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Utilisation of steel furnace slag coarse aggregate in a low calcium fly ash geopolymer concrete

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ABSTRACT

This paper evaluates the performance of steel furnace slag (SFS) coarse aggregate in blended slag and low calcium fly ash geopolymer concrete (GPC). The geopolymer binder is composed of 90% of low calcium fly ash and 10% of ground granulated blast furnace slag (GGBFS). Mechanical and physical properties, shrinkage, and detailed microstructure analysis were carried out. The results showed that geopolymer concrete with SFS aggregate offered higher compressive strength, surface resistivity and pulse velocity than that of GPC with traditional aggregate. The shrinkage results showed no expansion or swelling due to delayed calcium oxide (CaO) hydration after 320 days. No traditional porous interfacial transition zone (ITZ) was detected using scanning electron microscopy, indicating a better bond between SFS aggregate and geopolymer matrix. Energy dispersive spectroscopy results further revealed calcium (Ca) diffusion at the vicinity of ITZ. Raman spectroscopy results showed no new crystalline phase formed due to Ca diffusion. X-ray fluorescence result showed Mg diffusion from SFS aggregate towards geopolymer matrix. The incorporation of Ca and Mg into the geopolymer structure and better bond between SFS aggregate and geopolymer matrix are the most likely reasons for the higher compressive strength observed in GPC with SFS aggregate.

1. Introduction

The increasing potential threats to environment imposed by CO_2 have promoted the development of inorganic polymer binder called 'geopolymer' which involves the reaction between solid aluminosilicate materials with alkaline solutions. Geopolymerisation is an inorganic polycondensation reaction of alumina-silicate source materials (e.g. fly ash, slag and metakaoline) that yields three-dimensional tecto-aluminosilicate frameworks [1]. These frameworks are known as poli-sialates, where sialate (Si-O-Al) network consists of silicate (SiO_4) and aluminate (AlO_4) tetrahedras linked by sharing all oxygen atoms. Positive ions like sodium (Na^+) must be present to balance the negative charge of aluminium ions in 4-fold coordination [1]. The precursor contains aluminium and silicon species that are soluble in highly alkaline solutions. The dissolved species then undergo polycondensation to attain matrix structural integrity [2]. Geopolymer concrete (GPC) shows excellent performances and therefore, it has the potential to be a suitable alternative to OPC concrete [3–7].

The growing demand for aggregates to produce concrete for large scale infrastructure is depleting the natural resources. In order to preserve the natural resources, an effort has been noted over the last decades to utilise industrial waste or recycled materials in concrete production. Steel furnace slag (SFS) aggregate has been studied and proposed as a potential alternative to natural aggregates. Steel furnace slag, a by-product of steel making, is produced during the separation of molten steel from impurities in steel-making process in the basic oxygen furnace (BOF). The slag occurs as a molten liquid, which is a complex solution of silicates and oxides that solidifies upon cooling [8]. Steel furnace slag is dark grey in colour and characteristically harder than blast furnace slag (BFS) and has a density about 20–25% greater than basalt or BFS [9]. Steel furnace slags are highly angular in shape and have rough surface texture [8]. They also have moderate water absorption, <3%. Steel furnace slag has high deformation resistance, high wet and dry strengths, high impact resistance and high abrasion and skid resistance [10].

The cooling rate of steel furnace slag is sufficiently low so that crystalline compounds are generally formed [8]. The predominant compounds are wustite, magnetite, larnite, dicalcium silicate, tricalcium silicate, dicalcium ferrite, merwinite, calcium aluminate, calcium–magnesium iron oxide, and some free lime and free magnesia [8,11,12]. The relative proportions of these compounds depend on the steel-making practice and the steel furnace slag cooling rate. Free lime and magnesium oxides are not completely consumed in the steel furnace slag and hence steel furnace slag generally exhibits a propensity to expand in humid environments [8]. The free lime hydrates rapidly and can

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cause large volume changes over a relatively short period of time (weeks), while magnesia hydrates much more slowly and contributes to long term expansion that may take years to develop [13,14].

The viability of SFS aggregates as a potential alternative to natural aggregates in OPC concrete has been investigated in a number of previous studies by assessing the impact of using SFS aggregate on strength and durability of concrete [15–22]. However, in general, the composition of SFS aggregate varies across the world, leading to a lack of consistency in the results reported in the literature, suggesting SFS aggregate-based concrete performance to be sensitive to the grading and the chemical and physical properties of the SFS aggregate used, as well as the percentage of natural aggregate replaced by SFS aggregate and the experimental protocols.

But in practice, the main barrier for application of SFS aggregate in OPC concrete is its potentially expansive nature (volume changes up to 10% or more attributable to the hydration of free CaO and free MgO) [23] that could cause concrete cracking. As a result, SFS aggregates are considered not suitable for use in OPC concrete. Instead, due to their skid resistance, high impact and crushing strength compared to natural rocks and excellent affinity to bitumen, SFS aggregates are widely used for road construction [8].

In this paper, an alternative option for use of SFS aggregate in concrete is proposed. The idea is to incorporate SFS aggregate in a low calcium fly ash geopolymer binder. The drastic difference in calcium and magnesium contents between the SFS aggregate and the binder paste might cause free CaO and free MgO to diffuse towards the geopolymer matrix and be consumed in geopolymerisation reactions, minimising the risk of delayed expansion. To date, very limited attempt has been made to investigate the behaviour of SFS aggregate in geopolymer concrete. Palankar et al. [14] investigated the performance of geopolymer concrete by utilising SFS aggregates. However, the focus of this study was placed mainly on exploring the fatigue of geopolymer concrete made with SFS aggregate. To assess the suitability of SFS as coarse aggregates for geopolymer concrete, a thorough understanding of the effects of SFS aggregate on mechanical and durability properties of geopolymer concrete as well as, capability of geopolymer matrix to minimise or accommodate potential expansions caused by the free lime content of SFS aggregate is required. In this study, the mechanical, physical properties and shrinkage were assessed. Furthermore, the microstructure of geopolymer concrete with SFS aggregate was investigated using scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS) and Raman spectroscopy.

2. Experimental program

2.1. Materials

2.1.1. Geopolymer binders

Low calcium FA (class F), ultra-fine FA also known as Kaolite high performance ash (HPA) and GGBFS were used in this study as aluminosilicate sources. Low calcium FA and Kaolite HPA were obtained from Eraring Power Station in New South Wales, Australia and Callide Power Station in Queensland, Australia respectively while GGBFS was obtained from Australian Steel Mill Services, Port Kembla, New South Wales, Australia. The chemical compositions of the cementitious materials are shown in Table 1. The geopolymer binder is composed of 90% of low calcium fly ash and 10% of ground granulated blast furnace slag (GGBFS) and can be categorised as a low calcium content binder.

A mixture of sodium hydroxide (NaOH) solution and sodium silicate (Na_2SiO_3) solution were used with the ratio of 1:2.5 (by mass) according to Hardjito and Rangan [24]. The technical grade NaOH pellets obtained from Ajax Finechem were used to prepare NaOH solution and 361 g of NaOH pellets were dissolved into 639 g of Sydney tap water in order to obtain 12 M NaOH solution. The Na_2SiO_3 solution was obtained from PQ Australia and has a chemical composition of $Na_2O = 14.7\%$, $SiO_2 = 29.4\%$ and $H_2O = 55.9\%$ (by mass) with a modulus ratio (M_s) of 2 ($M_s = SiO_2/Na_2O = 2$). The activator solutions were mixed together 24 h prior to usage.

Table 1
Chemical compositions of cementitious materials.

Chemical composition and physical properties	Fly ash (wt.%)	Kaolite HPA (wt.%)	GGBFS (wt.%)	OPC (wt.%)
SiO_2	66.56	45.14	31.52	18.83
Al_2O_3	22.47	33.32	12.22	4.97
Fe_2O_3	3.54	11.99	1.14	2.84
CaO	1.64	4.13	44.53	63.82
MgO	0.65	1.37	4.62	1.03
Na_2O	0.58	0.07	0.21	0.3
K_2O	1.75	0.13	0.33	0.66
TiO_2	0.88	2.19	1.03	0.27
SO_3	0.1	0.48	3.24	3
Loss on ignition (LOI)	1.66	0.41	0.79	4.45
Specific Gravity	2.1	2.4	2.8	3.2

2.1.2. Aggregates

Sydney sand with specific gravity of 2.65 and water absorption of 3.5% was used as fine aggregate. SFS aggregate and basalt were used as coarse aggregate. The material characterisation of SFS aggregate will be discussed in the following sections. The nominal size of crushed basalt was 10 mm with specific gravity of 2.8 and water absorption of 1.6%. To accurately adjust the mix water, all aggregates were oven dried to drive away the moisture content and then water was added to ensure a saturated surface dry (SSD) condition.

2.2. Concrete mix design and batching procedure

Four types of concrete were cast; two were GPC with basalt and SFS as coarse aggregate and these mixes are referred to as GPC_BAS and GPC_SFS, respectively. The other two were OPC concrete with basalt and SFS as coarse aggregate which are referred to as OPC_BAS and OPC_SFS, respectively. The details of these mixes are presented in Table 2. It is to be noted that free water was added to both geopolymer mixes to control the workability. All mixes contain same binder content and the volume of coarse aggregate was kept constant for all mixes. This was done based on the SSD density of SFS aggregate and basalt which were 3.29 t/m^3 and 2.5 t/m^3, respectively.

For the case of geopolymer concrete, the solid contents except GGBFS were mixed dry for 5 min then for a further 15 min mix while gradually adding the alkaline solution and then the free water. To avoid rapid setting, GGBFS was added at the last stage and the mixing

Table 2
Mix proportions of geopolymer and OPC concrete.

Materials	GPC_BAS (kg/m^3)	GPC_SFS (kg/m^3)	OPC_BAS (kg/m^3)	OPC_SFS (kg/m^3)
Coarse aggregate	1221	1662	1221	1662
Fine aggregate	620.8	620.8	620.8	620.8
Fly ash	271.6	271.6	0	0
Kaolite HPA	77.6	77.6	0	0
GGBFS	38.8	38.8	0	0
OPC	0	0	388	388
NaOH solution	55.3	55.3	0	0
Na_2SiO_3 solution	138.7	138.7	0	0
Free water	13.3	13.3	175	175
Coarse aggregate/fine aggregate	1.97	2.68	1.97	2.68
Total binder (OPC or SCM)	388	388	388	388
Activator/SCM	0.5	0.5	N.A.	N.A.
Water/binder[a]	0.28	0.28	0.45	0.45
Na_2SiO_3/NaOH	2.5	2.5	N.A.	N.A.
Molarity of NaOH solution	12 M	12 M	N.A.	N.A.

[a] When calculating the water/binder ratio, water includes free water and the water present in the alkaline solutions.