Ductility enhancement of geopolymer concrete columns using FRP confinement

Abstract

Geopolymer concrete is an environmentally friendly, green construction material. However its use is constrained by its increased brittleness and lack of understanding of its behaviour under multi-axial loadings. Similar to Ordinary Portland Cement concrete (OPC), the ductility of geopolymer concrete columns can be increased by lateral confinement and using Fibre Reinforce Polymers is one option in doing that. This research paper aims at investigating the effect of different confinement on the ductility of geopolymer concrete.

Three different mixes with varying binder (fly ash and slag) and different curing conditions together with different levels of carbon fibre reinforced polymer (CFRP) and glass fibre reinforced polymer (GFRP) confinement were investigated in this research paper. FRP confined normal strength geopolymer concrete shows similar stress-strain behaviour to those for high strength OPC concrete When compared with the same level of confinement, CFRP confined geopolymer concrete marginally outperforms GFRP confined geopolymer concrete in 28 day compressive strength. However ductility levels with GFRP confinement are better than those with CFRP confinement.

Keywords

Geopolymer concrete, fly ash, slag, stress-strain relationship, ductility, confinement

Introduction

Climate change due to global warming is one of the biggest social, political, economic and environmental issues that have an effect on all of us. Emission of greenhouse gases such as carbon dioxide and nitrous oxide is a major contributing factor for global warming. It is reported that the production of cement contributes about 5-7% of CO_2 emissions globally while in 2008, Australia reported 1.3% of greenhouse gas emissions are due to the production of cement [1]. Production of one ton of Ordinary Portland Cement (OPC) releases approximately one ton of CO_2 into the atmosphere [2, 3]. Irrespective of this, OPC concrete is widely as a construction material around the world [2]. Given recent global recognition of the importance of self-sustainability and carbon friendly technologies, reducing this figure is becoming an increased priority in organisations all around the world. One such way to effectively reduce this carbon footprint from typical OPC concrete is through substitution with that of a green concrete. Several studies have concluded that by using geopolymer concrete as a replacement for traditional concreting methods, CO_2 emission figures can effectively be reduced by up to 80%. This is an extremely significant figure when considering the grandeur scale on the reliance and usage of traditional concreting methodology.

Decades ago, Davidovits [4] suggested that an alkaline solution could be used to react with silicon and aluminium of a material and produce binders similar to cement binder.

Since this chemical reaction is a polymerisation process, Davidovits [4] named this new binder as “geopolymer”. The source materials used to produce geopolymer concrete mainly comes from industrial waste materials such as fly ash, granulated blast furnace slag, metakaolin and rice husk ash. Although high calcium fly ash based geopolymer concrete is used in the international context [5, 6], low calcium fly ash based geopolymer concrete ranks better in regards to the setting time[7]. However, low calcium fly ash based geopolymer is popular to have longer setting times related to ambient curing than those with heat curing. Few research works to address this issue by blending fly ash with other materials have been reported in the literature. Using OPC and Ground Granulated Blast Furnace Slag (GGBFS) blended with low calcium fly ash is proven to give improved setting times [8, 9]. Statistics show that approximately 12 million tons of fly ash is produced per annum within Australia. However just over half of it, 6.5 million tons of fly ash stay unused [10]. Not only does this unused fly ash represent underutilised economic benefits in the fact that alternative raw materials are required to be sourced for the construction of OPC when unused fly ash stockpiles could be used for the construction of geopolymer products. It more importantly represents an increased negative environmental footprint for the same reasoning suggested above. Fly ash and alkaline solution make the binder for geopolymer concrete. This alkaline solution is normally made using either NaOH (Sodium Hydroxide) and Na_2SiO_3 (Sodium Silicate) or KOH (Potassium Hydroxide) and K_2SiO_3 (Potassium Silicate). Both Potassium

Silicate and Sodium Silicate are typically used as alkaline liquid activators as they effectively accelerate reactions compared to when only ‘hydroxides’ are used within the process [10]. A recent research shows that there is a possibility of using industrial effluent as a partial replacement for commercially available alkaline solutions [11].

Mechanical properties of geopolymer concrete depends mainly on the source material [12]. Past research documents that the properties of geopolymer concrete depend on the mix design and curing method [12]. Reed et al. [13] proposed that fly ash based geopolymer concrete is suitable for in-situ applications. The changes in the mortar with OPC and geopolymer are compatible with the changes in the OPC and geopolymer concrete [14]. Some mechanical properties of geopolymer concrete (tensile strength) are higher than those of OPC concrete [7, 12, 14], while some properties such as elastic modulus [7, 14] and flexural strength [7] are comparatively lower. Although design guidelines for geopolymer concrete are not very well documented, equations for some properties such as tensile strength, flexural strength and modulus of elasticity cab be found in the literature [12, 15].

Despite all the aforementioned benefits of geopolymer as an environmentally friendly alternative for traditional Portland cement based concretes, working with geopolymer concrete also comes hand in hand with its fair share of problems. Since geopolymer concrete exhibits higher brittleness than OPC concrete, careful consideration given in the structural design of high strength concrete (HSC) should be continued for the structural design of geopolymer concrete [14, 16].

Fibre reinforced polymers (FRP)

In the past decades, the use of fibre reinforced polymer (FRP) composites as the method of confinement has been gaining increased popularity. FRP wrapping has become one of the most common rehabilitation method for circular columns [17]. Fibre reinforcement refers to the process by which fibrous materials are used to strengthen cured resin systems (matrix) resulting in a product with increased performance specifications. Within practical applications, commonly used reinforcements include: Carbon Fibre Reinforced Polymers (CFRP), Glass Fibre Reinforced Polymers (GFRP) and Aramid fibres with other less common fibre reinforcements including cotton, rayon, wool, kevlar and asbestos [18]. FRP reinforcement can provide significantly higher confining stresses than the conventional steel reinforcement and therefore provides good level of ductility to high strength concrete [19]. Same method of confinement can be applied to improve the ductility of geopolymer concrete.

FRP confined concrete demonstrates a major gain in ductility and strength compared to that of steel confined or un-confined concrete products [20, 21]. It was also noted that increasing the number of FRP layers used for confinement greatly increased the ultimate strain and strength of the concrete specimen. FRP is most effective on circular columns or square columns with rounded edges allowing for maximised contact area where strength and ductility were up to eight times greater than the corresponding unconfined samples. A good mechanical bond between the FRP and the concrete being confined, significantly improves the performance of the specimen resulting in an even confining pressure being applied across the face of the specimen [22].

Having identified a gap in knowledge about addressing the issue of increased brittleness in geopolymer concrete, this paper outlines a research program to investigate the ductility enhancement of the material using FRP wrapping. It identifies the improvement of strength and ductility by the use of FRP wrapping in geopolymer concrete.

Experimental program

An experimental program was designed to prepare geopolymer concrete short column samples. It was carried out in two stages. There were three test variables in stage one, namely the compressive strength of concrete, the type of FRP and the level of confinement provided. Fly ash was used as the main binder in developing geopolymer concrete samples in this stage of the program. Two compressive strengths (Mix 1 and Mix 2), two types of FRP (CFRP and GFRP) and two levels of confinement (1 and 3 wraps) were investigated. Tests were performed in duplicate for each wrapping configuration, each type of FRP and each mix. Overall 16 and 4 specimens were tested for confined and unconfined compressive strength respectively in the first stage of the experiments.

In stage two, fly ash and Ground Granulated Blast Furnace Slag (GGBFS) were used as the binder in developing geopolymer concrete samples. 50% of the fly ash used in stage one was replaced by slag in stage 2 which is named as Mix 3 hereafter. There were two test variables in stage two, namely the type of FRP and the level of confinement provided. CFRP and GFRP were used as confinement with either one or two wraps. Overall 8 and 2 specimens were tested for confined and unconfined compressive strength respectively in the second stage of the experiments.

Materials

Low calcium fly ash (type F) which had a density of 1100 kg/m^3 and particle size of approximately 15 µm from Pozzolanic Millmerran in Queensland, Australia was used in this research. GGBFS was received from Australasian (iron & steel) Slag Association, Wollongong, Australia. GGBFS was approximately 45 µm and had a relative density of 2.88. Table 1 gives the chemical composition of these two ingredients.

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

Fine aggregate with particle size smaller than 425 µm and coarse aggregate with 7.5 mm and 10 mm maximum aggregate size were used in all the three mixes. Sand had a bulk density of 1494 kg/m^3 and water absorption of 8%.

Combination of sodium silicate and sodium hydroxide was used as the alkaline solution. Sodium silicate used in this project was of Grade D quality, modulus ratio of 2, 14.7% of Na_2O, 29.4% of SiO_2, 55.9% of water (by mass) and specific gravity of 1.5. Eight molar sodium hydroxide solution used in all the three mixes was prepared using 90% pure sodium hydroxide pellets.

Carbon fibre and glass fibre clothes had weights of 200 g/m^2 and 250 g/m^2 respectively.

Mix design

Table 2 gives the mix proportions used in both the stages of this research. This mix was originally used by Zhao and Sanjayan [23]. Aggregate weights given in the table should correspond to the aggregates of saturated surface dry condition (Figure 1). Samples from Mix 1 and Mix 2 were cured at 80^{0}C for 3 and 6 hours respectively while Mix 3 was cured in ambient conditions.

Table 2. Mix proportions.

Sample preparation

One day prior to sample preparation, eight molar sodium hydroxide solution was prepared by mixing sodium hydroxide pellets with distilled water. On the same day this mix was combined with sodium silicate solution to prepare the alkaline solution to be used the following day in geopolymer concrete mix.

Figure 1. Aggregates in saturated surface dry condition.

Having mixed the dry ingredients in a 120 litre mixer for about one minute, alkali activator was then poured slowly and mixed for another 4 minutes. Geopolymer concrete thus prepared shows a stiff behaviour until they were cast into 100 mm diameter and 200 mm high moulds and compacted using a vibrating table. All the mould filled with concrete were covered with a polyethylene sheet. Having cured in the oven at 80^{0}C for 3 hours (Mix 1), 80^{0}C for 6 hours (Mix 2) and room temperature for 24 hours (Mix 3), the samples were then cured in a constant temperature room (23^0C and 50% humidity) until the time of testing.

All the samples were taken out of the temperature controlled room and allowed to air dry and any existing surfaces pores were filled with a quick setting filler. Having applied an epoxy-based primer onto the concrete surface, it was allowed to cure for about 30 minutes before applying the wrap. An allowance of 30 mm was allowed in the lengthwise of the fibre wrap for overlapping. Laminating resin of equal mass as that of the fibre wrap was applied on the surface of the sample. Fibre cloth was ultimately wrapped around the concrete specimen and allowed to cure for three days. In order to find the lateral deformation two strain gauges of 90 mm gauge length were glued at the mid height in two diametrically opposite sides. Two samples thus prepared are shown in Figure 2.

Figure 2. Samples ready to be tested.

Testing

The fibre wrapped specimens were then tested in a Sans compression testing machine with 1500 kN loading capacity at a constant cross head speed of 2 mm/min. Axial strains were measured using platen to platen method and lateral strains were measured using the two longitudinal strain gauges glued diagonally opposite in the middle third of the specimen height. A commercially available data logging system named “System 5000” was used as the data acquisition system, which required a host computer for entering commands, reading the returned data and for managing the output channels. Compression testing was performed as per Australian Standards, AS1012.9 [24].

Results and discussion

Stress-strain behaviour

The axial stress, axial strain, lateral strain behaviours for the samples from Mix 1, Mix 2 and Mix 3 are shown in Figures 3, 4 and 5 respectively. The dotted lines in Figure 3 and 5 are the stress-strain relationship for unconfined geopolymer concrete in Mix 1 and Mix 2 respectively. Unfortunately corresponding data for Mix 3 was not recorded. There were experimental issues with the 2 layers GFRP wrapping samples of Mix 3. Hence this is not recorded in the results. Three tested samples are shown in Figure 6.

Figure 3. Stress-strain behaviour for Mix 1.

Figure 4. Stress-strain behaviour for Mix 2.

Figure 5. Stress-strain behaviour for Mix 3.

Figure 6: Tested samples

Mix 1, Mix 2 and Mix 3 had 28 day unconfined compressive strengths of ~~23.2~~19.7 MPa, 33.8 MPa, and 45 MPa respectively. Therefore, with increased curing time the unconfined compressive strength increases which is similar to the observations reported in the literature. At the same time, it can be observed that compressive strength increases with increasing level of confinement for geopolymer concrete which is a similar observation to confined OPC concrete. On the other hand Mix 3 was cured in ambient temperature, it included both slag and fly ash as the binder and it gave highest compressive strength of all. All the three mixes showed an increase in the compressive strength with the increased level of lateral confinement while CFRP outperforms GFRP marginally.

It can be seen from the experimental results that the stress-strain behaviour of geopolymer concrete is mainly dependent on the level of confinement of the FRP. With low level of confinement, stress-strain behaviour is similar to that of unconfined concrete. After axial stress reaches the peak strength of unconfined geopolymer concrete, the lateral dilation increases. If the level of confinement provided by the FRP is strong enough, then the confinement action takes place at this point and continues to apply increased confinement until FRP ruptures. Strain hardening can be observed in the stress-strain relationships when the level of confinement is higher. However if the level of confinement provided by the FRP is not so strong, the stress starts to reduce after the peak strength of unconfined geopolymer concrete and the specimen will fail with FRP rupture. Strain softening can be observed in this situation. Typical stress-strain behaviour for confined and unconfined geopolymer concrete are shown in Figure 7. When geopolymer concrete is subjected to axial compression, the confinement provided by the FRP wrapping is related to the lateral dilation of the material. Therefore, the lateral strains reported in this paper will be useful for the modelling of the FRP confined geopolymer concrete.

Figure 7. Typical stress-strain behaviour for geopolymer concrete.

When compared with the FRP confined normal strength concrete reported in the literature, it can be seen that even with one layer of CFRP shows a stress-strain relationship with strain hardening [25]. From the results reported in this paper, one layer of confinement still records a strain softening for geopolymer concrete and 3 layers of GFRP only provides strain hardening. The stress-strain relationships shown here for FRP confined geopolymer concrete have a similarity with the same reported for high strength concrete.

Ductility

Although ductility is an essential characteristic of a well-designed structure, there is no consensus on the best method of measuring ductility. Displacement ductility factor, energy dissipation, and stiffness are some parameters used to evaluate column performance. In column analysis, the most widely accepted definition of displacement ductility factor is the ratio of ultimate displacement of the column and the displacement of the column at first yield of axial reinforcement. Consensus on the definition of ultimate displacement/strain has not been achieved and varies depending on the researcher. Ahn and Shin [26] and Paultre et al. [27] defined it as the displacement corresponding to 80% of the peak load along the descending branch of the load versus displacement curve while Rui et al. [28] defined the same using 85% of the peak load.

Field Code Changed

Displacement ductility factor (μ) defined below is used to analyse the performance of the samples tested in this research.

$$\mu = \frac{\varepsilon_2}{\varepsilon_1} \quad . \tag{1}$$

Where ε_1 is related to the approximate limit of elastic behaviour and ε_2 is the strain corresponding to the 0.85 of the peak stress in the descending branch for confined geopolymer concrete with strain softening. ε_2 will be the ultimate strain for the confined geopolymer concrete with strain hardening. These terms are clearly defined in Figure 8 (a).

Figure 8. Ductility factor measurement.

The best fit line shown in Figure 8 (a) is obtained by the linear regression analysis for the linear part of the stress-strain curve for each specimen. This line is then extrapolated to intersect the peak stress of each specimen. This definition for the confined concrete with strain softening has been used to find the ductility of concrete columns previously and recently to obtain the ductility of geopolymer concrete mortar [29]. Ductility factor for confined geopolymer concrete with strain hardening was similar to the one used previously for confined concrete [30]. Application of this definition of ductility factor is shown in Figure 8 (b). The ductility factor comparisons for geopolymer concrete thus calculated are shown in Figure 9.

Figure 9. Ductility variation with the number of layers of CFRP and GFRP.

As expected, three layers of FRP showed improved ductility compared to one and two layers of FRP confined geopolymer concrete. GFRP confined geopolymer concrete shows a more ductile behaviour than that for the CFRP confined geopolymer concrete. Three layers of GFRP confinement shows a strain hardening region in the stress-strain relationships which resulted in higher ductility. Most of the specimens showed a bond failure between the geopolymer concrete and CFRP and GFRP.

Ductility levels for normal strength or low strength geopolymer concrete are similar to the ductility level for high strength OPC concrete. CFRP confinement provides higher compressive strengths while GFRP confinement improves the ductility of geopolymer concrete. FRP wrapping has been used in the past for rehabilitation of circular columns and FRP tubes in column applications of OPC concrete. This research records the effect of FRP confinement in geopolymer concrete as a new construction material. The outcomes of this research will be important in evaluating the ductility level enhancement that can be provided by FRP wrapping for geopolymer concrete. The use of FRP as the method of confinement is well known and it will soon be used with geopolymer concrete applications as well, whether it is in a rehabilitation or a new application. With the results reported as a basis, it is worth investigating different confinement methods and their effects on geopolymer concrete.

Conclusions

The influence of parameters such as curing time/method, effect of binder type and CFRP and GFRP confinement on geopolymer concrete was investigated in this research. The experimental investigation was based only on the compressive strength of geopolymer concrete. Following conclusions can be drawn from this research:

- It was observed that increased heat curing time enhanced the unconfined compressive strength of fly ash based geopolymer concrete. Having fly ash and slag as the binder resulted in the highest compressive strengths even with ambient curing conditions. This finding is very useful for in-situ applications of geopolymer concrete.
- Stress-strain behaviours for geopolymer concrete with low levels of confinement are different from those for normal strength concrete with similar confinement. Normal or low strength FRP confined geopolymer concrete shows similar overall shape in the stress-strain curves to those for FRP confined high strength OPC concrete.
- Ductility levels can be improved with the increased levels of confinement. GFRP confinement gives better ductility levels than CFRP confinement for all the mixes of geopolymer concrete investigated in this study. Reported results in

this paper can be used in enhancing the strength of geopolymer concrete columns. However the bond between the geopolymer concrete and FRP needs further investigation.

- The experimental results for the lateral dilation can be used for the modelling of geopolymer concrete subjected to FRP confinement.

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