Effect of strain rate on geopolymer concrete

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Abstract: Geopolymer concrete has been receiving a great attention by the researchers due to the world wide focus on using more environmentally friendly products in the construction industry. There is no literature available on the effect that differing strain rates have on geopolymer concrete, a gap in the literature that this project aims to fill. The mix design used in this project achieved different compressive strengths by varying the heat curing time. In Australia, fibre reinforced geopolymer concrete is being used in precast panels in underground constructions. Commercially available geopolymer cement and synthetic fibres are effectively being used to produce elements that are more durable. A total of eight different batches were made by having two curing regimes (oven curing with different times and ambient curing) and two different polypropelene fibre concentrations (0.05% and 0.15% fibres by weight). All the samples were 100 mm diameter and 200 mm high, tested on the 28 day and the tests were duplicated. These were tested under three different strain rates, 0.5 mm/min, 1 mm/min and 2 mm/min.

It was found that the compressive strength, modulus of elasticity and poisson's ratio of geopolymer concrete varies with varying strain rates. Ultimate strength and ultimate strain of geopolymer concrete increases with the increasing strain rate which is consistent with the reported literature for geopolymer mortar.

Keywords: Geopolymer concrete, strain rate, fibres.

1. Introduction

Although geopolymer concrete has been in development ever since the end of World War 2, it has only recently become commercially available on a global scale. One of the main reasons for this has been the global shift in focusing sustainable and environmentally friendly construction materials. Geopolymer is such an attractive option in light of this shift in perspective as the binder can be made from industrial waste materials, such as fly ash and slag that would otherwise have little use. During the production of one tonne of OPC, one tonne of CO_2 is released into the atmosphere, while commonly quoted figures for geopolymer concrete are that it gives off approximately 50-80% less greenhouse gases compared to OPC concrete. Geopolymer concrete shares many similarities with OPC, having comparable performance in most areas. However it is not identical, and the ongoing research is designed to investigate its performance in all possible situations and allow to formulate standard guidelines, similar to what is available for OPC.

Majority of the geopolymer studies in Australia are based on low calcium fly ash while the international researchers investigated the material made of high calcium fly ash [1-3]. However it is documented that low calcium fly ash is preferred because of the fast setting associated with the high calcium fly ash [4]. Although there is no difference in the cost of producing OPC concrete or geopolymer concrete [5], introduction of carbon tax will definitely pave the way for geopolymer concrete to outperform economically than its counterpart OPC concrete. Properties of this inorganic polymer concrete family varies significantly depending on the source material [6] and are superior to their OPC counterparts in terms of early strength gain, sulphate [7] and fire resistance [8] and very little shrinkage [4, 5]. Sofi et al. [6] concluded that the mechanical properties of geopolymer concrete depend on the mix design and curing method. Having investigated geopolymer and OPC paste and concrete, Pan et al. [9] concluded that differences in the pastes are consistent with the differences in the concretes. While the tensile strength of geopolymer concrete is higher than that of OPC [4, 6, 9], elastic modulus [4, 9] and flexural strength [4] of the same is reported to be lower. Equations for tensile strength, flexural strength and modulus of elasticity for geopolymer concrete have been proposed in the past [6, 10].

Throughout the design life of a member or a structure, it will be subjected to a different loading rates, although the range of loading rates will of course vary greatly depending upon the application. Like most materials in the field of civil engineering, the properties of concrete are sensitive to the loading rate, and therefore it must be accounted for in the design. In most cases the loading rate is not a major factor once an initial rate has been established; only noticeably changing the material properties if the loading rate changes by an order of magnitude. An experiment was conducted on OPC analysing the effect of stress-strain rates on a single mix using different curing methods Spooner [11]. They found that stress at failure for specimens cured in water was strain-rate dependent. Clearly this may not be the case with different mix designs, especially with completely different material like geopolymer concrete, however it illustrates that mechanical properties may change under different loading conditions.

Khandelwal et al. [12] reported the effect of strain rate on the strength properties of class F fly ash geopolymer mortar. The strain rates examined were 0.001, 0.005, 0.01 and 0.05 mm/s, and for all the strain rates the compressive strength, Poisson's ratio and modulus of elasticity were the observed properties. From the stress strain curves the authors determined the geopolymer concrete properties, confirming that as with OPC, geopolymer concretes mechanical characteristics improve with greater strain rates. It was determined that the increase in compressive strength, modulus of elasticity, and Poisson's ratio increased in a logarithmic manner with the increase in strain rate.

According to Xiao et al. [13], despite several research papers on the topic there is not a consensus on the amount of change required in the strain loading rate to effect a change on the strength of concrete. It was found increasing the strain rate increases the ultimate compressive strength of the concrete above that of a static loading rate. Some researchers found an increase of anywhere between 30% and 80% in the ultimate compressive strength, with others claiming an increase of less than 20% and the actual strain rate having no effect on the strength of the concrete. The experimental procedure carried out by Xiao et al. [13] concluded that differing strain rates have an effect on the ultimate compressive and tensile strength of concrete, while Poisson's ratio is not obviously dependent on the strain rate. Bischoff and Perry [14] analysed the dynamic compressive elements of concrete in order to examine the reason for differing results on the effect strain rate has on 25 MPa concrete. Due to the nature of dynamic behavior with varying the strain rates, there are far more factors that can affect the results than a static loading case, including specimen geometry, stress strain distribution throughout the specimen and stress wave propagation effects. Bischoff and Perry [14] concluded that the confusion about the effect on dynamic strength is because there is a large amount of factors that determine the strength under rapid loading, such as concrete quality, aggregate, age, curing and moisture conditions.

So far no research work is reported in the literature to investigate the effect of strain rate on the performance of fly ash based geopolymer concrete, although a paper has been published on the effect it has on geopolymer paste [12], as well as a broad spectrum of papers on OPC.

2. Experimental program

An experimental program was designed to prepare geopolymer concrete and test them for varying strain rates. There were three test variables, namely the curing method (compressive strength of concrete), percentage of fibres and the loading rate. Four compressive strengths (Mix 1, Mix 2, Mix 3 and Mix 4) and three different loading rates (0.5, 1 and 2 mm/minute) were investigated. Only for Mix 1 and Mix 2 two different percentages of fibres (0.05% and 0.15%) were added. Tests were performed in duplicate for each compressive strength, each fibre percentage and each loading rate. All together 30 specimens were tested with oven curing and 18 specimens were tested with ambient curing conditions for unconfined compressive strength in the experimental program.

2.1 Materials

Slag or fly ash has become the main ingredient in the binder of geopolymer concrete, as it contains silicon and aluminium. Fly ash is a byproduct in coal power stations and it is a fine grey powder. Generally fly ash particles are spherical, with the amount of incombustible material present in the coal determining the composition, ranging in colour from grey to brown. There are four main oxides in fly ash; silicon, aluminium, iron and calcium. A variety of other chemicals are also usually present in small amounts. The main factor determining the resultant composition of fly ash is the type of coal and the source [15]. Low calcium fly ash (class F), in which the content of calcium is less than 5% by mass, is the type produced by the majority of Australian power plants, and is light to mid grey in colour. For this to be used as a binder in geopolymer concrete it needs to have a silicon and aluminium content of around 80%, with a Si-Al ratio of 2-1 [16]. The remaining mass is mainly iron oxide, with a variety of trace metals making up less than 1% by mass.

While fly ash can be used to make its own geopolymer concrete its first application was in regular OPC. High volume fly ash concrete can replace up to 60% of the Portland cement, giving a stronger, more durable and more chemically resistant product. When used in concrete in this manner it acts as an artificial pozzolan, the silicon dioxide in the fly ash reacts with the calcium hydroxide in the cement hydration process to form calcium silicate hydrate gel.

Type F (low calcium) fly ash of approximately 15 µm was used in this research and it was sourced from Pozzolanic Millmerran. The chemical composition of the fly ashes is given in Table 1. Density of fly ash was found to be 1100 kg/m^3. Polypropylene fibres of 2 cm maximum length were added in some batches.

Table 1: Chemical composition of fly ash (by mass%).

Element	SiO_2	$A1_2O_3$	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3
Percentage	51.8	24.4	9.62	4.37	1.5	0.34	1.41	0.26

Fine aggregate used in this project was fine dry sand with a bulk density of 1494 kg/m3, water absorption of 8% and particle size smaller than 425 µm. Two different sizes of coarse aggregates were used in this mix (7.5 mm and 10 mm maximum aggregate size).

Alkali activators used to make geopolymer concrete included sodium silicate and sodium hydroxide solutions. Sodium silicate solution is available in different grades. Alkali silicate used in this research was Grade D sodium silicate solution with a modulus ratio (Ms) of 2 (Ms = SiO2/Na2O and Na2O = 14.7% and SiO2 = 29.4% and solids = 44.9% by mass) and specific gravity of 1.5. Sodium hydroxide with 90% purity in the pellet form was used to prepare sodium hydroxide solution. The concentration of sodium hydroxide solution used to make 40 MPa mix is 8 Molar. In order to make 8M solution, 262 g of NaOH pellets were mixed to make a kilogram of NaOH solution [16].

2.2 Mix design

The mix design used in this research was based on the work reported by Zhao and Sanjayan [9] and is shown in Table 2.

Table 2. Mix proportions.

Material	Quantity (kg/m^3)
Alkaline liquid/fly ash	0.45
Fly ash	381
NaOH solution (8M)	49
Na2SiO3 solution (Grade D)	122
Fine aggregate	554
Coarse aggregate 7.5 mm 10 mm	 647 647

Aggregate weights shown in Table 2 are in the saturated surface dry condition. Four batches of geopolymer concrete were prepared (Mix 1, Mix 2, Mix 3 and Mix 4) using the same mix design. However Mix 1 was cured in ambient conditions while Mix 2, Mix 3 and Mix 4 were cured in the oven at 80^{0}C for 3, 6 and 48 hours respectively. Two more batches of geopolymer concrete were prepared for Mix 1 and Mix 2 with 2 different percentages of fibres in them.

2.3 Sample preparation

Sodium hydroxide pellets were mixed with distilled water to get the sodium hydroxide solution with the required molarity. This was mixed with the sodium silicate solution to prepare the alkaline solution. Silicate solution was prepared one day before the mixing. During our trial batches it was concluded that the condition of the aggregates play an important role during the mixing process. When aggregates are mixed with the silicate solution, they should be in the saturated surface dry (SSD) condition so that they will neither absorb chemicals nor contribute more water to the mix. Aggregates thus prepared are shown in Figure 1.

Figure 1. SSD condition of aggregate

Sand and coarse aggregates that were in SSD condition and fly ash were initially dry mixed for about a minute in a 120 litre mixer. Polypropylene fibres were also included in this dry mix for the fibre reinforced batches. The pre-prepared alkaline solution was then introduced in the dry mix and further mixed for 4 minutes before casting into greased 100 mm diameter and 200 mm high cylindrical moulds. The fresh geopolymer concrete was stiff until compacted using a vibrating table. Concrete thus cast were covered with a polyethylene sheet before putting them in the oven for curing at 80^{0}C. Mix 1 was first cured in the ambient condition for one day while Mix 2, Mix 3 and Mix 4 batches were first cured in the oven for 3, 6 and 48 hours respectively and then in a constant temperature room (23^{0}C and 50% humidity) until the time of testing. The cylindrical specimens were allowed to air dry for a day after taking out of the fog room. Any surface pores were filled with a quick setting filler.

2.4 Testing

The samples in each batch were tested under various strain rates (0.5, 1 and 2 mm/minute) using 1500 kN capacity Sans compression testing machine. This testing range was duplicated for each mix resulting in testing six samples per batch. It was expected to observe the stress-strain relationships, the effect of heat curing and strain rate on the properties of low calcium fly ash based geopolymer concret. Further observation was to be made for effect of fibres on the properties of geopolymer concrete and whether they will change when subjected to different loading rates. In order to observe the Poisson’s ratio for these samples, strain gauges were used to measure the lateral strain of each specimen. Two strain gauges of 90 mm gauge length were placed laterally at the middle third in two diametrically opposite sides. All the specimens were prepared using this method. The specimen thus prepared were tested for varying strain rates (Figure 2) and the axial load and the platen to platen displacement together with the data from strain gauges using system 5000 were recorded.

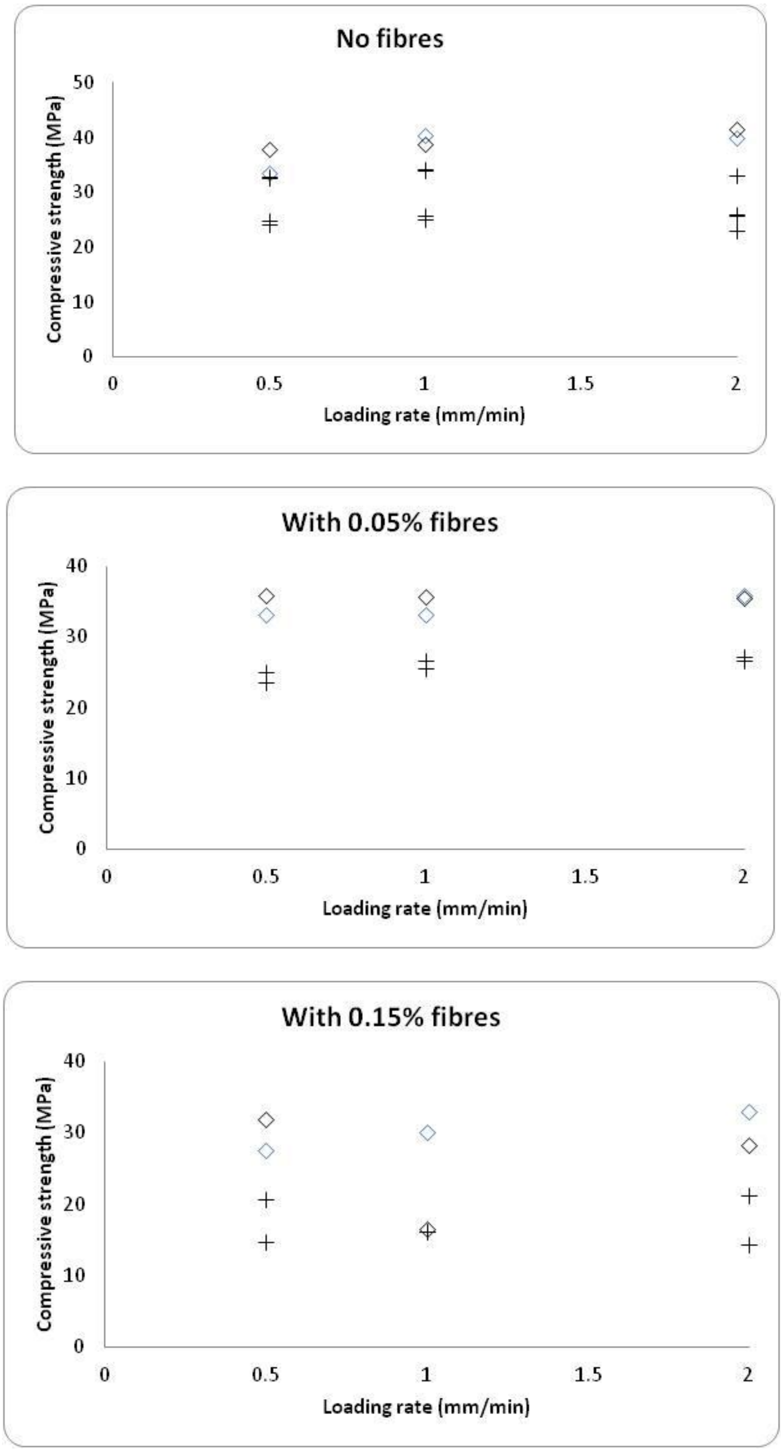
(a). Tested sample

(b). Experimental set up

Figure 2. Testing

3. Experimental results and discussion

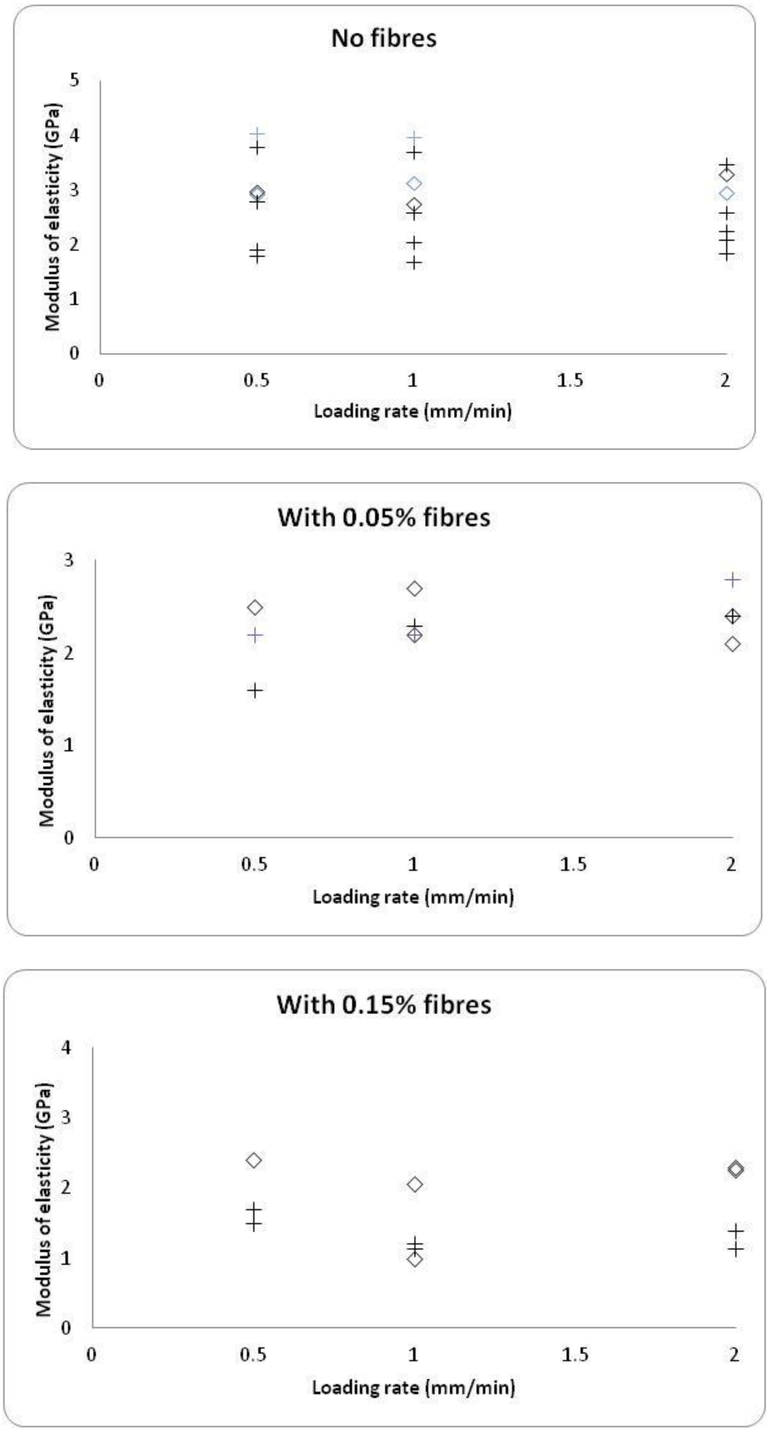
Data were recorded and analysed for the load and axial deflection as well as the strain gauges readings for the lateral strain. Figure 3 shows the compressive strength variation with the change in the loading rate as well as the effect of fibres on compressive strength.



+ Heat cured ◇ Ambient cured

Figure 3. Effect of fibres and strain rate on compressive strength

It can be seen that compressive strength increases with increasing strain rates for samples with either no fibres or 0.05% fibres. However for samples with 0.15% fibres, compressive strength decreases with increasing strain rate. Therefore the effect of strain rate on the compressive strength is marginal. Although 0.05% fibre reinforced geopolymer concrete is having a little higher compressive strength, it can be seen that for samples with 0.15% fibres show lower compressive strength. It could be due to the presence of increased number of fibres which might have an impact on the bond between the fibres, and geopolymer concrete. When the samples are subjected to varying loading rates, the effect of heat curing on the compressive strength is minimum.



+ Heat cured ◇ Ambient cured

Figure 4. Effect of fibres and strain rate on modulus of elasticity

Variation of modulus of elasticity with different loading rates and varying percentages of fibres is shown in Figure 4. It can be seen that for ambient cured samples with no fibres, modulus of elasticity increases with increasing strain rate which is consistent with that found for geopolymer mortar [12]. However for heat cured samples there is a trend of decreasing modulus of elasticity for the increase in the strain rate irrespective of the fibres.

A typical stress-strain relationship obtained for geopolymer concrete using platen-to-platen method and strain gauges is shown in Figure 5. When the stress-strain relationships for geopolymer concrete are analysed, it can be seen that ultimate strength and ultimate strain increases with increasing strain rate.

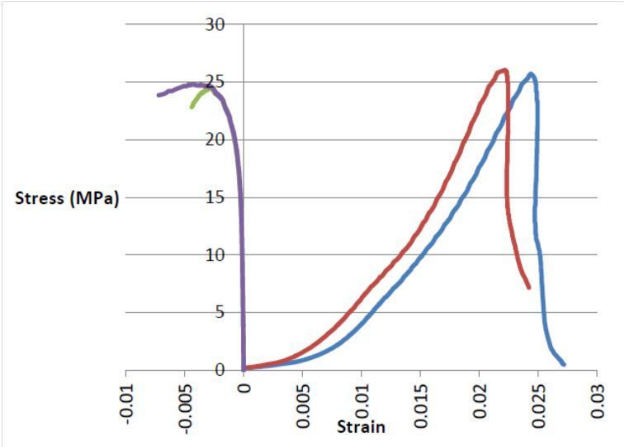


Figure 5. Typical stress-strain curve for geopolymer concrete

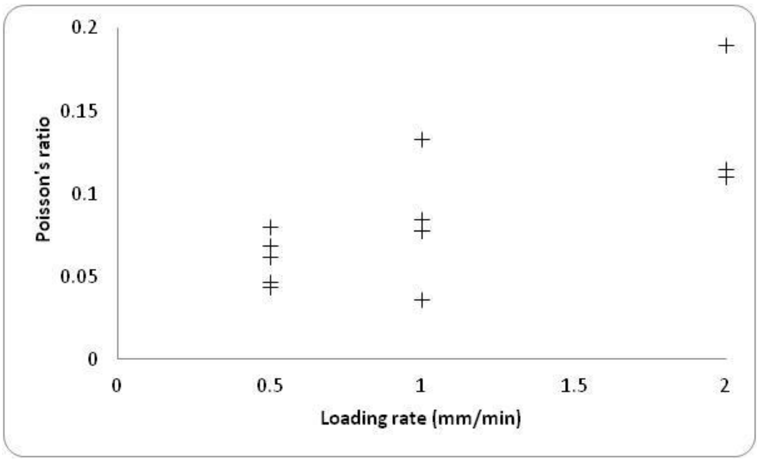


Figure 6. Effect of loading rate on poisson's ratio

Figure 6 shows the effect of strain rate on the Poisson's ratio for heat cured samples with no fibres. Poisson's ratio increases with increasing strain rate for heat cured geopolymer concrete. It is interesting to note that for some samples the Poisson's ratio is as low as 0.05.

4. Conclusions

Several conclusions can be made on the behavior of geopolymer concrete subjected to varying loading rates in compression. They are summarized as follows:

- Compressive strength increases marginally with increasing loading rate for geopolymer concrete with no fibres or with 0.05% of fibres. However the compressive strength decreases with increasing strain rate for geopolymer concrete with 0.15% of fibres.
- For ambient cured plain geopolymer concrete modulus of elasticity increases with increasing loading rate. However for heat cured geopolymer concrete modulus of elasticity decreases with increasing strain rate irrespective of the fibres.
- There is a clear increase in the Poisson's ratio for increasing loading rate for plain as well as fibre reinforced geopolymer concrete.

5. References

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