Construction and Building Materials 186 (2018) 454–475

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Mechanical and flexural performance of synthetic fibre reinforced geopolymer concrete

Amin Noushini [a,*], Max Hastings [a], Arnaud Castel [a], Farhad Aslani [b,c]

[a] Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, University of New South Wales (UNSW), Australia
[b] School of Civil, Environmental and Mining Engineering, University of Western Australia, Crawley, WA 6009, Australia
[c] School of Engineering, Edith Cowan University, WA 6027, Australia

ARTICLE INFO

Article history:
Received 18 February 2018
Received in revised form 5 June 2018
Accepted 14 July 2018

Keywords:
Polypropylene fibre
Fibre reinforced geopolymer concrete
Fracture toughness
Mechanical properties

ABSTRACT

A comprehensive experimental program was undertaken to analyse the structural and material characteristics of synthetic fibre reinforced geopolymer concrete. This study focused on the effect of monofilament and fibrillated polypropylene fibres and monofilament structural polyolefin fibres on mechanical and flexural performance of fly ash based geopolymer concrete. Five types of synthetic fibres at a 0.5% volume fraction were added to geopolymer concretes. The specimens' compressive strength, indirect tensile strength, modulus of elasticity, modulus of rupture, flexural toughness and fracture energy were determined. Where possible, comparative analyses where conducted to assess the performance of fibre reinforced geopolymer concrete against conventional Portland cement based systems. The flexural toughness parameters were obtained using procedure laid down in ASTM C1018, JCI-SF4 and ASTM C1609. The results indicated that the macro polyolefin fibres exhibited the largest fracture energy which is likely due to high mechanical bonding and low fibre aspect ratio. Relationships are established to predict the compressive and tensile strengths, modulus of elasticity, compressive stress–strain curve and relation between the deflection and CMOD of synthetic fibre reinforced geopolymer concrete.

1. Introduction and background

Concrete is the most widely used man-made material in the world. Ordinary Portland Cement (OPC), which is used as a binder in concrete, is associated with excessive consumption of natural resources. OPC production is a key contributor to global anthropogenic CO_2 emissions [1]. Most of the emission is generated from the chemistry of OPC production (i.e. calcination of limestone) and not the production methods or technology. Consequently, the concept of OPC replacement with more environmentally friendly materials has raised attention. Some industrial by-products such as fly ash (FA) and ground granulated blast furnace slag (GGBFS) are widely used as supplementary cementitious materials for partial replacement of OPC. Their prevalent use is attributed to their good cementitious and pozzolanic properties and relatively low price.

Geopolymers were first hypothesised by Davidovits in the late 1970s [2]. He conjectured that Aluminium (Al) and Silicon (Si) obtained from a geological source, or from by-products of industrial processes (e.g. fly ash and slag), had the potential to react with an alkaline liquid to form a strong polymer binder. It is now known that essentially any pozzolanic compound with a high Si and Al content in amorphous form, which is readily dissolved in an alkaline solution, will suffice as a geopolymeric precursor [3]. Motivation behind the study of this material not only resides in its enhanced sustainability but also potentially superior engineering properties.

The reason for concrete's unrivalled ubiquity as a construction material is its strength in compression. However, due to the material's brittle nature, its strength in tension is considerably inferior. A common approach to improve the post-peak performance of concrete is through the addition of randomly distributed short fibres as intrinsic reinforcement. Fibres have been shown to be effective in providing the necessary flexural performance in a timely manner [4,5]. Fibres bridge cracks, reducing their width and tendency to propagate, which increases post-elastic energy absorption (strain softening). This shifts the material's failure mode from brittle towards the more favourable ductile end of the spectrum.

Since Romualdi's et al. pioneering in the early 1960s [6,7], comprehensive research has been conducted on the effects of fibre addition to concrete matrices. The integration of steel fibres has

* Corresponding author at: School of Civil and Environmental Engineering, University of New South Wales (UNSW), Sydney, NSW 2052, Australia.
E-mail addresses: a.noushini@unsw.edu.au, a.noushini@gmail.com (A. Noushini).

https://doi.org/10.1016/j.conbuildmat.2018.07.110
0950-0618/

been comprehensively investigated and has revealed many benefits: improved tensile strength, flexural toughness, shrinkage, cracking and fracture toughness [7–14]. In the mid-1980 s synthetic fibres were introduced, broadening fibre reinforced concrete (FRC) research [5].

Polypropylene (PP) fibres are one of the cheapest and most abundantly available linear hydrocarbon polymer fibres [15]. PP fibres have some unique chemical properties that make them a good candidate for fibre reinforcement: high melting point, chemically inert hydrophobic nature and stability in alkaline environments. The microstructure of PP, as with many synthetic fibres, is arranged to encourage crystal formation, which leads to a good balance of chemical resistance and heat stability [16].

The vast majority of FRC research centres on OPC based concrete. Precedent research of fibre reinforced geopolymer concrete portrays a material with similar and in some cases superior post-peak behaviour [17]. Documentation of the effects of fibre reinforcement in geopolymer concrete (GPC) is still in its infancy, particularly in regards to GPCs with synthetic fibre reinforcement [18–23]. Throughout the review of the existing literature, it has become evident to the author that no significant research has been conducted on the flexural performance of fibre reinforced geopolymer concrete, particularly with the use of polypropylene and polyolefin fibres.

The limited research on this relatively new composite material is indicating the formation of a potentially tougher and more ductile system [21,24,25]. Heard et al. [21] investigated the properties of bundled monofilament polypropylene fibre reinforced geopolymer concrete (FRGPC). In their study, 41 mm fibres were used at a 0.25% volume fraction. Uniaxial tensile strength, flexural performance and fibre-matrix bond strength were studied. Their results show that PP fibres have the potential for crack bridging and slippage prior to fibre failure, which are vital criteria for global ductility enhancement. They concluded that bundled monofilament polypropylene fibres perform as well as fibre reinforcement in GPC. However, their tests do not probe the effects of different fibre contents or geometries, which is required to fully assess the benefits of this fibre reinforcement.

Bhutta et al. [24] investigated the flexural performance of several steel FRGPCs and compared the results with that of a length-deformed PP-FRGPC. They have concluded that the application of 0.5% volume fraction of macro fibre reinforcement enhances the flexural toughness of FRGCs. The steel-FRGPCs significantly outperformed the PP-FRGPC due to the advantageous fibre intrinsic properties, shape and higher fibre/matrix mechanical bonding.

In this study the addition of both micro and macro polypropylene and polyolefin fibres were investigated. Flexural tests were conducted on prismatic specimens to analyse the effect of fibre addition on flexural performance and energy absorption. Six different GPC mixes were prepared and tested. The first being a control mix with no fibre reinforcement; the remaining five mixes contained differing types of polypropylene and polyolefin fibres at a 0.5% dosage (by volume). Using precedent data in the literature, the performance of this new composite material was then compared against analogous OPC based systems.

Furthermore, relationships are established to predict the compressive and tensile strengths, modulus of elasticity, and compressive stress–strain curve for synthetic FRGPC. These relationships are time-related and compressive strength-related mechanical properties.

No analytical relationship between mid-span deflection and crack mouth opening displacement (CMOD) of synthetic FRGPC has been reported in literature. In the practical usage of FRGPC, the designers, researchers and engineers often want to predict the possible maximum crack width for a given deflection because the crack width is an important parameter both for the structure safety, for the serviceability and the durability of FRGPC elements and for the choice of the fibre length and fibre types which affect the flexural behaviour of FRGPC. Hence, in this study a new method to predict the relationship between mid-span deflection and the crack width of GPC mix with and without fibres is developed.

2. Experimental program

2.1. Materials

2.1.1. Aggregates

Crushed basalt aggregates and natural river sand were used in all geopolymer mixes. Course aggregates were sourced from Peats Ridge quarry in NSW, Australia, with a maximum nominal size of 10 mm and 20 mm and water absorption of 0.8% and 0.6% respectively. Fine aggregates consisted of both manufactured (ruck crushing material) and natural river sand with water absorption of 1.1% and 0.8% respectively were sourced from Peats Ridge quarry and Nepean river in NSW, Australia. The specific gravities of the basalt aggregates and Nepean river sand are 2.96 and 2.59 respectively. All aggregates were prepared to saturated surface dry (SSD) condition prior to batching. The individual and combined aggregate grading curves are shown in Fig. 1.

2.1.2. Aluminosilicate source materials

A mixture of two fly ashes and ground granulated blast furnace slag (GGBFS) were used as aluminosilicate source materials. The main source of fly ash (FA), which is a low-calcium type (ASTM C 618 Class F) FA, was sourced from Eraring Power Station, Australia's largest power station located at Lake Macquarie, New South Wales. The fineness of Eraring FA, determined by a 45 μm sieve was 86% passing (tested in accordance with AS 3583.1-1998). The second fly ash, which is an ultra-fine fly ash, was sourced from Gladstone power station in Queensland, Australia. The fineness of Gladstone FA was found to be 97% passing. Finally, the GGBFS was supplied by Australian Steel Mill Services (ASMS) in Port Kembla, New South Wales, and complies with the requirements of AS 3582.2.

The chemical compositions of the binders, as determined by X-ray fluorescence (XRF) analysis, are listed in Table 1.

The particle size distribution of the binders was determined using the laser diffraction technique with a Malvern Mastersizer 2000. The powders were dispersed in water and sonified prior to analysis on the instrument. The results are presented in Fig. 2.

The specific surface area of the aluminosilicate source materials was measured using the Micromeritics TriStar Plus instrument. The technique uses nitrogen physisorption to generate adsorption/desorption isotherms from which the specific surface area is calculated. Prior to analysis, the samples were degassed at 150 °C for 3 h. The analysis was performed using Brunauer, Emmett and Teller (BET) theory. The BET surface area of Eraring FA, Gladstone FA and GGBFS are 432.6, 658.9 and 555.9 m^2/kg, respectively.

The amorphous content of the raw materials was also measured using X-ray diffraction (XRD), specifically the spike method (using 5 wt% Zinc oxide). The amorphous content of Eraring FA, Gladstone FA and GGBFS was found to be 85.2%, 81.4% and 95.8% respectively. Crystalline phases in the fly ash samples consisted of Mullite ($Al_{2.17}O_{4.89}Si_{0.78}$), Quartz ($SiO_2$), Magnetite ($Fe_3O_4$) and Hematite ($Fe_2O_3$) whereas the crystalline phases in slag were Gypsum (CaH_4O_6S) and calcite ($CaCO_3$).

2.1.3. Alkaline solution

12 M sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) were combined to form the alkaline solution. The sodium hydroxide was prepared by dissolving technical grade NaOH pellets of 98% purity in water. The sodium silicate (manufactured by PQ Australia) had chemical composition: Na_2O = 14.7%, SiO_2 = 29.4%, and

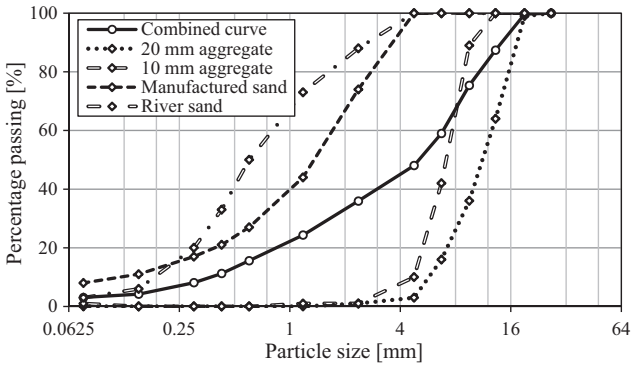

Fig. 1. Aggregates grading curve.