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Recycling of geopolymer concrete

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HIGHLIGHTS

- The properties of recycled geopolymer aggregates (RGAs) are studied.
- The properties of geopolymer concretes made with RGA are studied.
- Recycling is an effective strategy for dealing with geopolymer concrete debris.

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ABSTRACT

Due to its considerably lower embodied carbon and making use of industrial by-products including fly ash and ground granulated blast-furnace slag, geopolymer concrete (GPC) is considered as a sustainable alternative to Portland cement (OPC) concrete. However, prior to granting GPC a green label and encouraging its widespread use, a number of other important possible impacts associated with this new material throughout its life cycle need to be further investigated. One of the important aspects of sustainability which has received little attention with regards to GPC is the end-of-life impact. While end-of-life strategies such as recycling and reuse have been widely investigated for conventional concrete, the applicability of such strategies to GPC has not been investigated. This paper presents the results of an experimental study conducted to investigate the recyclability of GPC. Basic properties of recycled geopolymer aggregates (RGAs) including water absorption, density and Los Angeles abrasion loss as well as the effects of size of RGA on these properties were investigated. In addition, the effects of the different replacement ratios of coarse RGA for coarse natural aggregates on the properties of the new recycled aggregate geopolymer concrete (RAG) including compressive strength, flexural strength and modulus of elasticity were investigated. The RGA and RAG properties were compared with those of recycled OPC concrete aggregate (RCA) and recycled aggregate OPC concrete (RAC) produced under relatively similar conditions.

1. Introduction

Cement production is one of the biggest contributors to global warming by accounting for 5–7% of the total worldwide emissions and about 17% of the total emissions related to construction and building industry [1]. A great deal of research has been conducted to reduce the amount of cement used by the construction industry through partial or complete replacement of Portland cement with supplementary cementitious materials. Perhaps, the most significant achievement in this area is the development of geopolymer concrete (GPC) [2].

GPC uses the reaction of certain alkaline liquids with the silicon (Si) and the aluminium (Al) in a source material of geological origin or in a by-product material such as fly ash, ground granulated blast furnace slag (GGBFS) and rice husk ash to produce cement-like binders [3]. Heat curing of low calcium GPC is generally considered necessary to produce the strength development rate required by the concrete industry. The elevated temperatures assist and greatly speed up the geopolymerisation chemical reactions. An optimal curing in terms of required maturity development at a reasonable energy use has been reported to be achievable with a curing duration of around 24 h and a curing temperature between 60 °C and 80 °C [4]. Due to the need for heat curing, the application of GPC in practice is currently limited mainly to precast concrete [5]. Improving the strength development rate of the geopolymer concrete cured at ambient temperature is a subject of worldwide research [5–7]. Incorporating additional NaOH and Na_2SiO_3 in the alkaline activator has been recommended as a potentially effective way to increase the strength development rate and ultimate strength of the ambient cured GPC [6]. However, further research is required to investigate the properties of such GPC mixes before

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implementation in practice. In the present study, the focus is placed on heat cured GPC as the currently viable alternative to OPC.

Mechanical properties, durability and microstructure of geopolymer concrete have been investigated widely in available literature. Compressive strength, tensile strength and modulus of elasticity of GPC have been found to be comparable to or greater than those of OPC concrete (OPCC) [4,8–13]; though the modulus of elasticity has been reported to be highly sensitive to the particular concrete mix design [14]. Creep strain of heat-cured geopolymers has been found to be lower than OPCC, with one study showing GPC may achieve a creep coefficient less than 50% of the recommended values by Australian Standard AS3600 (2005) for OPCC [15]. Heat-cured GPC has been also found to experience extremely lower drying shrinkage than typical OPCCs [2]. GPC has been also reported to perform better than OPCC in terms of sulphate and sea water resistance, acid resistance and fire resistance [16–23]. Furthermore, Castel et al. showed that bond strength between steel reinforcing bars and geopolymer concrete is significantly better than with OPC concrete for similar compressive strength [24].

The promising properties reported in available literature highlight GPC as an attractive candidate to replace Portland cement concrete (OPCC). The production of GPC reportedly requires up to 80% less energy use and carbon emissions than OPCC [25]. Moreover, apart from reducing the embodied energy and carbon of concrete, GPC could also contribute significantly to improving sustainability in construction by making use of industrial by-products including fly ash and slag. However, prior to granting GPC a green label, other significant environmental impacts associated with GPC should be further investigated. One of the important aspects of sustainability which has received little attention for GPC is its end-of-life impact. In particular, the availability of sustainable end-of-life strategies such as concrete recycling to deal with huge amount of debris that is expected to be produced upon adoption of GPC as a replacement for OPCC has not been investigated.

Dealing with the huge amount of concrete waste produced every day has been a major focus of research in the field over the past few decades. Concrete waste is one of the common components of the C&D waste produced worldwide, accounting for up to 40% of the total C&D waste flux in some countries [26,27]. The United States alone produces around 140 million tons of construction and demolition (C&D) waste each year, accounting for almost 29% of the total solid waste generated in the US [28]. China produces an approximately 200 million ton of waste concrete annually [29]. Europe is estimated to produce about 970 million tons of C&D waste annually [30]. In Australia, about 14 million tons of solid wastes are dumped in landfills annually and 44% of this total is estimated to be attributed to the construction industry [31]. Concrete recycling is one of the oldest and most effective waste management strategies for dealing with the enormous amount of concrete debris produced worldwide. Concrete recycling can reduce the costs and energy use incurred in the dumping of debris at remote landfills, reduce landfill space needed and provide a sustainable source of concrete aggregates by turning concrete debris to aggregates suitable for use in a new concrete [32]. The use of recycled concrete aggregates (RCAs) in new construction could reduce considerably the need for extraction of the natural aggregates (NAs). Extensive literature is available on different aspects of concrete recycling including effects of the production process and parent concrete properties on the properties of RCA, fine-tuning the production process and use of additional beneficiation processes to improve the quality of RCA, effects of different percentages of coarse and fine RCA replacement on the mechanical properties and durability of concrete, etc. [33–51]. However, to the best of our knowledge there has not been any report on a systematic study investigating the properties of the recycled geopolymer concrete aggregates (RGAs) and the new geopolymer concrete (RAG) made with different proportions of RGA replacement for natural coarse aggregate. The available literature on concrete recycling with respect to GPC is limited only to the use of recycled concrete aggregate produced from OPCC concrete debris in a geopolymer concrete matrix [12,52]. GPC is a relatively new material with a currently slow adoption rate and thus very little GPC is expected to be available in short term for recycling. However, investigating the recyclability of GPC, as a common method for reducing its end-of-life impact, may provide crucial input to evaluation of GPC's life cycle sustainability as a viable replacement for OPCC.

This paper reports the results of a comprehensive experimental study conducted to investigate the recyclability of low calcium fly ash GPC as a potential sustainable alternative to OPCC. Basic properties of RGA including 24-h water absorption, bulk density and Los Angeles abrasion loss as well as the effects of size of RGA on these properties were investigated. In addition, the effect of the different replacement ratios of coarse RGA on the properties of the new recycled aggregate geopolymer concrete (RAG) was investigated. To compare the recyclability potential of geopolymer concrete with that of OPCC, the properties of RGA and RAG were compared with the corresponding properties of recycled OPC concrete aggregates (RCAs) and recycled aggregate OPC concrete (RAC), respectively. To ensure fair comparison, relatively similar parent concrete grade, similar natural aggregates and similar crushing procedures were used to produce RGAs and RCAs. The mechanical properties considered include compressive strength, flexural strength and modulus of elasticity.

2. Experimental program

2.1. Concrete mix and batching

Fly ashes (FAs) from Eraring Power Station in New South Wales, Australia, Kaolite high-performance ash (HPA) from Callide Power Station in Queensland, Australia and ground granulated blast-furnace slag (GGBS) supplied by Ecocem (Ecocem Pty. Ltd., NSW, Australia) were used. The chemical compositions of FA, HPA and GGBS are summarised in Table 1. The geopolymer concrete was cast according to the mix proportion presented in Table 2. Basalt natural coarse aggregates with a maximum size of 13 mm and natural Sydney sand were used. The grading of coarse aggregates based on the results of sieve analysis is shown in Fig. 1. Bulk densities of virgin coarse and fine aggregates in oven dry (OD) condition were 2580 kg/m^3 and 2605 kg/m^3, respectively. Furthermore, the respective 24-h water absorption capacities of virgin coarse and fine aggregates were approximately 1.82% and 1.52%.

The alkaline solution was made from a mixture of 12 M (M) sodium hydroxide (NaOH) solution and sodium silicate solution with Na_2O = 14.7%, SiO_2 = 29.4% and H_2O = 55.9% by mass. A constant mass ratio of sodium silicate solution to sodium hydroxide solution of 2.5 was used and the mass ratio of alkaline solution to aluminosilicate material was 0.55. All specimens were placed in a temperature-controlled

Table 1
Fly ash and GGBFS chemical compositions.

Oxide	FA (wt.%)	Kaolite HPA (wt.%)	GGBFS (wt.%)
Silicon dioxide, SiO_2	66.56	45.14	31.52
Aluminium oxide, Al_2O_3	22.47	33.32	12.22
Iron oxide, Fe_2O_3	3.54	11.99	1.14
Calcium oxide, CaO	1.64	4.13	44.53
Potassium oxide, K_2O	1.75	0.13	0.33
Sodium oxide, Na_2O	0.58	0.07	0.21
Magnesium oxide, MgO	0.65	1.37	4.62
Manganese oxide, MnO	0.06	0.23	0.36
Phosphorus oxide, P_2O_5	0.11	0.56	0.02
Titanium oxide, TiO_2	0.88	2.19	1.03
Sulphur trioxide, SO_3	0.10	0.48	3.24
Loss of ignition (LOI)	1.66	0.41	0.79
Appearance	Grey	Dark grey	Chalky white