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Effect of granulated lead smelter slag on strength of fly ash-based geopolymer concrete

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HIGHLIGHTS

- Granulated lead smelter slag is an effective supplementary cementitious material.
- Particle size has significate influence on compressive strength.
- Mechanical properties of concrete with slag are similar to those with fly ash.
- The addition of lead smelter slag results in a decrease of the drying shrinkage.

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ABSTRACT

Geopolymer concretes are manufactured from high-volume industrial waste materials in order to produce concrete that is low energy consuming, has a low carbon footprint, is sustainable and Portland cement-free. This paper presents an experimental study on the manufacture and behaviour of geopolymer concrete produced with a combination of granulated lead smelter slag (GLSS) and fly ash. The experimental program included 32 mix designs to investigate the influence of: fly ash replacement with slag as a binder, washed river sand replacement with slag as a filler, slag particle size to reactivity, alkaline activator-to-binder ratio, and curing period. It was found that incorporating 75% of slag as fly ash replacement and 100% of slag as fine aggregate produces concrete exhibiting compressive strength of 31 MPa. It was also found that significant improvements in the compressive strength of the hardened concrete (i.e., from 6 MPa to 65 MPa) could be obtained by super fine crushing the slag to a fineness similar to Portland cement and fly ash (<20 μm). The results showed that the mechanical properties of the fly ash/slag-based geopolymer concrete were similar to that of fly ash-based geopolymer concrete, whilst the drying shrinkage of geopolymer concrete containing high volume of GLSS was lower than that of fly ash-based geopolymer concrete.

1. Introduction

Geopolymer concrete, also known as alkali-activated cement [1], inorganic polymer concrete [2], and geocement [3], has emerged as an innovative engineering material with the potential to form Ordinary Portland Cement (OPC)-free concrete for both structural and non-structural applications [4]. Geopolymer concretes are commonly formed by synthesising industrial aluminosilicate waste materials, such as metakaolin, fly ash and slags, with a highly alkaline activator solution. The use of industrial waste materials in the manufacture of concrete not only introduces economic and environmental benefits [5], but it also resolves issues associated with the disposal of large volumes of waste materials, such as ash from coal-fired power stations and slags from metal production operations, which may otherwise jeopardise the environment [6]. There is therefore a compelling case to explore the use of geopolymer concretes manufactured from a range of waste materials as a sustainable alternative to traditional OPC concrete technologies.

The use of fly ash as the cementitious source in the manufacture of geopolymer concrete has been intensively investigated with regard to both the mechanism of geopolymerisation, as well as the mechanical properties of the resulting concrete. It has been shown that in general Class-F fly ash is the most suitable binder for manufacturing geopolymer concrete as the resulting product exhibits superior mechanical properties [7–14] and durability

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under thermal loading and in the presence of aggressive chemicals [15–18].

In industrially advanced countries increasing stringency in greenhouse gas emission regulations have created a degree of uncertainty in the longevity and sustainability of fly ash resources as coal-fired thermal power plants are increasingly being replaced with greener energy production technologies. There is therefore a need to develop suitable alternatives to fly ash in order to further drive the commercialisation of geopolymer concrete technology. A potential alternative can be found in slags obtained from various mineral processing operations. As shown in Fig. 1 and Table 2 these slags can have markedly different chemical compositions to typical Class-F fly ash [19] and as a result have been shown to improve the strength of geopolymer concretes manufactured using fly ash. For example, ground granulated blast furnace slag (GGBFS) was found to increase the compressive strength of Class-F fly ash-based geopolymer concrete due to the presence of calcium oxide (CaO). Yip and van Deventer [20] and Yip et al. [21] proved that it is possible to have geopolymeric aluminosilicate hydrate (A-S-H) gel and calcium silicate hydrate (C-S-H) gel forming simultaneously within a single binder. Copper slag was successfully integrated with OPC as cement clinkers, fine aggregate and coarse aggregate [22–25].

Whilst it has been shown that GGBFS is a viable cementitious material for the manufacture of geopolymer concrete, other forms of slags that are abundant have received less research attention. For instance, granulated lead smelter slag (GLSS), which is the focus of this paper, is an industrial waste material that is a by-product of heavy metal extraction during lead smelting process. The production of lead world-wide was estimated to be 3.9 million tonnes in 2009 from both primary and secondary resources [26], and the production of each ton of metallic lead generates around 100–350 kg of slag that is known as granulated lead smelter slag [27]. Despite its abundance, the studies on the behaviour of GLSS have so far focused on their characterisation and stability [27–31], and only one study to date has investigated the mechanical behaviour of geopolymer concretes and was limited in that only up to 10% maximum substitution of fly ash with GLSS was investigated [26]. Given the availability and potential suitability of GLSS for the use in structural and non-structural geopolymer concrete manufacture, it is of particular importance to understand the mechanical behaviour of GLSS-based geopolymer concrete.

1.1. Research significance

Geopolymer concrete has been the focus of a significant recent research interest due to its ability to solve environmental issues surrounding the greenhouse gas emissions of OPC manufacture, as well as those associated with the dumping of industrial waste materials. With this research effort, geopolymer concrete has moved beyond a laboratory-based technology into the real world; for example, the building of Global Change Institute (GCI) in the University of Queensland was completely built out of geopolymer concrete using fly ash as a binder [32].

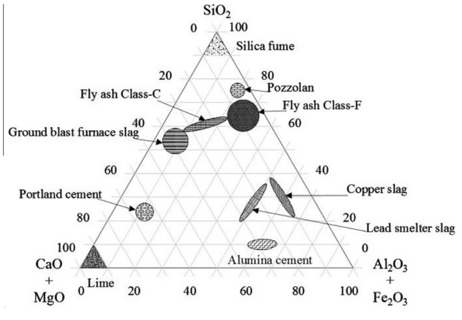

Fig. 1. Illustration of chemical compositions in cementitious materials.

Table 1
Mixture proportions.

Materials	Mixture proportions (kg/m^3)
Binder	424.8
Coarse aggregate	1180.8
Fine aggregate	595.2
[a]NaOH with Na_2SiO_3	156.7
Superplasticiser	31.2
Water	9.84

[a] Except for mixes 17 and 19, which had 212.4 kg/m^3 of NaOH with Na_2SiO_3, and mixes 18 and 20, which had 318.4 kg/m^3 of NaOH with Na_2SiO_3.

Alternatives to Class-F fly ash for use as a cementitious material in the manufacture of geopolymer concrete are required in order to further drive commercialisation and reduce costs, as well as to fill gaps in supply left by increased regulation around coal-fired power stations. Thus, the aim of this research is to find a supplementary or replacement binder for fly ash in the form of a previously untapped source of slags, namely granulated lead smelter slag (GLSS). This work is undertaken with the primary aim of identifying if GLSS can be used as a partial or full replacement for fly ash in the manufacture of structural grade geopolymer concretes.

The secondary aim of the research is to investigate the reactivity of the GLSS of various grain size distributions. This is done with the intent of identifying the minimum level of grinding required to achieve specific grades of concrete thereby minimising the greenhouse gas emissions associated with the energy intensive process of grinding. Finally, the potential of using GLSS as a filler is investigated to determine if it can be utilised in high volumes in the geopolymer concrete industry, thus reducing current stockpiles. Each of these aims represents the first investigations in the use of GLSS at high proportions, with previous studies reporting only on the use of GLSS as a replacement of up to 10% of the primary binder.

2. Experimental program

A total of 32 mix designs were trialled to quantify the influence of granulated lead smelter slag (GLSS) on the compressive strength of fly ash geopolymer concrete. The mixes are based on the results of previous studies conducted at the University of Adelaide by Nguyen et al. [33] who investigated the particle size of ashes, including bottom ash, middle ash and fly ash, and Albitar et al. [7] who investigated the water-to-binder (w/*b*), superplasticiser-to-binder (sp/*b*) and activator-to-binder (*a*/*b*) ratios of fly ash-based geopolymer concrete. It should be noted that both of these studies used identical materials to the current study. The mix proportions of the current study are presented in Table 1.

To investigate the influence of fly ash replacement with GLSS as a binder, five different fly ash-to-GLSS ratios were investigated (0, 0.25, 0.5, 0.75, and 1). To investigate the influence of washed river sand (WRS) replacement with GLSS as fine aggregate, four different WRS-to-GLSS ratios were considered, namely 0, 0.5, 0.75, and 1. To investigate the influence of GLSS particle size, four different fractions of unground GLSS were examined, including 550 μm, sub 400 μm, sub 250 μm, and sub 150 μm, additionally seven different grading of ground GLSS, these gradings were identified based on their D_{50}, that is the grain size of which 50% material passes namely 70 μm, 63 μm, 43 μm, 20 μm, 11 μm, 8.2 μm, and 5.8 μm. Finally,

Table 2
Chemical compositions by mass (%).

Oxides	Fe_2O_3	SiO_2	Al_2O_3	CaO	MgO	SO_3
Granulated lead smelter slag (Current study)	33.8	27.5	7.4	19.4	2.1	–
Lead smelter slag (de Andrade Lima et al. [27])	28.1	21.4	3.6	23.1	5.44	–
Fly ash (Current study)	2.8	49.0	31.0	5.4	2.5	0.3
OPC (Chi and Huang [8])	2.9	21.0	5.4	63.5	2.5	2.0
GGBFS (Chi and Huang [8])	0.44	34.5	13.7	40.6	7.1	0.56