



Waste glass as partial mineral precursor in alkali-activated slag/fly ash system

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ARTICLE INFO

Keywords:

Waste glass
Alkali activated material
Microstructure
Fly ash
Slag

ABSTRACT

The feasibility of a waste glass powder residue (GP) from glass recycling as partial mineral precursor to produce alkali-activated materials is investigated. GP served as powder coal fly ash (PCFA) replacement within a reference system composed of 50% PCFA and 50% ground granulated blast furnace slag (GGBS). Compared with PCFA, GP was better involved in the alkali activation process by having a higher silica and Ca dissolution. Furthermore, increasing GP replacement up to 30% prolonged the induction period, facilitated the gel formation and yielded a 35% higher 28-day compressive strength. These observations are similar to the effect of using both sodium hydroxide and sodium silicate as alkali activator in alkali-activated slag/fly ash systems. A higher polymerization of the gel network was also observed. Microstructure analysis indicated that the main reaction product is a calcium silicate hydrate type gel substituted with Al and Na (C-(N)-A-S-H type gel).

This work largely contributes to the understanding of the reactivity and potential of GP and promotes its practical utilization as a mineral precursor in the production of alkaline cements.

1. Introduction

Fast growing world population and its related industrialization have raised concerns about the environmental consequences of waste handling. Nowadays, many industries have started investing in optimization of waste disposal management systems to fulfill the national and international legislations. The development of a circular economy of mineral waste materials within the Netherlands and the European Union (EU) has been found to be highly potential and economical profitable. The potential waste materials are promoted to be recycled and re-used as primary or secondary raw materials in other industrial processes to lower their negative environmental impacts and preserve natural resources.

Within glass industry, the glass recycling has reached a relatively high average rate (> 70% in the EU and > 90% in the Netherlands) [1]. However, there are still some challenges related to non-recyclable glass fraction which does not meet the criteria for reuse in the production process of new glass. About 20,000 tons/year of such glass residue (glass powder and glass granular) are produced in the Netherlands [2] and most of this waste is sent to landfills. One possible solution for managing this waste glass fraction is to use it as a solid precursor in building materials. Previous studies [3–5] have already

shown attempts to incorporate glass fractions into Ordinary Portland cement (OPC) concrete, with general focus on replacement of fine aggregate. However, their use as supplementary cementitious materials (SCMs) in OPC concrete is still scarce.

In recent decades, alkaline activation technology has emerged as an effective tool able to use different wastes and industrial by-products as solid precursors to produce cementitious materials. Compared with OPC, alkali activated materials (AAMs) offer a large reduction in CO₂ emissions (up to 80%) [6] and have comparable or better performance (such as high mechanical strength at early ages, high stability in aggressive environments and resistance to elevated temperatures). Fly ash and blast furnace slag are currently the most intensively used solid precursors to produce alkali activated cement/concrete [7–10]. Many researchers have found that the binary system of alkali-activated slag/fly ash has an improved mechanical properties and durability [11–13]. The enhanced mechanical performance and durability of alkali-activated slag/fly ash have attracted great attention by both scientific community and construction industry. The previous studies on alkali-activated slag/fly ash are mostly on the microstructure and mechanical properties, as well as some efforts on understanding the chemical makeup and formation mechanism of the reaction products [10,14,15].

To our best knowledge, studies on using waste glass in alkali-

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<http://dx.doi.org/10.1016/j.cemconres.2017.08.012>

Received 29 November 2016; Received in revised form 9 August 2017; Accepted 11 August 2017

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activated slag/fly ash systems are still rare. Only few studies dealing with waste glass as precursor in AAMs can be found in the literature. For instance, Tashima et al. [16] investigated the properties and microstructure of glass fiber waste activated by alkaline metal sodium (Na) and potassium (K) solutions. A compressive strength of 77 MPa was found for mortars activated by 10 M NaOH solution and cured for 3 day at 65 °C. Pascual et al. [17] used metakaolin (MK) to replace a part of the GP to introduce Al and also to stabilize alkali ions in the system and observed increment of the compressive strength with MK content of up to 8%. In contrast, the compressive strength decreased when the content of the MK was lower than 3%. Redden et al. [18] reported that NaOH activated GP provides higher compressive strength than NaOH activated fly ash. Through microstructural analysis, they observed that the main reaction product was a sodium silicate gel in alkali activated GP, while a combination of sodium silicate and sodium aluminosilicate (N-A-S-H) gels was identified in GP-fly ash blends. Torres-Carrasco et al. [19,20] investigated the possible use of waste glass as an activator in alkali activated slag mortar and found that using NaOH/Na₂CO₃ and glass mixture solution as activator increases the compressive strength.

This work presents an investigation on the utilization of waste glass as partial mineral precursor in alkali-activated slag/fly ash systems for production of alkaline cements. The main aim is to valorize this kind of waste to enlarge its utilization in other industrial processes and to promote a sustainable construction.

2. Materials and methods

2.1. Materials

The mineral precursors used in this study are a granulated blast furnace slag (GGBS), a class F powder coal fly ash (PCFA) according to ASTM C 618 and a waste glass powder (GP) residue fraction supplied by Van Gansewinkel Maltha, the Netherlands. Unlike ordinary GP which is manufactured by crushing and grinding, this fine GP residue fraction is collected during the bottle glass recycling process. Material density for GGBS, PCFA and GP are 2890 kg/m³, 2440 kg/m³ and 2174 kg/m³, respectively. Their particle size distribution curves are shown in Fig. 1, with d50 particle size to be 17.88 μm for GGBS, 33.19 μm for PCFA and 5.07 μm for GP. Chemical compositions of all precursors were determined by X-ray fluorescence (XRF) considering the loss on ignition (LOI) at 950 °C and is shown in Table 1.

The alkaline activator solution was prepared by dissolving NaOH pellets (analytical grade, purity ≥ 98%) in distilled water. The selected NaOH concentration is 4 M, which is defined to be optimal taking into

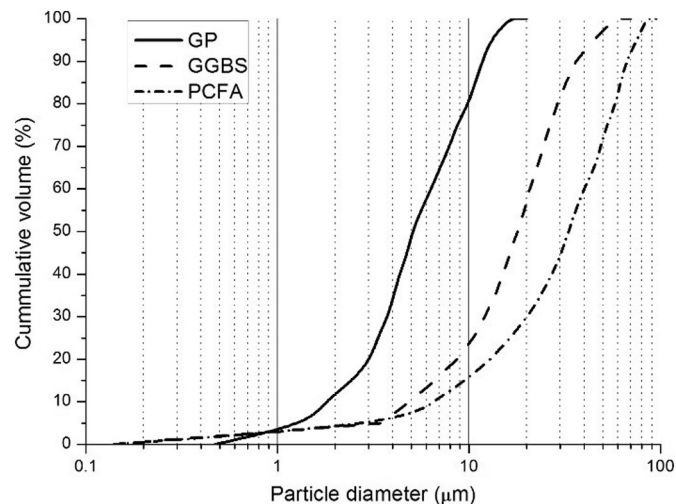


Fig. 1. Particle size distribution of GP, PCFA and GGBS.

Table 1
Chemical composition of solid precursors by XRF.

Oxide (wt%)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O	K ₂ O	LOI ₉₅₀
GP	65.60	2.37	2.40	22.06	2.17	0.39	1.99	0.86	2.00
PCFA	52.90	26.96	6.60	4.36	1.50	0.73	0.17	–	3.37
GGBS	32.91	11.84	0.46	40.96	9.23	1.60	–	0.33	1.15

Table 2
Paste mixture designs.

Sample	L/S ratio	Activator	GGBS (wt%)	PCFA (wt%)	GP (wt%)
R	0.42	4 M NaOH	50	50	0
G10		Solution		40	10
G20				30	20
G30				20	30

account the fresh and hardened performance of alkali activated GGBS/PCFA system [21–24] as well as the final costs.

2.2. Methods

2.2.1. Mix design

The starting point was a reference mixture of 50% PCFA and 50% GGBS (named R). Through a partial replacement of PCFA by GP, 3 paste mixtures with 10%, 20%, and 30% of GP (named respectively G10, G20 and G30) were prepared. The mix design of 4 mixtures is shown in Table 2. To study different levels of GP to PCFA replacement as main variables, the liquid to solid (L/S) ratio was kept at 0.42 to maintain a suitable workability for all the investigated mixtures. The solid precursors were firstly mixed for 5 min using a HOBART® mixer at a low speed. Alkaline activator solution was then added gradually and the batches were mixed for additional 5 min at a medium speed. The fresh paste mixtures were cast in polystyrene prism molds (40 mm × 40 mm × 160 mm) and then compacted with a vibration table for four times (each time for 30 s) before finally sealed with a plastic foil. The samples were cured in a climate room (20 °C and ≥ 98% RH) until testing.

2.2.2. Testing methods

The reactivity of both GP and PCFA were measured by chemical dissolution treatment as described elsewhere [25–27]. The solid minerals were dissolved in the concentrated acid solution and were afterwards treated with boiling potassium hydroxide solution. The obtained residue was rinsed, heated up to 950 °C and then was cooled to room temperature in a desiccator. The dissolved fraction corresponding to the mass loss after chemical dissolution treatment is determined as the amorphous phase content. The amount of reactive SiO₂ and Al₂O₃ was also calculated.

Element dissolution tests of PCFA and GP in alkali activator solution were performed following the modified NEN 7341 standard [25]. In total 5 g of mineral powder was added into 50 ml of NaOH solution and stirred at 300 rpm using a magnetic stirrer. For each precursor, different dissolution times were set as 5 min, 0.5 h, 1 h, 2 h, 6 h and 12 h. After these times, the solutions were separated from the remaining solids through vacuum filtration using a 45 μm glass micro-filter paper. The eluate was acidified with 5 vol% nitric acid and diluted 100 times before the Si, Al, Ca concentrations were measured using an Optima 5300 DV inductively coupled plasma optical emission spectrometry (ICP-OES).

Mechanical properties and microstructural characterization tests were performed on paste samples cured for 1, 7, and 28 days as follows:

- Compressive strength was measured in accordance with NEN-196-1 [28] at 1, 7, and 28 days.

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