

Geopolymer concrete for structural use: Recent findings and limitations

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Abstract. Geopolymer binders offer a possible solution for several problems that facing the current cement industry. These binders exhibit similar or better engineering properties compared to cement and can utilize several types of waste materials. This paper presents the recent research progress regarding the structural behaviour of reinforced geopolymer concrete members including beams, columns and slabs. The reported results showed that the structural behaviour of the reinforced geopolymer concrete members is similar to the known behaviour of the ordinary reinforced concrete members. In addition, the currently available standards have been conservatively used for analysis and designing of reinforced geopolymer concrete structures. On the other hand, the main hurdles facing the spread of geopolymer concrete was the absence of standards and the concerns about the long-term properties. Other issues included the safety, cost and liability.

1. Introduction

Concrete is the major construction material used all over the globe and its use is second only to water. The construction industry has become the largest consumer of global natural resources. According to the United Nations, it is expected that by the year 2050 more than 65% of the population will dwell in cities [1]. The growth of the developing countries means implementing the use of electricity and building infrastructures and houses, in other words, electricity and concrete. Ordinary Portland Cement (OPC) is the binding material used for concrete production. It is estimated that the production of 1 ton of cement will release a similar amount of carbon dioxide (CO₂) into the atmosphere. Generally, the cement industry accounts for 5-8% of the global CO₂ emissions [2]. A technological turnaround should be adopted in order to reduce the CO₂ emissions of this industry. Reduction of the CO₂ emissions is a global need and we should understand that the current emission rate if it continues, will form a real threat to the future generations.

Geopolymer binders have been proved to be green building materials that can totally replace the OPC in the concrete industry. Geopolymer technology can utilise many by-product materials, such as FA, granulated blast furnace slag (GBFS), palm oil fuel ash, rice husk ash, and mining wastes. Other

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resources may include natural reactive aluminosilicate powders or thermally activated aluminosilicates, which can provide a wide range of geopolymer binder sustainability and availability worldwide.

Geopolymer synthesis is based on the inorganic alkali activation chemistry, where aluminosilicate rich material is activated using a strong alkali solution to produce a three-dimensional aluminosilicate gel that has a characterisation that can compete with OPC. Geopolymer binders have shown the potential to be alternatives to OPC and currently attract more attention due to their superior features, including higher early strength, dimensional stability, durability, fire resistance, superior bond to reinforcement and aggregates etc. [3]. Currently, many researchers all over the world are focused on this topic. The geopolymer institute reported the exponential increase in the number of scientific publications in peer-reviewed journals with the keyword geopolymer; more than 400 publications were recorded in 2013. The current research trend is shifting from geopolymer chemistry to the engineering applications and commercialisation.

2. Structural Behaviour of Reinforced Geopolymer Concrete

Geopolymer binders showed increasing potential for use as a cement replacing materials in the concrete industry. These binders can produce concrete with a wide range of physical and mechanical properties. In order to prepare geopolymer concrete (GPC) with desired properties, Si/Al, M/Si (M denotes any alkali cations), and water/binder ratios need to be controlled. Hence, it is required to carefully characterise the alkali activator and the source material to determine these ratios.

GPC has a different strength development mechanism compared to cement concrete mixtures; hence, the available methods for analysis and design of cement concrete members should be evaluated and verified before use in GPC members. Available literature on GPC dwelled much on production, physical, mechanical, and durability properties. However, less attention was given to reinforced geopolymer concrete (RGPC) behaviour and structural applications.

2.1. Flexural behaviour of RGPC beams

Kumaravel et al. [4] studied the flexural behaviour of RGPC beams cast using the FFA+GBFS-based GPC and cured at 60°C for 24 hours. The beams were cast with grade 40 concrete with dimensions of 125x250x3000 mm and tested under the 4 points loading flexural test. The results were compared with the reference reinforced cement concrete (RCC) beams of the same concrete grade. The RGPC beams showed similar load-deflection curves for that obtained for the reference RCC beams; however, the RGPC beams displayed higher load capacity in terms of the first crack appearance, and ultimate and service loads. Compared to the RCC reference beams, the RGPC beams showed higher yield load, ultimate load, and maximum load by 3.57%, 2.7%, and 11.25%, respectively. Figure 1 shows the similarity of the cracking patterns for both RCC beams and RGPC beams under flexural testing. All the beams failed by yielding of the reinforcement in the tension zone followed by crushing of the concrete in the compression zone. The results for all the beams were predicted using ANSYS software and showed close agreement with the experimental ones.

A similar study conducted by Dattatreya et al. [5]; however, the beams were cured under ambient conditions. The beam dimensions were 100x150x1500 mm and the tensile reinforcement ratio varied between 82-110% of the balanced reinforcement ratio. The first crack load was 9-11% for the RGPC beams and 13-16% for the RCC beams as a percentage ratio of their ultimate loads. The average service loads were reduced by 12% for the RGPC beams compared to the RCC beams. The cracking patterns including the crack number, spacing, and width, and the failure modes were almost the same. Using the ACI 318 code [6] equations to predict the cracking moment, ultimate moment, and maximum deflection gave good correlation and fair agreement with the experimental results; however, the agreement degree was not the same for all cases. It was suggested to include an additional reduction factor. Further researches were recommended to investigate the stress block shape in the RGPC members.

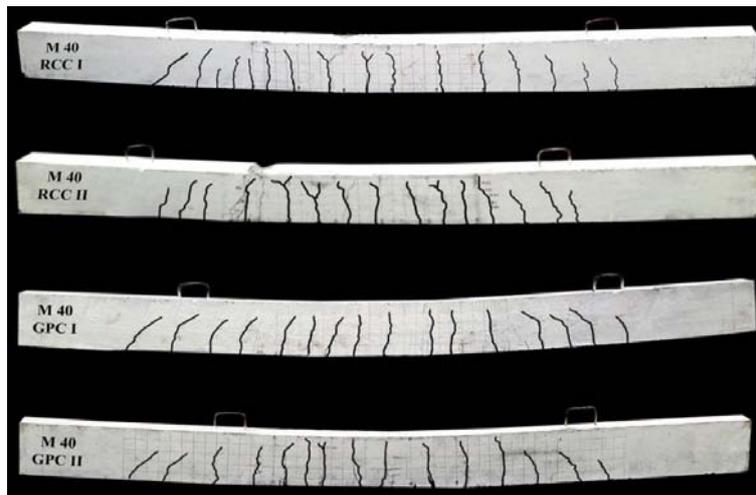


Figure 1. Cracking patterns of RCC (RCC I&II) and RGPC (GPC I&II) beams [4].

Another interesting study by Yost et al. [7, 8] has investigated the flexural behaviour of full dimension RGPC beams. The beams were cast using the FFA-based GPC of the dimensions 305x152x3200 mm and cured at 60°C for 24 hours using their newly developed system which was called “environmental curing chamber”. This system used the halogen lights as the source of the temperature increase. The compressive strength was in the range of 52-57 MPa. The beams were reinforced with three different arrangements representing the cases of the under-reinforced (U), over-reinforced (O), and shear critical reinforcement (S). The beams were tested under the 4-point loading system and the results compared with the reference RCC beams. The U-beams from both the RCC and RGPC showed nearly identical load-deflection curves. The reinforcement yielding loads were slightly higher than the predicted values for both the RCC and RGPC beams. A fully ductile behaviour was observed after which the concrete in the compression zone crushed. However, the RGPC beams showed a more brittle manner where the concrete disintegrated and the load fell directly at the point of failure whilst the RCC beams sustained awhile after failure. The RGPC beams recorded higher deflection values at the maximum loads. The side strain gauges showed that the neutral axis position could be described in 3 phases: transition, elastic, and inelastic. The theoretical and experimental results for the neutral axis location during different testing stages were fairly identical, which implies that the ACI 318 code [6] equations of the Whitney rectangular stress block can be used for the RGPC beam design. In the case of the O beams, the beams showed a linear load-deflection diagram up to failure while the RCC beams displayed a slight curvature prior to failure. The beams’ ultimate load was 8% higher than the predicted values. For the beams, the failure mode was by the diagonal shear mode. Identical cracking patterns were observed for both the RCC beams and RGPC beams, which suggests the similarity of the shear transfer mechanism for both types of concrete.

2.2. Shear behaviour of RGPC beams

The shear behaviour of the RGPC beams was investigated by Chang [9]. Nine beams of the dimensions of 200x300x1680 mm were cast using the FFA-based GPC. It was noted that the failure mode and the cracking patterns were similar for both the RGPC and RCC beams. The shear capacity of the beams was also found to be dependent on the longitudinal reinforcement ratios. The shear cracking load and the shear strength of the RGPC beams were predicted using the ACI 318 code [6] provision for shear calculations and gave conservative results. The VecTor2 programme was used to simulate the cracking patterns and the failure modes and to predict the shear strength. The predicted results indicated a very good correlation with the experimental data.

Madheswaran et al. [10] investigated the shear behaviour of thin webbed T-beams produced using the FFA+GBFS-based GPC. The results showed that both the RGPC and the RCC beams had similar

shear behaviour, where the beams' shear capacity was affected by the stirrups' spacing and the shear span to effective depth ratio. The beams failed by the typical diagonal tension shear failure mode, in which one of the flexural cracks in the shear span developed an inclined crack that extended toward the loading and supporting points after which a sudden brittle shear failure occurred. The load-deflection diagrams showed a linear relationship until cracking and even the post cracking portion also showed a linear relationship. The experimental values for the deflections were higher than the calculated values using the available ACI 318 code equations for the RCC beams. This may attribute to the lower modulus of elasticity of the GPC. It was reported that the available ACI 318 code provision for the shear design of the RCC beams is valid and can be safely used for the RGPC beam design; the upper limit provided by the code is also conservative. The same researchers has conducted similar study; however, on rectangular beams [11]. Twelve beams were cast with a span of 1600 mm and designed as shear deficient beams. The strain compatibility method was used to determine the ultimate moment capacity of the beams and the non-linear stress-strain relationship was used to estimate the complete load-deflection diagram. These methods showed an excellent correlation with the experimental results for both the RGPC the OPC beams.

Laskar et al. [12] highlighted the enhanced capacity of the RGPC beams against cyclic loading effects. It was reported that the RGPC beams had an increased capacity by almost 30% over the RCC beams. Moreover, the RGPC beams displayed a lower degradation in stiffness over time. Also, the RGPC beams showed higher capability for energy dissipation by 45% over the RCC beams, which promoted the higher ability of the RGPC beams to sustain earthquakes.

2.3. Behaviour of RGPC columns

Sarker [13] analysed the RGPC short slender columns under the combined stress of compression and uniaxial bending. They found that the analytical methods available for the RCC column analysis could be conservatively used for the analysis of the RGPC columns. However, some modifications were suggested for a proper stress-strain relationship. The predicted values of the ultimate loads, mid-height deflection, load deflection curves, and deflected shapes correlated well with the experimental data.

Rahman et al. [14] investigated the behaviour of the slender columns under axial compression and biaxial bending stresses. The columns were cast using the FFA-based GPC. The tested parameters included: concrete grade, reinforcement ratio, and eccentricity distance. The failure mode for all the columns was by the spalling of the concrete cover followed by the concrete crushing. For the small eccentricity distance, the failure was in a more brittle manner with a shorter post-peak on the load-deflection diagram. Increasing the eccentricity distance increased the measured deflection at the mid-height of the columns; also, the deflection increased for a higher reinforcement ratio and higher compressive strength. Generally, the failure modes and load-deflection behaviour are similar to that observed for the RCC columns. Bresler's reciprocal load formula and the stress block formula provided by the Australian standards were used to estimate the column load capacity. The results were found to be conservative and close enough to the experimental results. However, these formulas give higher accuracy in the case of columns with smaller eccentricities. A similar research by Sumajouw et al. [15] also confirmed the conservative results predicted by the Australian standards AS3600 and the ACI 318 code provision. The average experimental to estimated ratio was 1.15. Another study by Sujatha et al. [16] compared the loading behaviour of the RGPC short slender columns with reference to the RCC columns. The columns were prepared with a circular cross-section and 1800 mm height and tested for axial compression loading. The results showed that the RGPC columns had higher load capacity by 30% over the RCC columns. On the other hand, lower mid-height deflections were observed for the RGPC columns.

2.4. Behaviour of RGPC slabs

The Flexural behaviour of the reinforced GBFS+FA-based GPC solid slabs reported to be similar to the behaviour of OPC reinforced concrete slabs [17]. Slab strips were prepared with the dimensions of 1300x650x75mm and reinforced 8mm bars. The slabs were tested under different supporting

conditions and different loading types. The measured deflections at failure ranged from 4-30mm at mid span. Comparing the experimental results with the results calculated using the available OPC concrete equations showed good agreement for the maximum deflections; however, the calculated deflections at first cracks loadings gave higher values than the measured ones. Madheswaran et al. [18] investigated the behaviour of the reinforced GBFS+FA-based GPC solid slabs under impact loading. The results were compared with similar OPC concrete slabs. It was reported that the energy absorption of GPC slabs was higher than that for the OPC concrete slabs at both cracking and failure stages, and this may be attributed to the lower modulus of elasticity which will reduce the GPC stiffness. On the other hand, it was observed that introducing steel fibres will increase the absorption of the OPC concrete slabs more than that for the GPC slabs and the performance of both types became similar.

Ganesan et al [19] investigated the behaviour of the reinforced FA-based GPC panels in one-way action in compare to the OPC reinforced concrete panels. Similar cracking patterns and mode of failure were observed in both types of them. The failure mode was by crushing of the concrete near the edges associated with large lateral deflections with maximum values at mid span. The load-deflection curves showed linear response until the appearance of the first cracks, after which it showed a nonlinear behaviour. The GPC concrete panels showed steeper curves, which indicated the higher ductility of the OPC panels. This was referred to the softening behaviour due to the existence of more fine particles in GPC mixes, which resulted in a less ductile behaviour. The current available ACI 318 code model found to give conservative results in predicting the ultimate load of the GPC panels. However, the calculated results were always lower than the experimental results. The error ranged from 20-35% depending on the aspect ratio and slenderness ratio. This may introduce the need to apply additional safety margins for predicting of the ultimate load of the GPC panels.

3. Stress-strain Relationship

The stress-strain behaviour of the FA-based GPC is not much different from that for normal strength OPC concrete [20, 21]. Using the available OPC concrete equations to draw the stress-strain relationship or to predict the strain at peak stresses for the GPC gave acceptable results [7, 22]. Compared to the OPC concrete, the FA-based GPC showed a similar behaviour up to the ultimate strength, after which a rapid decline in stress occurred during the post-peak strain softening; whilst, the OPC concrete showed a gradual strain softening after the ultimate strength was reached. The GPC displayed a more brittle behaviour compared to the OPC concrete [20, 21]. This may be related to the predominance of microcracks spread over the geopolymer microstructure [23, 24].

Sarker [13] suggested a modified model to properly predict the post-crack portion by introducing a new expression for the curve fitting value (n) using the same equations proposed for the high strength concrete by Thorenfeldt et al. [25]. The new model gave good predictions correlated well with the measured values. The peak strain for the different mixtures of GPC was recorded in the range of 0.0015-0.0026 [7, 22, 26, 27]. This is less than the 0.003 strain that is usually used in the OPC concrete design equations. Similar results [28] displayed that for 25 different geopolymer concrete mixes based on different FA sources, the ultimate strain was less than 0.002 whilst the stress ranged between 20-55 MPa. It was reported that the GPC was largely affected by the Si/Al ratio, and it was possible to produce a ductile GPC that failed in a ductile manner by deformations, and this was achievable by using a Si/Al ratio higher than 24 molar [29].

Prachasaree et al. [30] proposed a simplified empirical stress-strain model and stress-strain block parameter for the GPC design. They used the Thorenfeldt et al. [25] model for the OPC concrete as a base model. They suggested that the maximum strain at the peak stresses should be used rather than the maximum compressive strength to find the appropriate factor in terms of the elasticity modulus. The proposed model displayed a good correlation with the experimental data; however, for the post-peak portion, a small deviation appeared. The proposed model was used to find the equivalent rectangular stress block parameters and new expressions were proposed. The flexural capacity was calculated using the new model and based on the ACI 318 provision for flexural analysis. The proposed model showed very good correlation with the experimental results with an error range from

9-16% compared to 34% when using the currently available ACI 318 code models. And, this was validated over the FA-based GPC of strength below 75 MPa. Ganesan et al. [21] noted that for the same value of strain on the stress-strain diagram, the stress values for the FA-based GPC were greater than that of the OPC concrete. In addition, the initial deformation increased at a slower rate until the stresses reached 80% of its ultimate values; then, the deformation increased rapidly at a higher rate compared to the OPC concrete.

4. Limitations and Challenges

Despite the huge researches that have been carried out, the geopolymer-based concrete faces many challenges that need to be addressed. One of the main challenges is the absence of the standards which should be created by a global committee. The adaptation of such new materials will be limited by the institutional issues and lack of specifications' or standards' flexibility, rather than the obstructions of the technical issues. Appropriate standards that consider the performance as a base for concrete evaluation may be the most suitable solution for the adaptation of such new materials. On the other hand, the term "geopolymers" covers a wide range of source materials, which can confuse the designers or specifiers; hence, a correct category of the source materials should be selected for use in the concrete industry.

The creation of new codes will be very expensive so it requires the collaboration of governments, industries, and researchers. The main motivation for the adoption of such new materials is sustainability and the environmental issues. However, these issues are not enough to motivate the unwilling markets; the demand for new material should be required by the market itself. This can be achieved by increasing the global awareness and the adaptation of new regulations for greenhouse gas emissions' taxes and awards. End users are more willing to deal with the enhanced substantial properties like strength, cost, and durability rather than the environmental issues. In terms of the relatively low cost of the by-product raw materials, GPC was expected to reduce the cost by 10-30% compared to the conventional concrete [29]. In reality, most of these raw materials are controlled by long period contracts supported by the cement companies. It requires the development of new effective methods to reduce the activating solution requirements and produce cheaper activating solutions taking into account the efficiency in terms of greenhouse gas emissions. In light of the currently expected prices, GPC commercialisation is likely to be limited to the high-performance applications, including chemical, heat and fire resistance and hazardous waste management.

The long-term performance creates another main question for the acceptance of GPC. Most of the design engineers request at least 20-30 years of real world verification before such new materials are adapted for the construction industries. Lack of such data makes it unsuitable when the safety of the user is a critical concern. The available durability tests give indications about the expected performance; however, a definitive approach is urgently needed. Other hurdles to be overcome are more specifically related to the variation in the mechanical and physical properties which are related to the variability of the quality and compositions of the source materials [31]. This makes it difficult to directly compare the results of the available research. Adaptation of any new material requires the predictability and reproducibility of the fresh and hardened properties. GPC may require a new chemical and engineering point of view in which the chemical composition and rheological properties form the base for the evaluation of the product. The requirement for elevated temperature curing of the GPC makes another challenge that limits the application of GPC to the precast applications. Ambient cured GPC and one part geopolymer binder are highly required for the wide acceptance of GPC products. Some researchers have tried to increase the reactivity of the FA by increasing the fineness [32] or the addition of a calcium source material [33, 34]; however, this may affect the cost and durability of the GPC. The location of calcium in the GPC structure is needed to be clarified [3]. It is required for a deeper understanding of the physicochemical nature of the geopolymerisation reactions. Also, this may contribute to understanding the role of the other oxides that may exist in the raw materials, such as Fe, Mg, etc.

Heidrich et al. [35] performed a survey in Australia regarding the barriers that are facing the usage and acceptance of GPC. The survey included a wide range of the concrete industry stakeholders. More than 60% of the respondents found that the absence of standards made the first of the main challenges for GPC acceptance, in the second position came the concerns about the long-term properties, and productivity and safety issues came in the third position; however, cost and liability were found to be lower concerns.

5. Conclusions

The present work has reviewed the structural behaviour of the RGPC beams, columns, and slabs in comparison to normal OPC reinforced concrete members. The FA and GBFS-based GPC members can provide physical and mechanical properties which are comparable with the conventional cement concrete. The existing design provision available in the ACI 318 code and the AS3600 code standards are reported to be applicable for the analysis and design of the RGPC structures and in most cases will give conservative results. However, it is recommended to apply an additional safety factor to adjust for the unexpected long-term behaviour. Compared to the OPC concrete, the stress-strain curves of the FA-based GPC show similar behaviour up to the ultimate strength, after which a rapid decline in stress occurs during the post-peak strain softening. The GPC displays a more brittle behaviour comparing to the OPC concrete members. The peak strain for the different mixtures of GPC was recorded in the range of 0.0015-0.0026, which is less than 0.003 known for OPC concrete. Regardless of the wide body of available literature geopolymer concrete, there is still a significant gap regarding the engineering properties and the structural behaviour of the RGPC. It is required to clearly determine the relationships between the different properties of the GPC including elastic modulus, Poisson's ratio, tensile strength, flexure strength, compressive strength, shear strength, and bond strength. More research is required regarding these areas. The unavailability of the standards makes the major challenge for the acceptance of the GPC; evaluation of the GPC based on its performance characteristics seems to be the best way for acceptance of such a new material.

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