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Review

Structural performance of reinforced geopolymer concrete members: A review

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HIGHLIGHTS

- Structural performance of geopolymer concrete members is summarized.
- No detrimental effects of using geopolymer concrete in structural members.
- General behaviour is similar with conventional reinforced concrete structural members.
- Design codes for structural member are applicable, but conservative.

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ABSTRACT

Due to the significant benefit of carbon footprint reduction with the use of cement-less geopolymer concrete, researches had shifted their focus towards the study of the behaviour of geopolymer concrete on micro- and macro-scales. The most important application of concrete in building construction is nonetheless reinforced concrete structural members. Therefore, this review aims to summarize and discuss the reported findings on the structural behaviour of geopolymer concrete members in order to give a clearer understanding of effects of such concrete in structural elements. Among the geopolymer concrete members highlighted in this review include reinforced concrete beams, columns, slabs and panels. It is found that generally there is no detrimental effect of using geopolymer concrete as structural member in terms of its load-carrying capacity, and standard codes of practice could be used to safely design the geopolymer concrete members. Nevertheless, it is suggested that further researches may be carried out to provide a more realistic and cost-effective design guidelines for utilizing geopolymer concrete in structural elements so as to expedite the use of such concrete for large-scale field applications in the future.

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1. Introduction

With the growing environmental and economic concerns associated with conventional concrete-based building materials such as reinforced concrete structures, researchers have been actively involved in exploring possibilities in using alternative materials to address these concerns. For instance, alternative concrete-making materials have been trialled in reinforced concrete structures such as recycled concrete aggregate [1,2] and agriculture waste materials [3], among others, in an attempt to reduce the dependency on conventional concrete constituent materials, which are fast depleting. One of the primary environmental concerns from concrete-based building materials is the high amount of carbon dioxide emission, which arises during the manufacturing of cement. Approximately 5% of the global carbon dioxide emission is contributed by the cement industry. In recent times, a cementless binder for producing concrete, termed as geopolymer concrete, is fast gaining popularity in concrete research work as the technology eliminates the need for cement. In order to produce geopolymer, a process termed as 'geopolymerization' is required which involves the reaction between aluminosilicate material and alkaline liquids. Common aluminosilicate material used for producing geopolymer is fly ash and slag, which are both industrial by-products and both of these materials have much lower carbon dioxide emission factor compared to cement. It was reported that the use of geopolymer could bring down the overall carbon dioxide emission by up to 64% in comparison with the use of cement [4]. Furthermore, in terms of economic consideration, due to the lower price of fly ash compared to cement, the price of fly ash-based geopolymer concrete could be as low as 10–30% cheaper compared to conventional cement-based concrete after taking into account the price of alkaline liquids [5].

While most of the research works on geopolymer concrete focus on micro-scale investigation, recent researchers on the use of geopolymer concrete extends to the investigation of the structural behaviour of geopolymer concrete in load-bearing members such as reinforced concrete beams, columns, slabs and more. The structural properties of the concrete members is one of the most vital component in effectively introducing such concrete for actual buildings and applications. The conformity of the performance of reinforced geopolymer concrete members with existing design provisions should be ascertained in order to evaluate the feasibility of using these design codes for geopolymer concrete members for the convenience of structural design engineers. In addition, practising engineers would also be able to produce a more realistic, safer and effective design of geopolymer structures in the long run based on knowledge and findings from research works, such as numerical models, empirical equations, appropriate assumptions and safety factors, among others. In view of the importance of the structural aspect of utilizing geopolymer concrete in reinforced concrete structures, this review summarizes and discusses the published findings of research works involving geopolymer concrete structures such as beams, columns, slabs and panels.

2. Summary of literature

2.1. Reinforcing bar-concrete bond

The structural performance of reinforced concrete members depends on the bond between concrete and reinforcement, in which the mechanism of bond influences the embedded length of reinforcing bar and consequently the load-bearing capacity of structural elements, crack opening and spacing [6]. ACI 408R [7] considers the bond strength as one of the structural properties and the understanding of the behaviour is critical to the eventual development of analysis and design basis of the structural member. Because of the difference in terms of chemical reaction and matrix formation of geopolymer concrete compared to conventional cement concrete, the bond properties of geopolymer concrete should be clearly understood before it is considered to be suitable to be used to replace conventional cement concrete in reinforced concrete structures. Reliance on conventional bond equations meant for normal concrete could lead to unsafe design, and this has led to numerous investigations to ascertain the bond behaviour of geopolymer concrete.

Due to the importance of bonding properties for structural members, researches have been undertaken to evaluate the bond strength between reinforcement and geopolymer concrete. The summary of the bond strengths obtained in literatures is given in Table 1. Sofi et al. [8] initiated the research on steel-geopolymer concrete bond behaviour through beam-end testing and direct

Table 1
Summary of reinforcement-geopolymer concrete bond strengths.

Experimental test	Bond strength (MPa)	Type of test	Remarks
Sofi et al. [8]	5.8–13.3 10.5–14.7	Beam-end test Direct pull-out test	Variables: i) Fly ash-slag ratio in binder ii) Type of fly ash iii) Bar diameter
Chang et al. [12]	3.59–8.77	Splice test	Variables: i) Concrete strength ii) Cover/bar diameter ratio iii) Splice length
Sarker [16]	10.61–19.42	Beam-end test	Variables: i) Cover/bar diameter ratio ii) Embedded length iii) Water content
Moser et al. [17]	3.58–19.68	Direct pull-out test	Variables: i) Curing period ii) Coating
Kim et al. [14]	14.48–35.61	Direct pull-out test	Variables: i) Bar diameter ii) Concrete strength
Topark-Ngarm et al. [15]	7.85–14.59	Direct pull-out test	Variables: i) Concentration of NaOH ii) NaOH: Na_2SiO_3 ratio iii) Type of curing
Castel and Foster [18]	24.10–31.90	Direct pull-out test	Variables: i) Curing period
Ganesan et al. [19]	12.73–16.57	Direct pull-out test	Variables: i) Bar diameter ii) Embedded length iii) Steel fibre volume
Maranan et al. [20]	19.39–23.96	Direct pull-out test	GFRP bars used Variables: i) Bar diameter ii) Embedded length
Tekle et al. [21]	9.60–19.60	Direct pull-out test	GFRP bars used Variables: i) Bar diameter ii) Embedded length iii) Compressive strength

pull-out testing. It was found that on average, the bond strengths of the fly ash-slag goepolymer concrete produced were 7.3–11.4 MPa and 10.5–14.7 MPa for the beam-end and direct pull-out testing, respectively. Based on the beam-end bond test results, Sofi et al. [8] concluded that the recommendations in standards such as AS 3600 [9], ACI 318 [10] and EC2 [11] could be used to safely predict the development length of geopolymer concrete as these codes were conservative in predicting the bond strength. Using results from lap-spliced beams, Chang et al. [12] also found that the code of provisions such as AS 3600 [9] and ACI 318 [10] gave conservative prediction of the bond strength of the lap-spliced geopolymer concrete beams, with test-to-prediction ratio of about 1.70. Chang et al. [12] added that for the lap-spliced beams, the bond strength model proposed by Canbay and Frosch [13] gave the closest match to the experimental bond strength of the geopolymer concrete beams, with average test-to-prediction ratio of 1.17. Although existing equations can be conservatively for the design of the development length and bond strength of geopolymer concrete, Kim and Park [14] and Topark-Ngarm et al. [15] suggested the following Eqs. (1) and (2), respectively which would give closer match to the experimental bond strength of geopolymer concrete:

$$\sigma = f'_c\left(2.07 + 0.2\left(\frac{c}{\phi}\right) + 4.15(\phi/l_d)\right) \tag{1}$$

$$\sigma = 2.12({f_c}')^{0.5} \tag{2}$$

where σ is the bond strength (MPa), f'_c is the cylinder compressive strength (MPa), c is the concrete cover (mm), ϕ is the bar diameter (mm) and l_d is the development length (mm).

The bonding behaviour between steel reinforcement with fly ash-based geopolymer concrete and cement concrete in beam-end specimens was also later carried out in few investigations [16,22]. The obtained bond strengths of geopolymer concrete were between 10.6 and 19.4 MPa, depending on the cover/bar diameter ratio. While similar splitting failure mode was observed for both geopolymer and cement concretes, for the same cover/bar diameter ratio, similarly, the bond strength of geopolymer concrete was found to be higher than the cement concrete [16,22]. The higher bond strength of geopolymer concrete was attributed to its higher splitting tensile strength compared to normal concrete [12,16] and this also corresponds well to the report by Maranan et al. [20] and Tekle et al. [21] for geopolymer concrete reinforced with glass fibre reinforced polymer (GFRP) bar, as well as the observation of Sofi et al. [8] who found that the tensile strength of the concrete relates closely to the bond strength in beam-end test specimens. Similarly, in a separate investigation, Castel and Foster [18] who conducted direct pull-out test on fly ash-slag geopolymer concrete, found that the bond strength of geopolymer concrete was on average 10% higher than cement concrete. Fernandez-Jimenez et al. [23] observed that the steel-geopolymer concrete bond was so strong that the failure mode observed in the pull-out testing was through rupture of the steel bar whereas pull-out failure was found in the case of the steel bar bonded to normal cement-based concrete. Similarly, due to higher bond strength of geopolymer concrete, Tekle et al. [21] reported splitting failure of GFRP bar-reinforced bond specimens compared to the pull-out failure of normal concrete. Because of the higher bond strength of geopolymer concrete compared to cement concrete, Sarker [16] suggested that existing bond equations could be utilized as a conservative prediction for the case of geopolymer concrete. Castel and Foster [18] agreed that existing bond models could be applied for the case of geopolymer concrete due to the similarity in the bond-slip diagrams for both types of concrete. Even though generally higher bond strength was found for geopolymer concrete, Castel and Foster [18] noted that cement concrete had higher bond strength when smooth steel bar was used and this should be of attention in the use of geopolymer concrete in bonding with smooth straight steel bars.

In terms of the effect of constituent material on the bond strength of geopolymer concrete, Sofi et al. [8] commented that the geopolymer concrete containing coarse aggregates gave higher bond strength than the concrete without coarse aggregate, and the former gave similar bond strength as normal cement concrete. In addition, the types of fly ash used in the geopolymer concrete was observed to have minor effect on the bond strength [8]. On the other hand, it was found that the inclusion of microwave-incinerated rice husk ash by 3% in fly ash-based geopolymer concrete could enhance the bond strength with steel reinforcement by up to 38% [24]. Topark-Ngarm et al. [15] observed increase in the bond strength when the concentration of NaOH used in the alkaline solution for the geopolymer concrete was higher. The effect of steel fibre addition on the bond strength of geopolymer concrete was highlighted by Ganesan et al. [19] in which it was found that depending on the cover/bar diameter ratio, the addition of steel fibres had varying effects. For instance, for specimens with smaller bar diameter, the addition of up to 1.0% steel fibres had positive effect in enhancing the bond strength, while in the case of larger bar diameters, the positive effect of steel fibres diminished due to the local disturbance caused which prevented proper compaction and thus poorer bond between the geopolymer concrete and steel bar. Based on the experimental results, Ganesan et al. [19] introduced a modified bond strength equation based on Orangun et al. [25] which takes into account the fibre reinforcing index as follow:

$$\sigma = \sigma_{th}(0.009I_f^2 + 0.022I_f + 1.4) \tag{3}$$

where I_f is the fibre reinforcing index given by $I_f = \tau V_f(l_f/d_f)$ in which τ is the matrix interfacial bond stress (MPa), V_f is the volume of fibres (%), l_f is the fibre length (mm) and d_f is the diameter of fibre (mm); σ_{th} is the bond equation proposed by Orangun et al. [25] given by $\sigma_{th} = 0.083[1.2 + 3(c/\phi) + 50(\phi/l_d) + (A_t f_{yt}/500\, s\phi)](f'_c)^{1.2}$ in which A_t is the area of transverse reinforcement (mm^2), f_{yt} is the yield strength of the transverse reinforcement (MPa) and s is the spacing of the transverse reinforcement (mm).

Moser et al. [17] applied reactive vitreous enamel coating on steel reinforcement and found that the coating improved the reinforcement-geopolymer mortar bonding by 2.5 times compared to the bonding between the uncoated reinforcement and geopolymer mortar. The average bond strength was increased from 4.9 MPa to 12.3 MPa in the presence of coating on steel bar after 28 days of curing. The increased bonding strength was attributed to the reactive calcium silicate on the surface of the coating which could have reacted with the fresh geopolymer. When using sand-coated glass fibre reinforced polymer (GFRP) bars instead of conventional steel bar, Maranan et al. [20] found that the bonding strength with geopolymer concrete was similar to that when reinforced with conventional steel bar, which was reported to be about 23 MPa. It was suggested that the GFRP bars could be an alternative for reinforcing geopolymer concrete. Therefore, the following modified relationship in Eq. (4) and Table 2 were used to represent

Table 2
Values of parameters Δ_r and α [20].

Bar diameter (mm)	Δ_r	α
12.7	0.20	9
15.9	0.14	5
19.0	0.12	4

the bond-slip relationship of GFRP bar reinforced geopolymer concrete for varying bar diameters:

$$\frac{\tau}{\tau_m} = \left[1 - e^{\left(-\frac{\Delta}{\Delta_r}\right)}\right]^{\alpha} \tag{4}$$

where τ is the bond stress (MPa), τ_m is the peak bond stress (MPa), Δ is the corresponding slip at τ (mm), Δ_r and α are parameters based on curve-fitting of experimental data which define the slope of linear stiffness and nonlinear to peak stress shape of the bond-slip curve, respectively.

Maranan et al. [26] also investigated the effects of using anchor headed GFRP bar in fly ash-slag geopolymer concrete and found improved anchorage capacity compared to straight GFRP bar by up to 77%. Due to the improved bonding strength, the failure mode was changed from pull-out to splitting failure of the geopolymer concrete. It was suggested that the anchor heads is beneficial in cases where bending of GFRP bar is not possible, especially in congested reinforcement area, and if long lengths cannot be produced due to limited space available to anchor the bar in concrete [26]. The following Eqs. (5) and (6) were proposed to predict the bond strength of straight GFRP and anchor-headed GFRP bars in geopolymer concrete, respectively:

$$\sigma = f_{t-gfrp}\left[0.085\left(l_d \times \frac{c}{\phi^2}\right)^{0.4916}\right] \tag{5}$$

$$\sigma = f_{t-gfrp}\left[0.085\left(l_d \times \frac{c}{\phi^2}\right)^{0.4916} + 0.2944\left(e^{-6\times10^{-4}\left(l_d \times \left(\frac{c}{\phi^2}\right)\right)}\right)\right] \tag{6}$$

where $f_{t\text{-}gfrp}$ is the nominal tensile strength of GFRP bar (MPa) and $5\phi < l_d < 90.19(\phi^2/c)$.

2.2. Reinforced concrete beam

Works on the structural behaviour of fly ash-based geopolymer concrete beams were initiated by Sumajouw et al. [27] where a total of six under-reinforced concrete beams with varying reinforcement ratios (0.64–2.69%) were tested for flexural failure. As expected, the flexural load-carrying capacity increased with increased the tensile reinforcement ratio and when compared to the design provisions given in AS 3600 [9], the test-to-prediction ratio were between 0.98 and 1.28, whereby majority of the predicted values were conservative. In the investigation by Sumajouw et al. [28], sixteen reinforced geopolymer concrete beams (Fig. 1) with varying tensile reinforcement ratio (0.64–2.69%) and concrete compressive strength (37–76 MPa) were tested. In short, Sumajouw et al. [28] reported that the general behaviour of the geopolymer concrete beams was similar to conventional cement-based concrete beams in terms of effect of tensile reinforcement ratio on flexural capacity and ductility index.

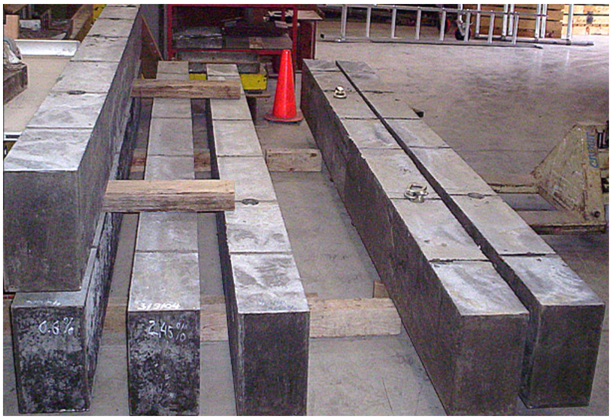

Fig. 1. Geopolymer concrete beams by Sumajouw et al. [28].

In other researches, it was also reported that under-reinforced fly ash-based geopolymer concrete beams behaved similarly (first cracking load, crack width, load-deflection relationship, flexural stiffness, ultimate load and failure mode) as conventional reinforced concrete beams subjected to flexural loading [29–33]. On the other hand, Dattatreya et al. [29] observed lower post peak ductility of geopolymer concrete beams and this was echoed by Yost et al. [30] who found a more brittle failure during concrete crushing compared to conventional cement-based concrete. In contrast, Jeyasehar et al. [34] found higher first crack load, mid-span deflection and ultimate load as well as smaller crack width for the case of reinforced geopolymer concrete beams as compared to conventional cement-based concrete beams.

Similar to the previous investigation in Sumajouw et al. [27], Sumajouw et al. [28] evaluated the flexural load capacity of the sixteen reinforced geopolymer concrete beams in accordance with AS 3600 [9] and the average test-to-prediction ratio was found to be 1.11. Considering that the beams were under-reinforced, the effect of the geopolymer concrete compressive strength was marginal. In addition, the maximum mid-span deflection at service load prediction given in AS 3600 [9] was found to be conservative, with average test-to-prediction ratio of 1.15. Yost et al. [30] also found compliance in the use of ACI 318 [10] to predict the ultimate load of the under-reinforced geopolymer concrete beams. On the other hand, based on IS 456 [35], although there is fair agreement between predicted and experimental values of the cracking, service and ultimate moment capacity as well as deflection of the reinforced geopolymer concrete beams, Dattatreya et al. [29] suggested that improvement could be made to predict the structural behaviour of the geopolymer concrete beams. Prachasaree et al. [36] noted this and introduced equivalent stress block parameters meant for fly ash-based geopolymer concrete which gave good agreement with experimental findings for geopolymer concrete beams. An average of 13% difference in the nominal moment capacity was found, reducing the difference between prediction and test results by about 1.4 times. Prachasaree et al. [36] reported that the proposed design parameters could be used with the design procedure in ACI 318 [10] and AS 3600 [9]. In the proposed method, firstly, a simplified stress-strain model was proposed for geopolymer concrete using modified Popovics equation (Eq. (7)) below:

$$\frac{f_c}{f'_c} = \varepsilon_c n / \left[\varepsilon'_c\left[n - 1 + \left(\frac{\varepsilon_c}{\varepsilon'_c}\right)^{nk}\right]\right] \tag{7}$$

where f_c is the compressive stress (MPa), ε_c is the concrete strain, ε'_c is the strain corresponding to the maximum compressive stress given by $\varepsilon'_c = 0.0051 - 4(f'_c)/10^5$ based on experimental data, n is the curve fitting factor given by $n = 0.5 + (f'_c/14.3) - [3(f'_c)^2/10^4]$ and k is a factor whereby k = 1 when $\varepsilon_c/\varepsilon'_c < 1$ and k. > 1 otherwise.

Secondly, based on the modified stress-strain equation, Prachasaree et al. [36] proposed the following flexural design parameters k_1, k_2 and k_3 (Eqs. (8) and (9)) for the determination of the equivalent stress block for the case of geopolymer concrete and hence the nominal moment capacity of geopolymer concrete beams could be determined through standard design procedures using these proposed parameters.

$$k_2 = 0.384 - \left(\frac{f_c{}'}{10^3}\right) \tag{8}$$

$$k_1 k_3 = 1.070 - \left(\frac{f_c{}'}{76.3}\right) + 9(f'_c)^2/10^5 \tag{9}$$

where k_1 and k_3 are the equivalent stress block parameter and the parameter k_2 defines the centroid of the compressive forces.

Utilizing ANSYS programme to conduct numerical analysis to predict the flexural behaviours of under-reinforced geopolymer concrete beams, Kumaravel et al. [32] and Kumaravel and Thirugnanasambandam [31] found good comparison of the predicted and experimental load-deflection relationships. In addition, in the research done by Nguyen et al. [37], although finite element simulation with ABAQUS software gives slight difference in the predicted deflection values, good agreement still existed between the experimental and simulated load-deflection behaviour of reinforced geopolymer concrete beams. Based on these researches, it was suggested that the ANSYS and ABAQUS softwares could be a useful tool in simulating the behaviour of structural members made of geopolymer concrete, and this could benefit design engineers dealing with reinforced geopolymer concrete members in the future.

Researchers also explored the structural behaviour of under-reinforced geopolymer concrete beams containing different concrete materials. For instance, Andalib et al. [38] incorporated 30% palm oil fuel ash (POFA) into the geopolymer concrete to produce geopolymer concrete beams and they observed similar cracking and ultimate moments as well as crack pattern as conventional reinforced concrete beams. On the other hand, although the flexural capacity of the reinforced geopolymer concrete beam was increased by up to 23% with the inclusion of recycled concrete as up to 75% coarse aggregate replacement, similar first crack load was observed for all cases of recycled concrete content (0%, 25%, 50%, 75% and 100%) [39]. Design provision in ACI 318 [10] was also found to give conservative prediction of the ultimate moment of the geopolymer concrete beams with test-to-prediction ratios ranging between 1.02 and 1.25. In addition, from the same research by Kathirvel and Kaliyaperumal [39], the geopolymer concrete beams containing higher amount of recycled concrete aggregate were observed to exhibit increasing deflections and ductility, higher number of cracks as well as greater crack widths. Devika and Deepthi [40] investigated the effects of hybrid steel-polypropylene fibre addition into reinforced geopolymer concrete beams. It was found that the flexural load capacity of the geopolymer concrete beam was improved by up to 30% in the presence of the hybrid steel-polypropylene fibres in a ratio of 70:30 while the presence of the fibres also significantly enhanced the energy absorption and displacement ductility of the reinforced concrete beams. In another research, Srinivasan et al. [41] evaluated the effects of glass fibre addition on the flexural behaviour of reinforced geopolymer concrete beams. Similarly, the flexural load capacity of the geopolymer concrete beams was found to be increased by up to 35% in the presence of up to 0.02% volume fibres which was attributed to the increase in tensile strain carrying capacity of the concrete. Further addition of glass fibres to 0.04% led to reduction in the flexural load bearing capacity due to induced voids within the concrete [41].

While similar ultimate load was observed for both under-reinforced geopolymer and cement-based concrete beams, in the case of over-reinforced geopolymer concrete beams, however, Yost et al. [30] reported that the ultimate load was 35% higher compared to the cement-based concrete beams when subjected to flexural loading, and the failure mode of the geopolymer concrete beam was characterized by an explosive compression failure. The higher load-bearing capacity of the over-reinforced geopolymer concrete beams was likely due to the higher geopolymer concrete compressive strength reported in the study [30].

Un et al. [42] showed that using rational methods such as effective modulus method (EMM) and age-adjusted effective modulus method (AEMM) which were originally developed for conventional cement-based concrete structures, the long-term deflection of reinforced geopolymer concrete beams could be estimated. Nevertheless, Un et al. [42] suggested that more work needs to be carried out to determine the long-term behaviour other structural elements as well as identifying the input parameters for the case of geopolymer concrete in predicting the long term deflection of the geopolymer concrete structures.

The flexural behaviour of reinforced geopolymer concrete beams subjected to corrosion was also evaluated. Under accelerated corrosion in sodium chloride solution, Wanchai [33] found that the reinforced fly ash-based geopolymer concrete beams exhibited greater degradation in the flexural capacity compared to the control beam containing conventional cement-based concrete. When immersed in sulphuric acid and combination of hydrochloric and sulphuric acid solutions for 180 days, Kannapiran et al. [43] observed little reduction (less than 8%) in the flexural capacity of reinforced concrete beams and no significant changes to the load-deflection relationship.

There are few research works carried out to evaluate the shear behaviour of shear-critical reinforced geopolymer concrete beams under flexural loading. Considering the similar crack shape and failure mode, Yost et al. [30] reported that the shear force transfer is similar in both geopolymer and cement-based concrete beams. The shear strength of the reinforced concrete beams were also similar for both types of concrete. On the other hand, Mourougane et al. [44] observed higher shear strength for the reinforced geopolymer concrete beams than the corresponding conventional cement-based concrete beams, in the range of 5–23%. Nevertheless, Mourougane et al. [44] found that ACI 318 [10] gave good prediction of the shear strength of geopolymer concrete beams, with an average test-to-prediction ratio of 0.96. Based on the investigation on a series of shear-critical geopolymer concrete beams with varying longitudinal and transverse reinforcement ratios, Chang [45] concluded that method of calculations for conventional concrete beams could be safely used to predict the shear strength for the geopolymer concrete beams such as AS 3600 [9] and ACI 318 [10], which gave average test-to-prediction ratios of 1.70 and 2.55, respectively. In addition, a more accurate prediction of

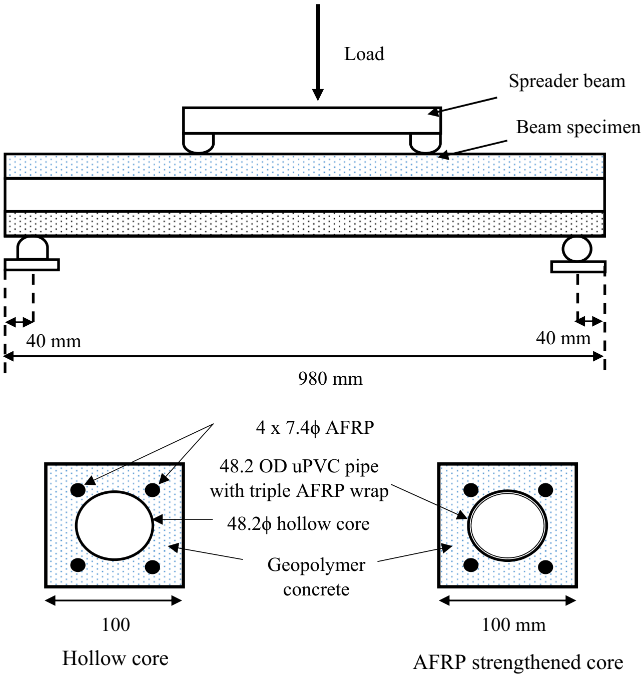

Fig. 2. Specimen details of lightweight steel fibre geopolymer concrete composite beam by Ng and Foster [48].

the shear strength of geopolymer concrete beams could be achieved by using Vecchio's [46] Disturbed Stress Field Model (DFSM), with test-to-prediction ratio of 1.08 reported [45].

Ng et al. [47] found that as steel fibres were added into the geopolymer concrete, the shear cracking of the resulting reinforced concrete beams was delayed, and more but finer cracks were formed in the specimens. Consequently, cracking load and ultimate strength of the steel fibre geopolymer concrete beams were increased. In addition, use of straight steel fibres resulted in smaller crack width compared to the addition of hooked-end steel fibres in the geopolymer concrete beams and this was due to the smaller diameter of the straight steel fibres. It was found an average test-to-prediction ratio of 1.06 was obtained for the shear capacity of steel fibre geopolymer concrete beams when predicted using the combination of sectional shear model and strut-and-tie model. Ng and Foster [48] also evaluated the shear strength of lightweight steel fibre geopolymer concrete composite beam reinforced with aramid fibre reinforced polymer (AFRP) bars and AFRP strengthened core (Fig. 2). The specimen with AFRP strengthened core exhibited increased flexural stiffness and the ultimate shear strength was increased by 40% and 60% for plain and steel fibre reinforced geopolymer concrete beams, respectively. The addition of steel fibres in the geopolymer concrete beam was found to contribute to increase of 139% and 150% in the shear strength compared to the corresponding plain geopolymer concrete beam without and with AFRP strengthened core, respectively. Similar to the observation by Ng et al. [47], there were also higher number of cracks but finer in terms of the crack width for the specimens with the addition of steel fibres in the shear-critical geopolymer concrete beams [48].

Rathinam et al. [49] carried out experimental investigation on the use of GFRP sheets to strengthen reinforced geopolymer concrete beams. It was found that GFRP 'U' shaped wrapping contributed to enhanced load carrying capacity, stiffness and ductility of the geopolymer concrete beams, and these improvements were greater when the number of layers of the wrappings were increased. Application of GFRP sheets at the soffit of the geopolymer concrete beams, however, although gave rise to the load carrying capacity and stiffness, did not contribute to enhancement of the ductility of the beams [49].

Based on their previous researches on producing GFRP bar-geopolymer concrete composite, Maranan et al. [50] evaluated the flexural behaviour of GFRP reinforced geopolymer concrete beams. In the research, the variables investigated include different types of GFRP bars (straight and headed) with different bar diameters and compared with conventional deformed steel bar reinforced geopolymer concrete beams. Due to the need for over-reinforced design in GFRP reinforced concrete beams because of the brittle nature of GFRP bars (in accordance with ACI 440.1R [51] and CSA S806 [52]), it is clear from Fig. 3 that the load-deflection response of the GFRP reinforced geopolymer concrete beams was different compared to the geopolymer concrete beams reinforced with conventional steel bar (denoted as DS-RGC-3-16.0 in Fig. 3). While there was a significant portion of plateau in the load-deflection response in the latter due to the yielding of steel bar, there was a non-linear response in the load-deflection curve for the GFRP reinforced beams caused by the cracking and crushing of the geopolymer concrete up until concrete crushing failure in the compression zone. On the other hand, there was no difference observed in the load-deflection behaviour in the geopolymer concrete beams reinforced with straight (SG-RGC series in Fig. 3) and headed (HG-RGC series in Fig. 3) GFRP bars. Besides that, due to the over-reinforced design of GFRP reinforced geopolymer concrete beams, there was no noticeable effect of reinforcing bar diameter and the reinforcement ratio on the flexural load-capacity of the beams. Rather, the increase in GFRP reinforcement ratio was useful for only crack control and serviceability performance of the GFRP reinforced geopolymer concrete beams [50]. Depending on the method in determining the bending moment capacity at service condition, while it was similar in the case of straight and headed GFRP bars, these were very different compared to conventional steel bar and this was mainly due to the difference in the elastic modulus of the reinforcing bars. For similar reinforcement ratio, the beams reinforced with GFRP bars exhibited higher flexural load-carrying capacity compared to that for steel reinforced beams and this was due to the early yielding of steel bars. When the flexural load-capacities of the GFRP reinforced geopolymer concrete beams were compared with codes of practices such as ACI 440.1R [51] and CSA S806 [52], it was found that the codes of practices were conservative, with test-to-prediction ratios of 1.31 and 1.23, respectively [50].

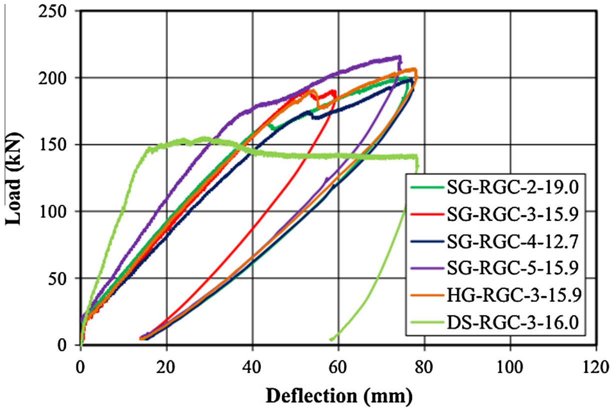

Fig. 3. Flexural load-deflection relationships of GFRP reinforced geopolymer concrete beams [50].

Similar to the GFRP reinforced geopolymer concrete beam, when using basalt rebar instead, the load-deflection behaviour of the geopolymer concrete beam was different than conventional steel reinforced cement-based concrete beam whereby there was an absence of the yielding stage [53]. Moreover, deflection of basalt rebar reinforced geopolymer concrete beam was about 4 times higher than that for conventional reinforced concrete beam for a given load. Nevertheless, according to Fan and Zhang [53], the ultimate flexural capacity of the basalt rebar reinforced geopolymer concrete beam obtained from experiment was close to that using ACI 440.1R [51] recommendation for FRP reinforced concrete beam.

2.3. Reinforced concrete column

One of the most important structural members is reinforced concrete column, designed to carry compressive axial loading. Reinforced concrete column is generally divided into two categories – short and slender columns. Due to architectural aesthetics and efficiency in the use of working space, slender columns are used in building structures around the world. In the effort to promote utilization of geopolymer concrete in reinforced concrete structural members, several research works have been carried out in the past to evaluate the performance of geopolymer concrete in slender reinforced concrete columns. This is considered to be vital as the composition of geopolymer concrete is different compared to conventional cement-based concrete and the structural performance of such concrete in compliance with codes of practices should be determined such that the use of such concrete in actual structures could be realized.

Sujatha et al. [54] fabricated and tested 12 slender circular reinforced concrete columns made of geopolymer and cement-based

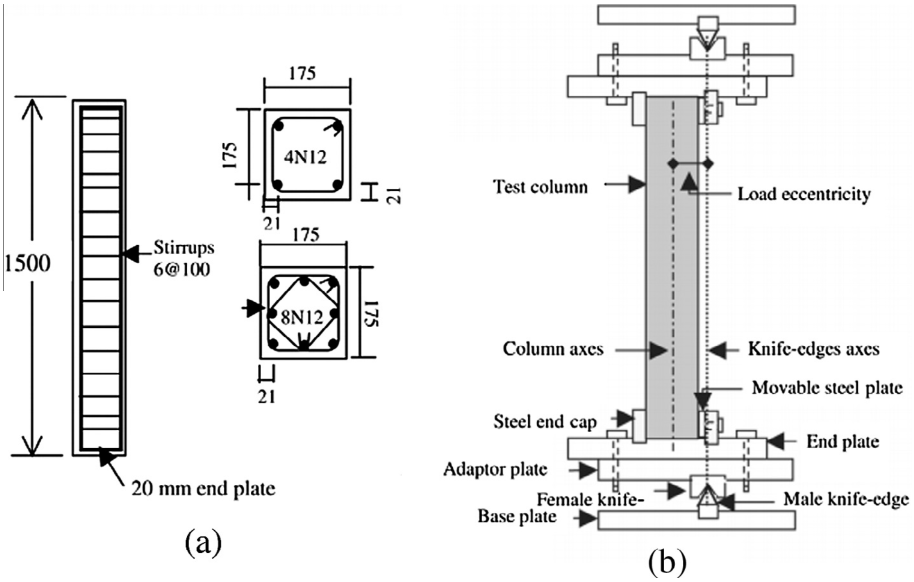

Fig. 4. Details of column specimen and test set-up [28].

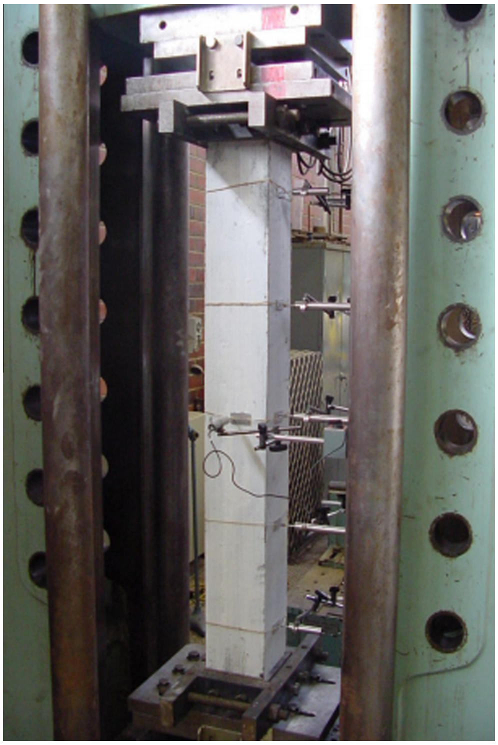

Fig. 5. Slender geopolymer concrete column test [28].

Table 3
Details of slender geopolymer column test under load eccentricities [28].

Column	Concrete compressive strength (MPa)	Load eccentricity (mm)	Longitudinal reinforcement	
			Bars	Ratio (%)
GCI-1	42	15	4Y12	1.47
GCI-2	42	35	4Y12	1.47
GCI-3	42	50	4Y12	1.47
GCI-4	43	15	8Y12	2.95
GCI-5	43	35	8Y12	2.95
GCI-6	43	50	8Y12	2.95
GCII-1	66	15	4Y12	1.47
GCII-2	66	35	4Y12	1.47
GCII-3	66	50	4Y12	1.47
GCII-4	59	15	8Y12	2.95
GCII-5	59	35	8Y12	2.95
GCII-6	59	50	8Y12	2.95

concretes of compressive strength grades 30 and 50 MPa. The reinforced concrete columns were tested under compressive axial loading without eccentricity. It was found that the geopolymer concrete columns had up to 34% higher load-carrying capacity as well as having greater rigidity compared to the corresponding cement-based concrete columns. Ganesan et al. [55] investigated the effect of steel fibre addition on the behaviour of slender square geopolymer concrete columns with 2.01% reinforcement ratio. In this research, the effects of different volume of steel fibres (up to 1.0%) as well as aspect ratio (l/d) of the slender columns were investigated. The slender columns were tested under monotonic axial loading. It was found that the inclusion of steel fibres increased the load-carrying capacity of the geopolymer concrete columns by up to 56%, and this was due to the fibre-bridging effect which prevented early concrete cover spalling. Increase in strain at the peak axial compressive stress and area under the stress-strain curve suggested that there was considerable improvement in the ductility (up to 29% increase) of geopolymer concrete column when steel fibres were added.

Research works were also carried out on slender fly ash-based geopolymer concrete column under load eccentricity carried out in Curtin University of Technology in Australia [28,56,57]. The details and set-up of the column test are shown in Figs. 4 and 5. In these researches, the slender columns tested had longitudinal reinforcement ratios of 1.47% and 2.95% and targeted concrete strength grades of 40 and 60 MPa; the column specimens were tested at specified varying load eccentricities from 15 to 50 mm (Table 3).

The columns had similar failure mode characterized by crushing of concrete in the compressed face near the mid-height of the columns (Fig. 6). Brittle failure mode was observed in columns with smaller load eccentricity, higher concrete strength and higher reinforcement ratio [57]. Similarly, the load-carrying capacity of the columns were increased with decrease in load eccentricity, increase in concrete strength and longitudinal reinforcement ratio [28]. On the other hand, the mid-height deflection of the tested

Fig. 6. Failure mode of slender geopolymer concrete columns [28].

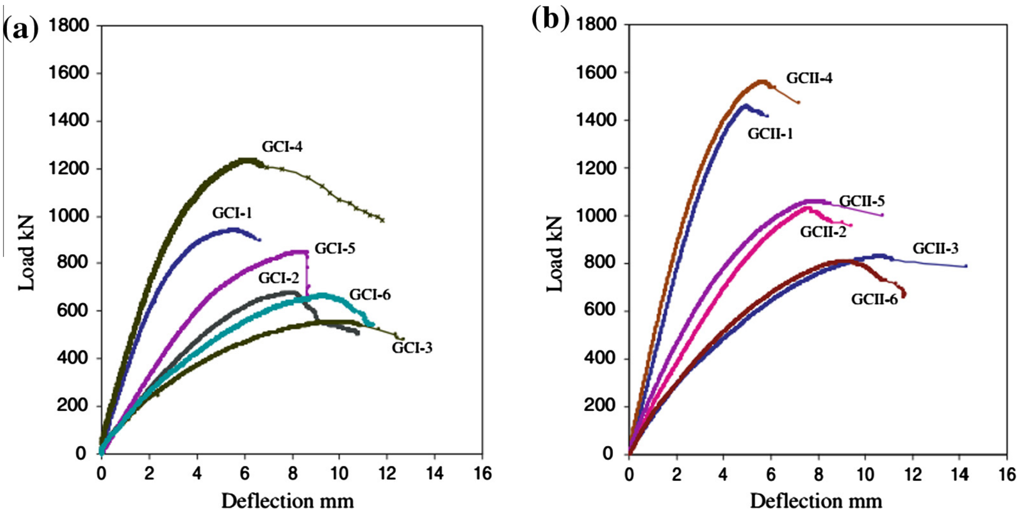

Fig. 7. Load-deflection graphs for tested slender geopolymer columns [57].

geopolymer columns increased with the increase in load eccentricity, decrease in concrete strength and reinforcement ratio [57]. The load-deflection diagrams for all tested geopolymer columns are shown in Fig. 7.

In the experimental works carried out by Sumajouw et al. [57], the load-carrying capacity of the slender geopolymer concrete column was compared with the design provisions from AS 3600 [9] and ACI 318 [10]; generally good agreement existed as the average test-to-prediction ratio was 1.03 and 1.11 for the case of AS 3600 [9] and ACI 318 [10], respectively. Therefore, the results demonstrated that the design provisions can be used in the case of the slender geopolymer concrete column. In addition, it was suggested that the simplified stability analysis proposed by Rangan [58] gave excellent correlation with the experimental values obtained for the load-carrying capacity of the slender geopolymer concrete column, in which the average test-to-prediction ratio obtained was 1.01. Sarker [59] utilized a non-linear analysis which incorporated a modified Popovics stress-strain equation (Eq. (7)) to predict the ultimate loads, load-deflection curves and deflected shapes for the previously published results of tested slender geopolymer concrete columns by Sumajouw et al. [57]. In the modified equation (Eq. (7)) by Sarker [59], the term curve fitting factor n was given by $n = 0.8 + (f'_c/12)$, the term $k = 0.67 + (f'_c/62)$ when $\varepsilon_c/\varepsilon'_c > 1$ while an additional factor k_3 of 0.90 was taken to account for the difference in concrete strengths between the compressive cylinder and

Table 4
Constants m′, q′, p′, m, q and p based on regression analysis by Ganesan et al. [55].

m′	p′	q′	m	p	q
1.25	5.9	0.3	1.15	9.5	0.2

Table 5
Constants a, b, h, a′, b′ and h′ based on regression analysis by Ganesan et al. [55].

	a	b	h	a′	b′	h′
Ascending	−0.00160	−1.434	1.251	-1.12×10^{-6}	−3.22	0.65
Descending	−0.00327	−2.477	2.013	−0.00086	−1.401	1.315

column. The analytical method was found to give very good average test-to-prediction ratios of 1.03 for the ultimate load and 1.14 for the mid-height deflection. Besides that, based on Eq. (7), in order to directly predict the stress-strain behaviour of slender fibre-reinforced geopolymer concrete columns, Ganesan et al. [55] also proposed a modified Popovics stress-strain relationship in which the terms of stress, maximum stress, strain and strain corresponding to maximum stress of concrete was replaced those of concrete column, denoted by f_{cc}, f'_{cc}, ε_{cc} and ε'_{cc}, respectively. In order to solve for the equation, the following expressions were used:

$$f'_{cc} = f'_c\left[\frac{m'}{\left(\frac{l}{d}\right)^{p'}} + q'I'_e\right] \tag{10}$$

$$\varepsilon'_{cc} = 0.002\left[\frac{m}{\left(\frac{l}{d}\right)^{p}} + qI'_e\right] \tag{11}$$

where m′, q′, p′, m, q and p are constants based on regression analysis given in Table 4, while I'_e is the effective reinforcing index given by $I'_e = (0.062 + 166.95V_f)/f'_c$. The curve fitting factor of n and factor of k in Eq. (7) for fibre-reinforced geopolymer concrete column were determined based on the following equations:

$$n = a(I'_e)^b + h \tag{12}$$

$$k = a'(I'_e)^{b'} + h' \tag{13}$$

where the constants a, b, h, a′, b′ and h′ were obtained based on regression analysis and the values are given in Table 5.

Columns subjected to compressive axial load at biaxial eccentricities, so-called bi-axial bending, are common in reality [60]. The corner columns in a building frame and columns in a bridge are the most common examples of columns under bi-axial bending. Axial load combined with biaxial bending is also common in internal columns of building frames [61]. Rahman and Sarker [61] tested fly ash-based geopolymer concrete columns subjected to axial load and biaxial bending. The columns of reinforcement ratios of 1.74% and 2.95% were tested for different combination of bi-axial load eccentricities, ranging from 15 to 70 mm for each direction (Table 6). Failure occurred by crushing of concrete on the compression face at the mid-height of the column and similar to the slender column subjected to load eccentricity, a brittle and explosive failure occurred in specimens with smaller load eccentricity and higher concrete strength due to the greater load-carrying capacity. It was highlighted that the failure and the load-deflection behaviour of the slender geopolymer concrete column was similar with conventional cement-based concrete column [61]. The obtained results by Rahman and Sarker [61] are shown in Table 6.

Using Bresler's reciprocal load formula to predict the failure load of the slender column subjected to bi-axial bending, Rahman and Sarker [61] found that the average test-to-prediction ratio was 1.18, and therefore the method of calculation is conservative for the case of geopolymer concrete columns. This suggests that the analytical method can be used as a conservative prediction of the strength of geopolymer concrete columns subjected to bi-axial bending.

When comparing circular columns reinforced with GFRP bar, Maranan et al. [62] observed that the strength of the column made from geopolymer concrete was higher than that for cement-based concrete, although no significant difference in terms of ductility and confinement efficiency was observed. The ductility of the columns reinforced with GFRP could be improved through the use of spiral-confinement compared to hoop-confinement [62].

In the experimental study conducted by Nagan and Karthiyaini [63], the performances of short reinforced fly ash-based geopolymer concrete columns with and without GFRP wrapping were evaluated. In the research, columns reinforced with 2.89% longitudinal reinforcement ratio were tested under compressive axial loading. The geopolymer concrete column was found to have about 30% higher load-carrying capacity and less deformation compared to conventional cement-based concrete column. When two layers of GFRP wrapping was applied to the short reinforced geopolymer concrete column, good confinement effect was observed, as enhanced load-carrying capacity (up to 69% increase) and ductility were observed [63].

2.4. Concrete filled steel tubular (CFT) column

Concrete filled steel tubular (CFT) columns have been increasingly used in structures such as bridges, high-rise buildings, transmission towers and warehouses etc. This is due to the excellent structural behaviour of CFT columns such as high strength, high ductility, high stiffness and full usage of construction materials [64]. Shi et al. [65] utilized geopolymer recycled concrete as concrete fill in steel tubular columns and tested the structural behaviour of the CFT columns. It was reported that in the geopolymer CFT columns, the load capacity was reduced in the increased ratio of recycled concrete as coarse aggregates, and this reduction was more significant compared to in cement-based CFT columns. On the other hand, the increased in the recycled concrete in geopolymer CFT columns resulted in increase in the peak strain, smoother falling branch, and hence greater ductility index (up to 87% improvement). Similarly, the effect of recycled concrete in geopolymer CFT columns was found to be more sensitive in enhancing the ductility of the column compared to the corresponding cement-based CFT columns [65]. Espinos et al. [66] demonstrated that when geopolymer concrete was used as concrete infill in conventional CFT columns, there was no particular effect; however, when used as outer core concrete infill in an innovative double tube CFT (Fig. 8), the fire resistance time was significantly delayed in comparison with using conventional concrete. The improvement in the fire resistance was caused by the delay in the temperature rise in the inner core conventional concrete as the outer core geopolymer concrete had lower thermal conductivity. On the other hand, poorer performance was observed when

Table 6
Summary of test results by Rahman and Sarker [61].

Specimen	Longitudinal reinforcement		Eccentricity		Compressive strength (MPa)	Failure load (kN)	Mid-height deflection	
	Bars	Ratio (%)	e_x (mm)	e_y (mm)			Δ_x (mm)	Δ_y (mm)
C-1	4Y12	1.74	15	25	37	953	3.44	4.40
C-2	4Y12	1.74	15	50	45	641	4.80	5.99
C-3	4Y12	1.74	30	70	47	392	6.06	8.20
C-4	8Y12	2.95	35	35	59	739	4.51	7.06
C-5	8Y12	2.95	50	40	53	572	8.17	7.16
C-6	8Y12	2.95	70	50	58	428	10.49	9.48

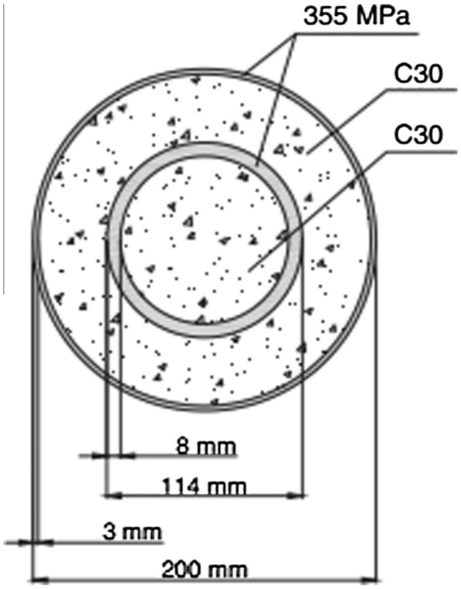

Fig. 8. Double tube CFT by Espinos et al. [66].

geopolymer concrete was used as inner core and conventional concrete in the outer core of the double tube CFT due to the quicker rise of temperature in the outer tube.

2.5. Reinforced concrete panel

Reinforced concrete wall panels are considered as important structural member as beams, slabs and columns. However, reinforced concrete wall has slenderness effect, leading to stability problems. Therefore, Ganesan et al. [67] investigated the strength performance of reinforced concrete wall panel made using geopolymer concrete in order to fill the research gap on the behaviour of structural members made of geopolymer concrete. It was observed that the main difference between the reinforced geopolymer concrete and cement-based concrete wall panels when subjected to axial loading was the greater deflection of the former even though the load-carrying capacity was similar. This geopolymer wall panels exhibited more softening behaviour and thus was being said of behaved in a more ductile manner, which was attributed to the presence of larger amount of fine particles in its matrix [67]. It was noted that ACI 318 [10] gave conservative prediction of the ultimate strength of the geopolymer concrete wall panels and hence Ganesan et al. [67] proposed the following equation to predict the ultimate strength of the geopolymer concrete wall panels.

$$P_u = 0.585\left[f'_c Lt + (f_y - f'_c)A_{sc}\right]\left[1 + \left(\frac{h}{40t}\right) - \left(\frac{h}{30t}\right)^2\right]\left[1 - \left(\frac{h}{18L}\right)\right] \tag{14}$$

where P_u is the ultimate load (kN), L is the length of panel (mm), t is the thickness of panel (mm), f_y is the strength of steel reinforcement (MPa), A_{sc} is the area of steel reinforcement (mm^2), h is the height of panel (mm).

Sarker and Macbeath [68] evaluated the fire endurance performance of reinforced fly ash-based geopolymer concrete panels and found that the heat transfer rate of the geopolymer concrete panel was greater than the corresponding cement-based concrete panel when exposed to high temperature of up to 1000 °C. However, the damage to the specimen after high temperature exposure was less severe in the case of the geopolymer concrete panel and this was due to the smaller temperature differential in the concrete. Because of this, the residual-to-original strength ratios of the geopolymer concrete panels were higher at 0.61–0.71 compared to those of the cement-based concrete panels which were about 0.50–0.53. The results suggested superior fire endurance of reinforced geopolymer concrete panels compared to the cement-based concrete specimens. The conformity of structural geopolymer concrete panels towards fire resistance requirements in AS 1530 [69] was also reported by Aldred and Day [70].

2.6. Other reinforced concrete structures

Mohana and Nagan [71] carried out flexural tests on geopolymer reinforced ferrocement slabs and compared the performance with conventional ferrocement slabs. It was found that the cracking load, yielding load and ultimate load of the geopolymer ferrocement slabs were all higher compared to the corresponding conventional ferrocement slabs. Interestingly, the geopolymer ferrocement slabs could sustain larger deflection at yield and failure, as well as exhibiting more micro-cracks, thus suggesting enhanced ductility (up to 26%) and energy absorption (up to 109%) compared to conventional ferrocement slabs. In terms of cracking behaviour, the number of cracks was observed to be more in the case of the geopolymer ferrocement slab while the average crack width and spacing were higher in the case of conventional ferrocement slab [71]. A series of 24 geopolymer ferrocement slabs with varying volume fractions of reinforcement and type of reinforcement were tested under drop weight impact loading in an experimental investigation carried out by Nagan and Mohana [72]. It was found that there were similar failure patterns of the slabs made of conventional ferrocement and geopolymer ferrocement while the increase in volume fraction of reinforcement contributed to up to 10 times increase in the impact energy absorption of the geopolymer ferrocement slabs. It was noted that the best performance was observed in the geopolymer ferrocement slab reinforced with a combination of 4 layers of chicken mesh and 1 layer of weld mesh.

When reinforced concrete pipes were tested under three-edge bearing test, Shrestha [73] found that the pipe made of geopolymer

Fig. 9. Failure mode of (a) reinforced geopolymer concrete pipe and (b) conventional reinforced concrete pipe [73].

Table 7
Summary of test-to-prediction ratios.

Experimental test	Codes of practice	Test-to-prediction ratio*	Type of specimen	Remarks
Sumajouw et al. [28]	AS 3600	0.97–1.42 (1.11)	Reinforced geopolymer concrete beam under flexural loading	Variables: i) Tensile reinforcement ratio ii) Concrete strength
Dattatreya et al. [29]	IS 456	0.82–1.11 (1.02)	Reinforced geopolymer concrete beam under flexural loading	Variables: i) Fly ash-slag ratio in binder
Yost et al. [30]	ACI 318	1.20–1.30 (1.26)	Reinforced geopolymer concrete beam under flexural loading	
Kathirvel and Kaliyaperumal [39]	ACI 318	1.02–1.25 (1.10)	Reinforced recycled aggregate geopolymer concrete beam under flexural loading	Variables: i) Coarse aggregate replacement level using recycled concrete aggregate
Yost et al. [30]	ACI 318	1.41–1.51 (1.46)	Over-reinforced geopolymer concrete beam under flexural loading	
Maranan et al. [50]	ACI 440.1R CSA S806	1.26–1.42 (1.34) 1.17–1.32 (1.24)	Over-reinforced geopolymer concrete beam with GFRP reinforcement under flexural loading	Variables: i) Straight and headed GFRP bars ii) Tensile reinforcement ratio
Fan and Zhang [53]	ACI 440.1R	1.08	Over-reinforced geopolymer concrete beam with basalt reinforcement under flexural loading	
Chang [45]	ACI 318 AS 3600	1.76–2.97 (2.55) 1.21–1.89 (1.70)	Reinforced geopolymer concrete beam under shear loading	Variables: i) Tensile reinforcement ratio ii) Transverse reinforcement ratio
Mourougane et al. [44]	ACI 318 AS 3600 IS 456	0.67–1.20 (0.96) 0.95–1.75 (1.43) 0.88–1.59 (1.30)	Reinforced geopolymer concrete beam under shear loading	Variables: i) Tensile reinforcement ratio ii) Transverse reinforcement ratio
Yost et al. [30]	ACI 318	1.49–1.54 (1.52)	Reinforced geopolymer concrete beam under shear loading	
Sumajouw et al. [57]	ACI 318 AS 3600	0.99–1.23 (1.11) 0.94–1.14 (1.03)	Reinforced geopolymer concrete slender column under axial loading	Variables: i) Concrete strength ii) Load eccentricity iii) Longitudinal reinforcement ratio
Rahman et al. [61]	AS 3600	0.98–1.53 (1.18)	Reinforced geopolymer concrete slender column under axial loading and bi-axial bending	Variables: i) Concrete strength ii) Load eccentricity in x- and y-directions
Ganesan et al. [67]	ACI 318	1.22–1.87 (1.46)	Reinforced geopolymer concrete wall panel under axial loading	Variables: i) Slenderness ratio ii) Aspect ratio
Sofi et al. [8]	ACI 02 AS 3600 EC2	1.56–2.01 1.51–1.93 2.18–2.80	Steel-concrete bond strength of beam end specimen	Variables: i) Fly ash-slag ratio in binder ii) Fly ash type
Chang et al. [12]	ACI 318	1.49–1.94 (1.70)	Steel-concrete bond strength of splice specimen	Variables: i) Cover/bar diameter ratio ii) Splice length iii) Concrete strength

* Values in parentheses denote average values.

concrete exhibited more uniformly distributed crack lines with smaller crack widths, as compared to the distinct wider crack line of the pipe made of conventional cement-based concrete (Fig. 9). This may also suggest a more ductile failure mode of the geopolymer concrete than the normal concrete, which was similarly observed in the finding mentioned above. It was also reported that sewer pipes could be fabricated using reinforced geopolymer concrete and the pipes passed the Australian Standard for load-carrying strength, with the ability to withstand considerable internal hydrostatic pressures using geopolymer concrete with 7-day compressive strength of 40–60 MPa [74].

Gourley and Johnson [74] highlighted that high load bearing, high profile precast railway sleepers made of geopolymer concrete (compressive strength of 60–80 MPa) passed the requirements of Australian Standard for static and cyclic loading with ease. An advantage observed in the use of geopolymer concrete railway sleepers was that the steel-concrete bond was so great that there was no steel slippage at the ultimate load whereas in conventional design, steel wire failed in tension before slippage could occur. Uehara [75] also observed that by using geopolymer concrete to produce prestressed concrete sleeper, the performance of the sleeper achieved the load-bearing capacity requirements in terms of the bending test at rail position, bending test at centre of sleeper and pull-out test of fastening insert, in accordance with the Japanese Standard. However, the geopolymer prestressed sleeper had comparatively poorer demoulding performance compared to that for prestressed sleeper from conventional cement-based concrete, thus requiring automatic demoulding machine with additional hammering vibration.

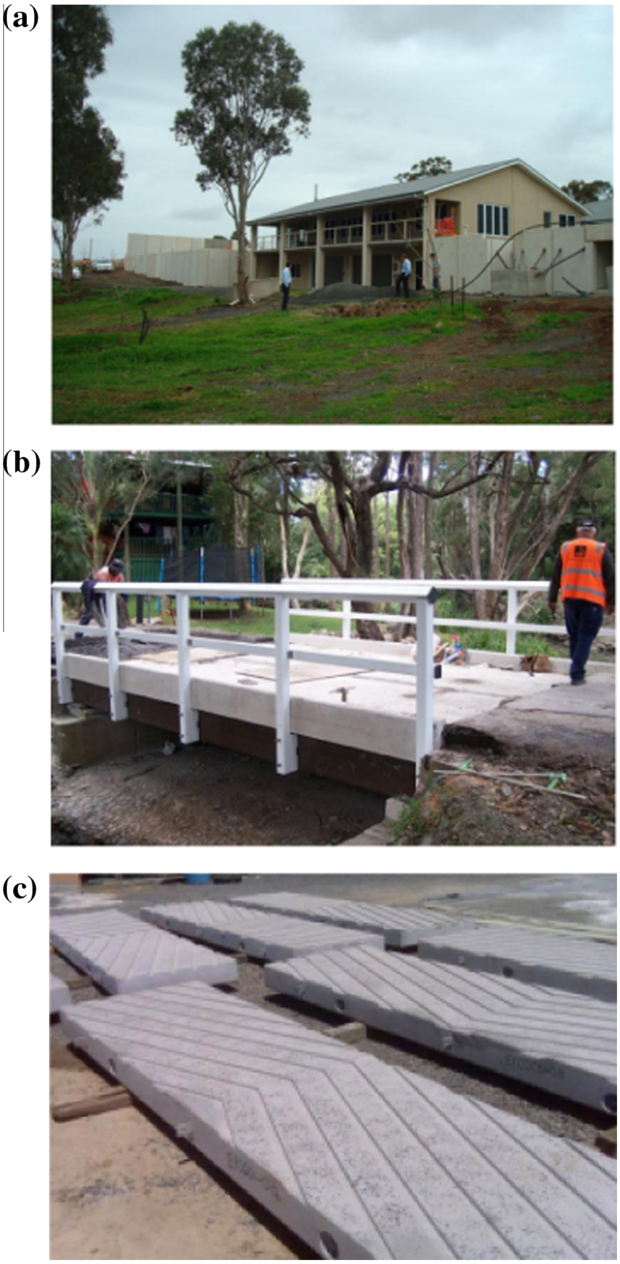

Fig. 10. (a) Precast retaining wall, (b) precast bridge deck, (c) precast boat ramp [70].

Dhakal et al. [76] fabricated a New Jersey type median barrier and tested the barrier to failure. It was found that the performance of geopolymer median barrier was in compliance with AASHTO and therefore could potentially be used in work zones in most roads. In addition, the investigation showed that the use of finite element and yield line analysis gave good agreement with the experimentally measured value, suggesting that the structural analysis and design approach for conventional cement-based concrete structures can be adopted for geopolymer concrete structures.

3. Discussion and suggestions

Based on the literatures studies, it is clear that till date, most research on using geopolymer concrete in structural members were mainly focused in reinforced concrete beams and columns, as well as the steel-concrete bond interaction. Generally, most of the performance of these reinforced geopolymer concrete members were found to exhibit similar, if not enhanced load-bearing capacities compared to the corresponding conventional reinforced cement-based concrete members. Because of this, most of the researches suggested that the use of design codes meant for conventional reinforced concrete members such as AS 3600 [9] and ACI 318 [10] are applicable for geopolymer concrete members, since these codes were mostly conservative in estimating the strength of the reinforced geopolymer concrete members. Table 7 summarizes the test-to-prediction ratio of the reinforced geopolymer concrete structural members using various codes of practices. Considering the relatively high test-to-prediction ratios, in order to produce a more economic structural design for geopolymer concrete structures, there are opportunities in research to either develop alternative design method for geopolymer concrete structures or determine the design parameters meant specifically for geopolymer concrete.

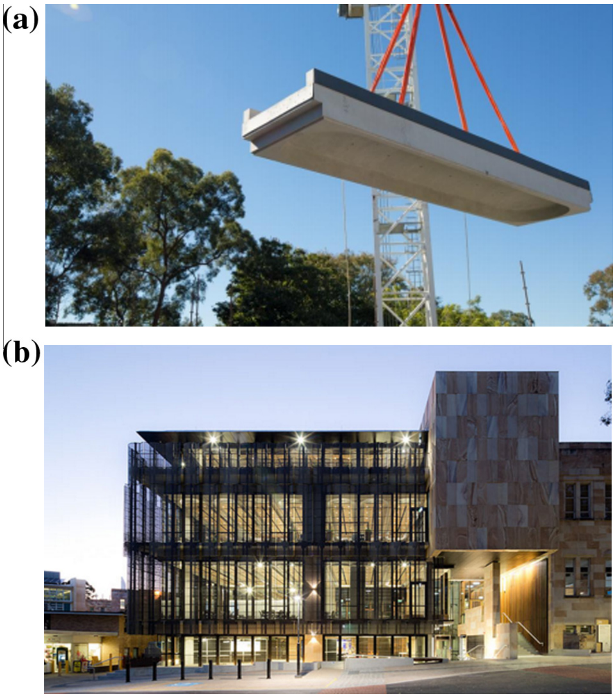

Fig. 11. (a) Precast geopolymer concrete beam used in (b) Global Change Institute [70].

In addition, due to the similarity in the general structural behaviours such as load-deflection, cracking characteristics and failure mode of the geopolymer concrete members with conventional concrete members, researchers generally agreed that geopolymer concrete members could be designed in the same way as conventional concrete members.

Generally, based on published results, the bonding between steel reinforcement with fly ash-based geopolymer concrete was superior compared to that for conventional cement-based concrete. The enhanced steel-geopolymer concrete bond strength could be beneficial for reinforced concrete structures in terms of design of development length, as well as ensuring lower slippages between steel reinforcement and concrete. Additional research work may be carried out in the future to provide improved accuracy in the prediction of bond strength of geopolymer concrete, such that a more economic structural design of geopolymer concrete structures can be achieved.

In terms of the ductility behaviour of structural members, while some researchers found reduced ductility of geopolymer concrete beams compared to conventional cement-based concrete beams, contrasting findings of enhanced ductility were reported in the case of geopolymer concrete panels, slabs and pipes. Considering the lack of agreement in this regard, it is suggested that more research is required to address the ductility of geopolymer concrete members such that necessary consideration could be taken into account in the structural design stage for geopolymer concrete members.

Considering that the use of geopolymer concrete have good potential for precast reinforced concrete elements, prestressing behaviour in such geopolymer concrete can be investigated in order to expedite and accelerate the use of geopolymer concrete in actual structural members for the future. In addition, since geopolymer concrete is known to have excellent durability and fire resistance, it will be interesting and appealing for the construction industry to have a more detailed knowledge on the performance of geopolymer concrete structures in extreme conditions, such as exposure to aggressive environment as well as in the event of fire. This should help to extend service life of structures with the use of geopolymer concrete and potentially reduce extensive repairing and maintenance costs involved when structures are exposed to extreme conditions.

4. Field application

In Australia, reinforced geopolymer concrete application had been utilized for actual field application, by using both precast geopolymer concrete elements and casting in-situ of the geopolymer concrete. Examples of these include precast retaining wall, precast bridge decks and boat ramp (Fig. 10) using geopolymer concrete of grade 40 [70]. In 2013, being the first application of geopolymer concrete in multi-storey building, precast geopolymer concrete floor beams were utilized as structural floor elements in the construction of The University of Queensland’s Global Change Institute (Fig. 11) [70].

5. Conclusion

Based on the review of the performance of the structural properties of geopolymer concrete members, it is concluded that the geopolymer concrete members such as beams and columns could be designed using design codes for conventional reinforced concrete members as most of the codes gave conservative estimation of the ultimate load-capacity of the geopolymer concrete members. Moreover, the general behaviour and failure mode of reinforced geopolymer concrete members were similar with those of conventional reinforced cement-based concrete members, and this should further enhance the use of available codes of practices to design structural members using geopolymer concrete. Although a number of design equations meant for geopolymer concrete structures were proposed in the past, these are still fairly limited and therefore there are still opportunities in further researching the structural behaviour of geopolymer concrete in order to develop a standard design method for reinforced geopolymer concrete member which are more economic, effective and realistic. This is essential in order to fully introduce geopolymer concrete for large-scale structural applications in the future, which would ultimately result in a more environmental-friendly and sustainable construction industry. The possibility of using geopolymer concrete in large-scale application is also further vindicated and supported by from the actual field application of the geopolymer concrete carried out in Australia.

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