Toughness of Polypropylene Fibre-Reinforced Sprayed Geopolymer Concrete

Z. Xu, L. Hanžič and J. Karlovšek

Abstract Geopolymer, as a more sustainable binder material alternative to conventional Portland cement, is attracting attention in the construction industry. One reason is that the production of geopolymer concrete releases less carbon dioxide, and helps to consume a portion of the by-product from power plants and steel production. In the application aspect, it has better mechanical properties as well as being fire and chemical resistant. However, current applications of geopolymer concrete are focused on precast and cast in situ concrete, and it is rarely used as sprayed concrete. This study is aimed at investigating the use of sprayed fibre-reinforced geopolymer concrete as an application in underground construction. The results indicate that the post-crack performance of sprayed geopolymer concrete is comparable to cast geopolymer concrete. Further to that, there is potential for the use of geopolymer concrete to be extended to sprayed concrete in underground construction with current techniques.

Keywords Fibre-reinforced geopolymer concrete · Round determinate panel · Toughness · Sprayed concrete · Post-crack behaviour

1 Introduction

The incentive for this study stems from an awareness of sustainability and the realisation of low-carbon emission in the field of underground construction, as well as the necessity to find an alternative to large amounts of Ordinary Portland Cement (OPC) consumption in the mining and tunnelling industry. OPC has been criticised for the high emission of carbon dioxide during the production due to the combustion of fossil fuel and calcination of limestone. In contrast, the production of geopolymer

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C. M. Wang et al. (eds.), *ACMSM25*, Lecture Notes in Civil Engineering 37,
https://doi.org/10.1007/978-981-13-7603-0_47

concrete not only emits less carbon dioxide compared to OPC but also uses waste power plant materials such as fly ash (FA) or ground granulated blast-furnace slag (GGBS) from steel production [12]. The use of geopolymer concrete is gaining interest in the construction industry, as a more sustainable alternative to OPC, with high early strength, low permeability and good chemical and fire resistance [7, 14].

Geopolymer is an inorganic material which hardens through poly-condensation initiated by activators such as sodium silicate and sodium hydroxide. FA based geopolymer requires heat curing to harden, while geopolymer containing GGBS can harden in atmospheric conditions [16]. With heat curing, geopolymer concrete can gain high strength in short duration due to a high polymerization process [13]. However, in underground construction, especially tunnels built with the sequential excavation method, heat curing is not practical. Hence, attention has been focussed on the development of ambient cured geopolymer concrete.

Geopolymer has been successfully used on commercial scale projects such as in situ pavements and precast elements [9]. Applications of geopolymer concrete for underground infrastructure are currently restricted to precast products like tunnel segments [9, 18]. Despite this, the feasibility of using geopolymer concrete as fibre-reinforced sprayed concrete has rarely been studied.

Sprayed concrete is a specific type of concrete projected pneumatically to substrates at a high velocity. It is one of the structural supports used in the sequential excavation method in underground construction. As it is applied by spraying, it can be rapidly and easily used for a wide variety of geological substrates to provide sufficient ground support.

Like OPC concrete, the brittleness of geopolymer concrete also can be reduced by the addition of macro fibres [17]. The inclusion of polypropylene fibre in concrete enhances crack resistance and improves flexural response as well as post-crack behaviour [11, 17]. The fibres embedded in concrete can bridge cracks, restrict crack growth and decrease the crack width.

Toughness is important for sprayed concrete applications in underground constructions as it enables large deformation, withstand load and absorb energy without collapse [8]. Toughness is defined as energy absorption during deflection, which is a parameter to describe post-crack behaviour [4].

Among various methods of characterising toughness of fibre-reinforced concrete, a round determinate panel (RDP) test, according to ASTM C1550-12a [4] is considered one of the most reliable methods. As RDP moulds provide a large surface to spray on, good-quality sprayed specimens can be produced. Moreover, due to the test setup of RDP test, specimens display a significantly lower variation in energy absorption and more predictable crack pattern compared to standard beam test and European Specification for Sprayed Concrete (EFNAC) square panel test [6].

The purpose of this study was to investigate the flexural toughness of fibre-reinforced geopolymer concrete to extend its use to underground construction.

2 Materials and Methods

Geopolymer concrete was supplied by a commercial ready-mix concrete plant. The mix design is listed in Table 1. The nominal compressive strength of the supplied geopolymer concrete was 40 MPa at the age of 28 days. The mix of 3 m^3 was delivered to the site in an agitator truck. The geopolymer concrete was used to first prepare cast and sprayed specimens without fibres.

At the second stage, 60 mm long polypropylene fibres were added into the agitator truck to produce cast and sprayed specimens containing fibres. The surface of fibres is continuously embossed, their tensile strength and modulus of elasticity are 640 MPa and 12 GPa, respectively. The actual fibre dosage was determined from three samples taken from the agitator truck at different discharge times. The average measured fibre dosage was 9.4 kg/m^3.

In addition to the cast and sprayed RDP specimens, cylinders for compression test and beams for the flexural tensile test were made. The summary of specimens is given in Table 2.

The spraying of geopolymer concrete was conducted by a certified concrete spraying team using a manual spraying equipment. Sprayed specimens were prepared by directly spraying geopolymer concrete into the moulds without any extra vibration.

Table 1 Geopolymer concrete mix design

Material	Mass for 1 m^3 of geopolymer concrete (kg)
10 mm aggregate	710
Medium sand	366
Fine sand	574
Ground granulated blast-furnace slag	335
Fly ash	150
Poly-condensation activators	51
Water	186
Admixtures	7

Table 2 Specimen configuration and amount

Specimen	No fibres		Fibres	
	Cast	Sprayed	Cast	Sprayed
RDP Φ800/75 mm	6	6	9	9
Cored cylinders Φ75/150 mm	–	18	–	18
Cast cylinders Φ100/200 mm	24	–	18	–
Beams 100 × 100 × 360 mm	6	–	–	–

RDP stands for round determinate panel. Cored cylinders were extracted from sprayed blocks at the age of five days

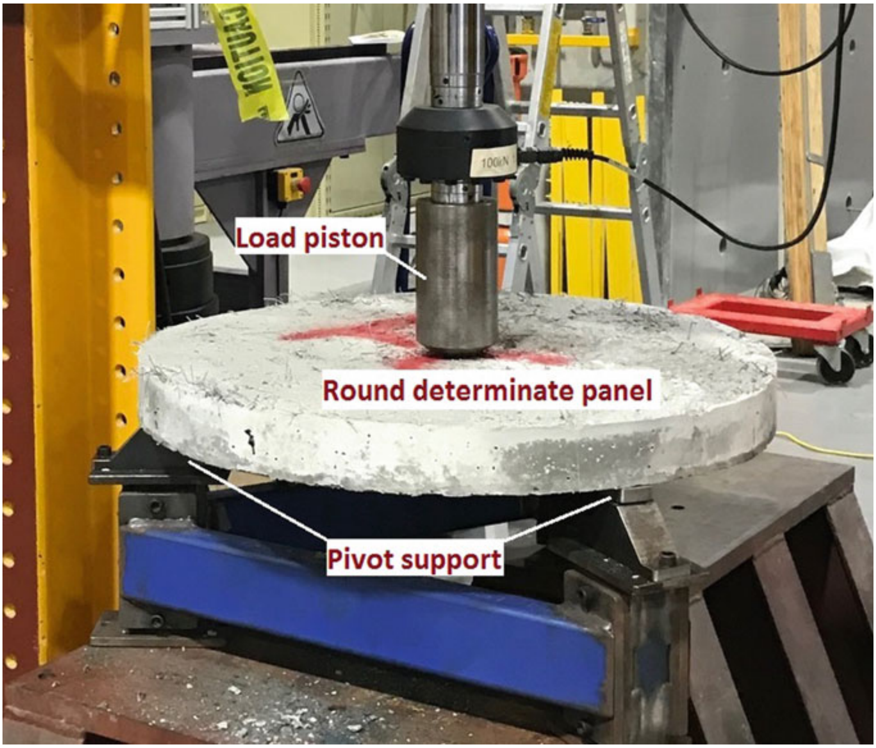

Fig. 1 Round determinate panel (RDP) test set-up

Cast RDP specimens were compacted with needle vibrators while cast cylinders and beams were compacted on a vibration table.

After the completion of the concrete placement, the top surface of the moulded specimens were sprayed with curing compound to reduce water evaporation and prevent cracking. As hardening of geopolymer concrete does not experience hydration reaction like OPC, wet curing is not necessary [10] and air-cured geopolymer concrete can develop higher strength than water cured [15].

Cast cylinders and beams were demoulded at the age of one day and were ambient cured next to the RDPs. A set of three cast cylinders was wrapped in plastic to prevent water loss and stored in a temperature-controlled room at 23 ± 1 °C. This set was used as a reference for compressive strength. Cored cylinders were extracted from sprayed blocks at the age of five days.

RDP specimens were tested as per ASTM C1550-12a [4]. Test set-up is shown in Fig. 1. The specimen is supported on three symmetrically arranged pivot supports and the point load is applied centrally on the top surface. A hydraulic actuator, with a capacity of 100 kN, was used to apply a load in displacement-controlled mode. A constant rate of 4.0 ± 1.0 mm/min was applied up to a central displacement of at least 45.0 mm. Three specimens of each type were tested at the age of 7, 28 and

56 days to evaluate the development of flexural toughness. Results obtained from individual specimens were corrected for the difference between nominal and actual specimen dimension.

Cylinders were used to determine compressive strength and modulus of elasticity according to AS 1012.9 [3] and AS 1012.17 [1] respectively, and beams were used for flexural tensile strength as per AS 1012.11 [2].

3 Results and Discussion

Based on the ASTM C1550-12a [4], the toughness of RDP is defined as the absorbed energy from the onset of loading up to a specified central deflection. It is determined as the area underneath the load-deflection curve. The toughness of RDP, at a deflection of 5 mm, indicates the post-crack performance at a low level of deformation due to the importance of crack control. The toughness at the displacement of 40 mm is used to estimate the performance at a high level of deformation; this is typical for mining applications where large cracks are allowed.

A typical graph obtained from the RDP test is shown in Fig. 2. The shaded area corresponds to energy absorption at 20 mm deflection. Peak load and energy absorption determined from the graph need to be corrected for the actual specimen dimensions. Average of three corrected values for the cast and sprayed geopolymer concrete specimens are given in Table 3. By comparing corrected peak load of fibre-reinforced and non-fibre-reinforced specimens, it can be seen that the inclusion of polypropylene fibres plays a very minor role in the peak load.

It can be seen that the peak load increases up to 28 days and remains constant after that. Table 4 shows compressive strength measured on the cast and cored cylinders. These results show 5% increase of compressive strength on cast cylinders but not on

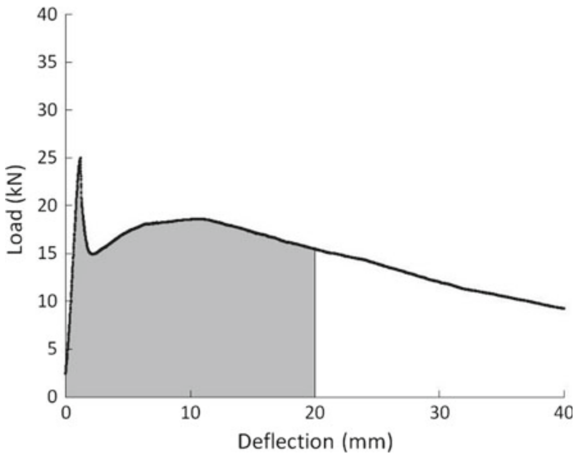

Fig. 2 Typical load—deflection graph obtained in round determinate panel (RDP) test (shaded area represents uncorrected absorbed energy at 20 mm deflection)

Table 3 Peak load and energy absorption for cast and sprayed round determinate panels (RDPs)

Fibres	Placement	Age (Day)	Peak load (kN ± 1 kN)	Energy absorption at given deflection (J ± 10%)			
				5 mm	10 mm	20 mm	40 mm
No fibres	Cast	7	24	–	–	–	–
		28	29	–	–	–	–
	Sprayed	7	20	–	–	–	–
		28	27	–	–	–	–
Fibres	Cast	7	24	79	172	341	589
		28	30	89	193	384	624
		56	29	92	198	363	612
	Sprayed	7	22	65	136	274	525
		28	26	81	175	346	556
		56	26	81	178	348	593

Values given are an average of three specimens with results corrected for actual specimen dimensions

Table 4 Mechanical properties of cast/sprayed geopolymer concrete at different age

Fibres	Placement	Specimen	Compressive strength (MPa ± 2 MPa)				
			Age (days)				
			3	7	14	28	56
No fibres	Cast	Cast cylinder	33	37	42	50	53
	Sprayed	Cored cylinder	–	33	40	45	45
Fibres	Cast	Cast cylinder	30	35	39	44	52
	Sprayed	Cored cylinder	–	35	42	50	45

sprayed cored cylinders. Compressive strength on a set of three cast cylinders kept in a controlled environment was found to be 59 MPa at the age of 28 days. We can thus conclude that compressive strength is predominantly gained within the first 28 days and is higher in a favourable environment.

The compressive strength of ambient cured geopolymer concrete was 85% of the reference specimens cured in the controlled environment. However, the development of compressive strength of ambient cured specimens was comparable to OPC concrete, with 67, 75 and 85% of their 28-day strength achieved at the age of 3, 7 and 14 days, respectively.

The reduction of compressive strength in sprayed geopolymer concrete compared to cast concrete is comparable to sprayed OPC concrete [5]. It is noted that the compressive strength of some sets of sprayed fibre-reinforced geopolymer concrete is higher than the counterpart of cast fibre-reinforced geopolymer concrete which indicated that the specimens compacted by spraying were better than specimens prepared with the vibration table. This may be caused by the delay of cast fibre-reinforced geopolymer concrete specimen, and setting had started in some specimens before the moulding finished.

Table 3 also shows that toughness evaluated as absorbed energy increases with specimen age. The increase can be attributed to a higher peak load as well as a higher post-crack load bearing capacity. The latter is caused by increased bonding between geopolymer matrix and polypropylene fibres.

The toughness of sprayed geopolymer concrete compared to the toughness of cast geopolymer concrete is about 12% lower. However, the reduction of mechanical properties is comparable to OPC concrete [5]. This indicates that the compaction achieved by kinetic energy from spraying geopolymer concrete at a high velocity can be sufficient. In addition, the advantage of spraying may compensate for the reduction of mechanical properties.

The modulus of elasticity measured at 28 days on the cast and cored cylinders with and without fibres was found to be 34 ± 3 GPa. The measured difference between the groups of specimens was less than experimental error. The flexural tensile strength measured on cast specimens without fibres was found to be 3.7 and 4.8 ± 0.3 MPa at the age of 7 and 28 days respectively.

4 Conclusion

This research investigates the strength development and the toughness of polypropylene fibre-reinforced geopolymer cast and sprayed concrete. Based on the discussion, it is concluded that there is a potential to extend the use of ambient cured geopolymer concrete to sprayed concrete application in underground construction.

Even though geopolymer concrete cured in ambient condition cannot gain the strength as high as those cured in favourable environments, the ultimate strength is not significantly reduced. The results also show that the current concrete spraying technique can provide sufficient compaction to sprayed geopolymer concrete. Although some reduction of strength occurs in sprayed geopolymer concrete specimens, compared to cast specimens with vibration, the differences are comparable to OPC concrete. Considering that the benefits of using sprayed concrete outweigh the reduction of mechanical properties, the application of sprayed geopolymer concrete is promising.

The results of toughness of polypropylene fibre-reinforced sprayed geopolymer concrete indicate satisfactory post-crack behaviour in underground construction. This is due to the bonding between geopolymer matrix and polypropylene fibres and the resultant post-crack loading bearing capacity.

The experimental results obtained from the RDP test need to be further evaluated with numerical models. The modulus of elasticity as well as tensile and compressive strength will be used as input information for numerical modelling.

However, as currently there is no accelerator developed for sprayed geopolymer concrete, spraying geopolymer concrete to overhead area is still not practical. Furthermore, due to the alkalinity of some types of chemical activator, there is possibly an issue with geopolymer being sprayed in a confined space. Despite the limitation mentioned above, excellent chemical resistance makes geopolymer concrete suitable for environments where septic waste (sewer) runs.

Acknowledgements The authors would like to acknowledge contributions of *Wagners* for supplying geopolymer concrete, *BarChip Inc*. for supplying polypropylene fibres, *Jemna Pty Ltd* for providing spraying services and ICARUS program of the School of Civil Engineering in the University of Queensland for helping for this research.

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