



Durability evaluation of geopolymer and conventional concretes



M. Albitar^{a,*}, M.S. Mohamed Ali^b, P. Visintin^b, M. Drechsler^c

^aSchool of Civil, Environmental and Mining Engineering, University of Adelaide, South Australia 5005, Australia

^bSchool of Civil, Environmental and Mining Engineering, University of Adelaide, Australia

^cUniversity of Adelaide, Engineering Geologist SMEC, Australia

HIGHLIGHTS

- Geopolymer concretes are superior to conventional concrete in an acidic environment.
- Fly ash and GLSS concretes are more chemically stable than conventional concrete.
- OPC concrete has lower water absorption and sorptivity than geopolymer concretes.
- Geopolymer concretes exhibit superior mechanical properties under chemicals attack.

ARTICLE INFO

Article history:

Received 3 November 2016

Received in revised form 16 January 2017

Accepted 17 January 2017

Keywords:

Durability

Fly ash

Lead smelter slag

OPC concrete

Geopolymer concrete

ABSTRACT

Durability of concrete strongly influences the service life of structural members. Durable concrete protects embedded reinforcing steel from corrosion and reduces the potential for concrete spalling under chemical attack. This paper evaluates the performance of geopolymer concretes manufactured using either class-F fly ash or blended fly ash and granulated lead smelter slag (GLSS). The performance of ordinary Portland cement (OPC) concrete is also investigated as a reference for evaluating the durability characteristics of geopolymer concretes. All concrete specimens were continuously immersed up to nine months in four different chemical solutions: 5% sodium chloride, 5% sodium sulphate, 5% sodium sulphate + 5% magnesium sulphate, and 3% sulphuric acid. Throughout the exposure period, the change in mass, compressive strength, splitting tensile strength, flexural strength, water absorption, sorptivity and porosity were evaluated. The influence of wetting–drying and heating–cooling cycles on the mass loss and compressive strength was also investigated. The results revealed that the OPC concrete has lower water absorption and sorptivity than the geopolymer concrete. Furthermore, it is shown that sodium sulphate has the greatest impact on geopolymer concretes, while OPC concrete is more susceptible to sulphuric acid attack. The results showed that, in general, the durability performance of geopolymer concrete is superior to that of OPC concrete within the range of the considered exposure.

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1. Introduction

Ordinary Portland Cement (OPC) concrete has long been used in construction of civil infrastructure and its deterioration over time due to sulphate attack has been widely observed and documented [1–4]. Investigations have revealed that the degradation of OPC concrete takes place due to reactions between cement hydration products and sulphate-bearing solutions. That is when concrete is exposed to poorly mineralised or acidic water, the acid leaches into the concrete and reacts with the concrete chemical components in a phenomenon known as diffusion-reaction [5]. Degradation of concrete strength due to sulphate attack takes place when

the calcium and hydroxide ions dissolve out of the matrix, causing an increase in porosity and permeability of the concrete surface [5]. The most susceptible products of cement hydration to sulphate attack are alumina-bearing phases and calcium hydroxide, as these two products produce calcium sulphoaluminate (ettringite) and gypsum when they react with sulphate [6]. The calcium hydroxide $\text{Ca}(\text{OH})_2$ decomposes at a pH level below 12, whereas calcium sulphoaluminate decomposes at a pH level below 11 [7].

Geopolymer concrete is a novel material prepared using alkali-activated binders, such as fly ash, lead smelter slag, ground granulated blast furnace slag and palm oil fuel ash [8–12]. Geopolymers have the potential to resolve major concerns surrounding the storage and disposal of wastes from mineral extraction and process industries by utilising these wastes as cementitious materials. Before geopolymer concretes can be widely adopted in commercial

* Corresponding author.

E-mail address: mohammad.albitar@adelaide.edu.au (M. Albitar).

applications, a clear understanding of durability characteristics of these new type of binders is required. Several studies have investigated the mechanism of fly ash geopolymer concrete degradation due to corrosion [13], sulphate attack [14], and acid attack [15], but only one study to date has investigated the selective sulfidation of lead smelter slag [16].

Despite the vast number of investigations conducted on the traditional concrete when exposed to sulphate ions, the degradation mechanism is yet to be fully understood, particularly for blended cements. Ramyar and İnan [6] stated that when calcium hydroxide reacts with sulphate ions, both monosulphate and hydrogarnet convert to ettringite and the formation of ettringite then causes expansion. This mechanism was further explained based on diffusion-reaction-based phenomenon. In a sulphate-bearing environment, the sulphate ions will react with portlandite (calcium hydroxide and calcium aluminates hydrate) and form gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), which in turn will react with products resulting from the hydration of C_3A to form calcium sulphoaluminate (ettringite). Both gypsum and ettringite can be expansive and this expansion results in the development of internal stresses that can damage the concrete and leads to a reduction in strength [5,17–19]. The chemical components of geopolymer concrete are different to that of OPC concrete in which geopolymers are formed from geopolymeric aluminosilicate hydrate (A-S-H) gel instead of calcium silicate hydrate (C-S-H) gel. Therefore, it is of particular importance to investigate the diffusion-reaction of geopolymer concrete. This paper investigates the durability characteristics of two different cementitious-based geopolymer, namely low calcium class-F fly ash and granulated lead smelter slag (GLSS), and compares their behaviour to the corresponding behaviour of similar OPC concrete.

Continuous immersion of test specimens does not necessarily represent service conditions. In service, concretes are usually subjected to environmental effects such as wetting–drying and heating–cooling, especially those near the coasts or those used in piping systems [20]. Marine environments are found to be very aggressive, since sea water consists mainly of sodium chlorides and sodium sulphates. In fact, heating–cooling cycles in combination with the presence of water and salts represent several degradation scenarios, such as freezing and thawing and chemical attack. In addition, heating–cooling and wetting–drying cycles are the prerequisite for several deterioration mechanisms, such as crystallisation pressure and thermal stresses. Therefore, it is essential to evaluate the mechanisms of deterioration in this case to be able to predict the behaviour of a concrete subjected to wet–dry and heat–cool conditions during its service life.

2. Experimental program

The present experimental program aims to investigate the durability characteristics of fly ash and lead smelter slag based geopolymer concretes exposed to chemical solutions and compare their behaviours to that of OPC concrete. The investigation involves two different programmes of accelerating the degradation: (i) continuous immersion in highly concentrated solutions up to nine months and (ii) wetting–drying and heating–cooling cycles up to ten cycles in which each cycle consists of full immersion for six days in 5% sodium chloride (NaCl) with 5% sodium sulphate (Na_2SO_4) solution and one day in an oven at a temperature of 110 °C. The chemical solutions used in the continuous immersion method were: (i) 5% sodium chloride (NaCl), (ii) 5% sodium sulphate (Na_2SO_4), (iii) 5% sodium sulphate with 5% magnesium sulphate (Na_2SO_4 with MgSO_4) and (vi) 3% concentric (10 N) sulphuric acid (H_2SO_4). The selection of sodium chloride and sodium sulphate was based on the dominance of chloride and sulphate-based environments, which have previously been shown to have

significant detrimental impact on concrete [3]. Additionally, magnesium sulphate was considered because it is generally accompanied with sodium sulphate in most coastal regions. Finally, sulphuric acid with pH level of 0.8 was considered in order to simulate the end conditions of biogenic corrosion in waste water sewers. That is because in sewer systems, the corrosion of concrete is initiated by chemical reaction in which the acidophilic sulphur oxidising microorganisms (ASOM) oxidises the hydrogen sulphide (H_2S) to sulphuric acid by bacteria of the genus *Acidithiobacillus* [21,22].

Two different exposure regimes were considered to expedite the degradation process and to simulate field conditions: (i) continuous immersion, or (ii) wetting–drying and heating–cooling conditions. Prior to undergoing exposure to chemical attack, all specimens were ambient cured for a period of 90 days. This extended curing period was considered important in order to ensure the hydration and geopolymerisation reactions were complete to avoid further strength development during the course of investigation. The selection of a 90-day curing period was based on previous research findings [11,12].

Following the commencement of exposure to chemical attack, the resistance of the concretes to the chemicals attack was observed by measuring (i) weight loss, (ii) compressive strength loss, (iii) flexural strength loss and (iv) splitting tensile strength loss. In addition, other significant parameters were also measured, such as stress–strain relationship, water absorption, sorptivity and porosity of the concretes.

2.1. Materials specifications

Three different concrete types were investigated including: a class-F fly ash-based geopolymer, a blended class-F fly ash and granulated lead smelter slag (GLSS) geopolymer and an OPC concrete. The chemical compositions of the fly ash, GLSS and OPC were determined by X-ray fluorescence (XRF) technique and the results are documented in Table 1. Fly ash and GLSS geopolymer concretes were activated by an alkaline solution phase consisted of a combination of sodium silicate (Na_2SiO_3) and 14 M sodium hydroxide (NaOH), pre-mixed with a ratio of Na_2SiO_3 -to-NaOH of 1:1.5. All mixes consisted of crushed coarse aggregate with a nominal maximum size of 10 mm. Washed river sand was used as a fine aggregate in both fly ash and OPC concretes, whereas raw GLSS was used as the fine aggregate in GLSS geopolymer concrete. Concrete mix proportions for all mixes are tabulated in Table 2.

2.2. Test procedure

All the solutions were made by adding laboratory grade chemicals to distilled water. Solid chemicals, such as sodium chloride, sodium sulphate and magnesium sulphate were dissolved initially in hot distilled water and then were diluted with distilled water maintained at a room temperature (23 ± 2 °C). All the solutions were replaced every two months to maintain their concentrations. A summary of the test measurement regimes for each chemical exposure is given in Table 3.

The cyclic immersion of specimens consisted of 10 cycles in which every cycle comprised of exposure to 5% NaCl with 5% Na_2SO_4 at room temperature for 6 days and 24 h in the oven at 110 °C. The solution was replaced with a fresh solution every two cycles (i.e., 14 days). The change in weight was measured at the end of each cycle, whereas the compressive strength measurements were performed every two cycles (i.e., 2, 4, 6, 8 and 10 weeks upon drying and cooling).

The other tests including determination of stress–strain relationship, water absorption, sorptivity and porosity were performed on all the immersed specimens at the end of the chemical exposure

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