
LFA	52.31	27.04	6.85	3.32	1.23	1.29	1.15	1.47	0.99	2.75	1.60
GBFS	30.53	13.67	0.33	46.00	5.09	0.36	0.24	–	0.80	2.76	0.22