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Review

Structural and material performance of geopolymer concrete: A review

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HIGHLIGHTS

- The taxonomy in the field of geopolymer concrete studies, both performances in material and structure are discussed.
- Parameters tested in the previous studies in geopolymer concrete is critically reviewed.
- The research lacking in this area is discussed.
- Barriers to the widespread use of geopolymer concrete in construction industry are critically analysed.

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ABSTRACT

Off late, the continuously depletion of the ozone layer and global warming issue have increased the awareness of the construction industries in using more eco-friendly construction materials. Against this background, geopolymer concrete has started to gain significant attention from the research scholars and construction practitioners, due to its advantageous in using by-product waste to replace cement and reducing greenhouse gas emission during its production. It also possesses better mechanical properties and durability compared to conventional concrete. Despite its advantageous, the use of geopolymer concrete in practical is considerably limited. This is mainly due to the lacking in the studies in terms of structural elements, design and application studies. This paper reviewed the material and structural performances of geopolymer concrete to identify the research gaps in this area for future research development. Analysis shown that geopolymer concrete can replace conventional concrete as they presented better mechanical properties, higher durability and more desirable structural performances compared with conventional counterparts. More studies are still needed for practical design standards and finally, the full scale studies on the structural elements should be established to ensure its feasibility in practical.

Contents

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1. Introduction

Geopolymer is adjudged as the latest wave of cement, after gypsum cement and ordinary Portland cement (OPC). It has appeared to be one of the major construction material internationally. 'Geopolymer' can be referred as amorphous alkali aluminosilicate or alkali-activated cements [1]. Geopolymer concrete can be produced by polymerizing the aluminosilicates such as fly ash (FA), metakaolin (MK), slag (SG), rice husk ash (RHA), and high calcium wood ash (HCWA) through activation using alkaline solution. Hence the efficiency in producing geopolymer concrete is highly dependent on the activators as well as types of aluminosilicates resources [2].

In general, geopolymer is one of the inorganic polymers. It is amorphous rather than crystalline compared to other natural zeolitic materials [3]. The polymerization requires a considerably quick reaction of silica (Si)-alumina (Al) under alkaline condition which subsequently create three-dimensional polymeric chain of Si—O—Al—O bonds. Dissimilar to OPC or pozzolanic cements, geopolymer utilizes the polycondensation of silica and alumina and a high alkali content to attain compressive strength [4]. On the other hand, geopolymer incorporating OPC develops calcium silicate hydrates (C-S-H) as well as polycondensation of silica and alumina and a high alkali content to attain compressive strength. The following reactions occur during geopolymerization [5].

$$(Si_2O_5Al_2O_2)_n + H_2O + OH^- \rightarrow Si(OH)_4 + Al(OH)^{4-} \qquad (1)$$

$$Si(OH)_4 + Al(OH)^{4-} \rightarrow (\underset{|}{\overset{|}{Si}} - O - \underset{|}{\overset{|}{Al}} - O)_n + 4H_2O \qquad (2)$$

Anything that contains amorphously Si and Al can be used to produce geopolymer concrete. These materials can be either natural mineral or industrial by-product. It was found that the products of hydration of FA/MK are sodium aluminosilicate hydrate gels. Meanwhile, the hydration products of SG activation are calcium silicate hydrate gels [1]. MK-based geopolymer is better than the other hydrates as it can be as its properties is more persistent. Despite its advantages, it required higher water-demand hence resulted in severe rheological problems. In the meantime, FA-based geopolymer presented higher durability. SG-based polymer, on the other hands, has higher early strength and greater acid resistance [2].

Fig. 1 shows the current trend in the research of geopolymer concrete. Apparently, the studies done on geopolymer concrete before 2001 is considerably limited. The number of studies increased dramatically from year 2016, indicating the high attention given by global scholars in this particular field. Despite vast and substantial studies being performed in this regard, geopolymer concrete has yet to procure international acceptance as construction material. The causes can be summarized as follows:

a) The cost of production of geopolymer concrete requires to be reasonably competitive.
b) Extensive and more reliable data are needed on the practicality of using geopolymer concrete as structural elements.
c) The establishing of design of geopolymer concrete elements is perquisite.

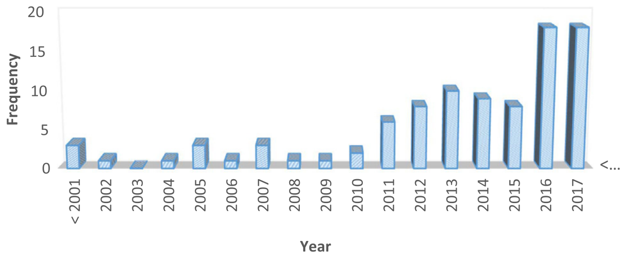

Fig. 1. Research trend in geopolymer concrete.

This review paper is targeted to contribute an all-encompassing understanding and assessment of geopolymer concrete. Against this background, a comprehensive database is created based on past literatures. Assessment and analysis are conducted on the influencing variables and their effects on the performances of geopolymer concrete. Eventually, a crucial debate is demonstrated on the facets that significantly affect the properties and performances of geopolymer concrete. It is certain that this review will assist in narrowing the intermission between academic/fundamental research to the construction industry.

2. Previous studies on geopolymer concrete

2.1. Research in materials

Extensive studies have been performed to assess the performances of geopolymer concrete. They including the effects of C-S-H phase, admixtures and curing conditions. Yip et al. [6] reported that in MK/SG-based geopolymer pastes, C-S-H and aluminosilicate gel (N-A-S-H) can be found. This is quite similar to a high calcium FA-based geopolymer, activated particularly by sodium hydroxide (NaOH), as reported by Somna et al. [7]. The strength of concrete paste is contributed by the C-S-H and N-A-S-H. In other words, the strength of geopolymer pastes is highly dependent on the alkalinity level of activators used. Besides, it was also reported that the temperature plays very important role in activating the aluminosilicates. Research found that in FA/SG blends, the activation process at lower temperature (at approximately 27 °C) is dominated by SG activation, whereas at higher temperature level (at approximately 60 °C), both FA and SG is activated. Nevertheless, the SG is contributing in the strength of pastes due to its compactness of microstructure [8]. The hardening of FA/SG- based geopolymer is due to C-S-H and C-A-S-H formation. The hardening is followed by the formation of C-S-H, N-A-S-H and C-A-S-H. However, the formation of hydrate gels is dependent on the calcium ions and pH levels. Prinya et al. [9] reported that acidic environment producing N-A-S-H gel in FA-based geopolymers. High concentration of calcium ion in class C FA-based geopolymers can result in higher compression strength [10]. The presence of high potassium oxide content in HCWA contributed to the early strength development [106] and contributed to the self-activation of geopolymer without the use of alkaline activator [107].

More recent studies shown that material with amorphous structure is most desirable in term of mechanical properties of geopolymer concrete. These are affected by the parameters such as SiO_2/ Al_2O_3 ratio, R_2O/Al_2O_3 ratio, SiO_2/R_2O ratio and liquid-solid ratio (R denotes either Na^+ or K^+) [11–16]. Compression strength of geopolymer paste increased with alkali content. In contrast, strength decreases with level of silica. This is the SiO_2/R_2O ratio effects and contribute to the forming of ring structure. It was reported by Zhang et al. [13] that activation by NaOH alone can form crystalline zeolite or nanosized crystals of another zeolite, depending on the Si/Na ratio. The addition of Sodium Silicate can reduce the crystallite formation significantly. Fig. 2 shows the effects of activators dosage in the microstructure distribution. Higher pore volumes will reduce the strength of pastes. It was also reported that the setting time of paste increase with SiO_2/Al_2O_3 ratio [14].

Effects of different admixtures were studied extensively in the past [17–19]. It was reported that sucrose formed insoluble metal complexes hence retard the hydration process. Citric, on the other hand, reduce the setting time and accelerate

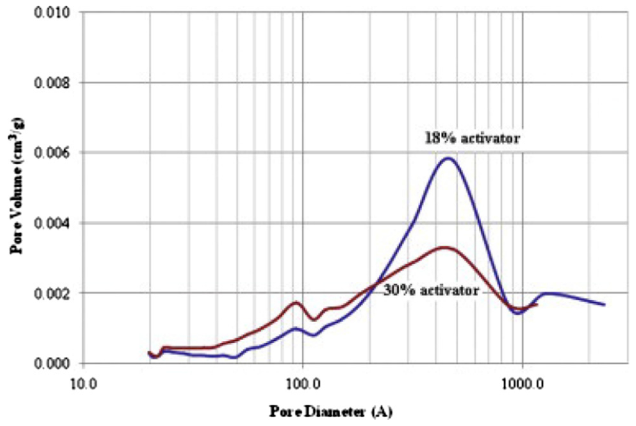

Fig. 2. Pore volume distribution at different activator dosages [14].

Table 1
Summary on structural performance of geopolymer concrete.

Structural element	Researchers	Concrete type	Testing variable	Remarks
Beam	Sumajouw et al. [77]	Fly ash-based	Reinforcement ratio	Flexural strength enhanced when the reinforcement ratio is increased, similar with the behaviour of conventional RC beams
	Sumajouw et al. [78]	Fly ash-based	Reinforcement ratio, concrete compressive strength	The effect of reinforcement ratio on geopolymer concrete beams is almost similar with conventional RC beams in regards of flexural capacity and ductility
	Dattatreya et al. [79]	Fly ash- based	Fly-ash slag ratio	Lower post-peak ductility was observed
	Ng et al. [80]	Fly ash- based	Steel fiber content	Shear capacity was delayed due to fibre, finer crack was also observed
	Mourougane et al. [81]	Fly ash-based	Different reinforcing configuration	Higher shear strength was observed for geopolymer concrete
	Yost et al. [82]	Fly ash- based	Tensile reinforcement ratio	No significant different in the shear behaviour between geopolymer concrete beam and ordinary RC beam
	Andalib et al. [83]	POFA + Fly ash-based	POFA-Fly ash ratio	Similar cracking pattern as RC beam
	Srinivasan et al. [84]	Fly ash-based	Glass fiber content	Flexural capacity increased approximately 35% with glass fiber. Over-utilization of fiber led to capacity reduction
	Devika and Deepthi [85]	Fly ash-based	Proportion of steel fiber and hybrid polypropylene	Flexural capacity improved 30% with the incorporation of hybrid steel-polypropylene fiber
	Kathirvel and Kaliyaperumal [86]	Fly ash-based	Proportion of recycled aggregate	Higher number of cracks, greater crack width but better deflection and ductility
	Visintin et al. [93]	Fly ash-based	Shear span ratio	Results of the direct shear tests show that the shear-friction properties for the geopolymer concrete utilised in the experimental investigation fall within the range of shear-friction properties of established OPC concrete
Column	Sujatha et al. [87]	Fly-ash based and cement-based	Concrete compressive strength	Geopolymer concrete columns is better to RC columns up to 34% in ultimate strength
	Rahman and Sarker [88]	Fly ash-based	Reinforcement ratio and bi-axial load eccentricities	Failure occurred by crushing at concrete on compressive side similar with conventional RC columns
	Sumajouw et al. [78]	Fly ash-based	Longitudinal reinforcement ratio and concrete compressive strength	Similar failure by crushing with brittle manner
	Ganesan et al. [89]	Fly ash-based	Steel fibers volume and aspect ratio	The inclusion of stel fibers increased the load carrying capacity by up to 56%
	Nagan and Karthiyaini [90]	Fly ash-based	Effect of confinement	Ultimate strength of geopolymer concrete column is about 30% improved. Confinement further enhanced the load carrying capacity and ductility
	Albitar et al. [94]	Fly ash/ slag-based	Eccentricity and slenderness ratio	Results reveal that fly ash/GLSS-based geopolymer concrete exhibits similar structural behaviour to ordinary Portland cement (OPC) concrete. The results also highlight potential issues with the scaling of ambient-cured geopolymer concrete to the structural level
Slab	Rajendran and Soundarapandian [91]	Fly ash-based	Volume fraction of reinforcement and types of reinforcement	Enhanced ductility and energy absorption compared to ferrocement slabs
	Nagan and Mohana [92]	Fly ash-based	Volume fraction of reinforcement and types of reinforcement	Increase in volume fraction can improve about 10 times of impact energy absorption

the hydration process [17]. For commercialized superplasticizer, it was found that both naphthalene and poly carboxylate-based superplasticizer can increase the workability [18,19]. However, a reduction of approximately 1/3 of the compressive strength was observed when polycarboxylate-based superplasticizer was used. Meanwhile polycarboxylate-based superplasticizer can retard the hydration of FA/SG-based.

2.2. Research in structural elements

The research of geopolymer concrete has been extended to structural elements such as beams, columns and slabs. It was found that the structural behaviour of FA-based geopolymer concrete beam similar to the ordinary reinforced concrete beams [78]. To increase the performance of geopolymer concrete beam, the effects of additional steel fiber were investigated by Ng et al. [80]. It was found that the shear capacity of beam was delayed due to additional fiber, finer crack was also observed. It was reported that lower post-peak ductility was observed when SG is added to FA-based geopolymer concrete [79]. As in FA-based geopolymer concrete column, trivial difference in failure mode was observed compared to conventional column [88]. Brittle failure was reported for geopolymer concrete columns [78]. To increase the load carrying capacity and the ductility of geopolymer concrete column, steel fibers and confinement can be used [89,90]. While in geopolymer concrete slabs, it was found that the ductility and energy absorption are better compared to ferrocement slabs [91,92]. Table 1 shows the summary of past literatures on geopolymer concrete elements. Detail of the structural performances of geopolymer reinforced concrete has been reported by Mo et al. [108].

3. Taxonomy on geopolymer concrete research

In general, the literature reviews have clearly indicated that geopolymer concrete can be classified by fly ash-based, metakaolin-based, slag-based and combination of either one of these aluminates resources as presented in Fig. 3. In addition, the relationships each parameter with the geopolymer concrete types are illustrated. Also, Fig. 3 highlights on methods or approaches used for performances assessment of geopolymer concrete with the effects of various variables.

The findings of the past studies with different activators, parameters and methods to assess the performance were listed Table 2. In this table, it shows the aggregation frequency of subject areas with regards to different authors, the activators utilized, and the methods or approaches adopted to assess the performance of geopolymer concrete. In Table 2, forty-two (45) studies have been performed on FA-based, seven (7) on MK-based, six (6) on SG-based, two (2) on RHA-based and HCWA-based whilst nineteen (19) focused on combined aluminosilicates resources. Table 2 also shows that sixty-four (64) authors used NaOH, seven (7) authors used KOH, fifty-five (55) authors used Na_2SiO_3 and four (4) authors used K_2SiO_3. It can also be seen that two (2) authors did not used

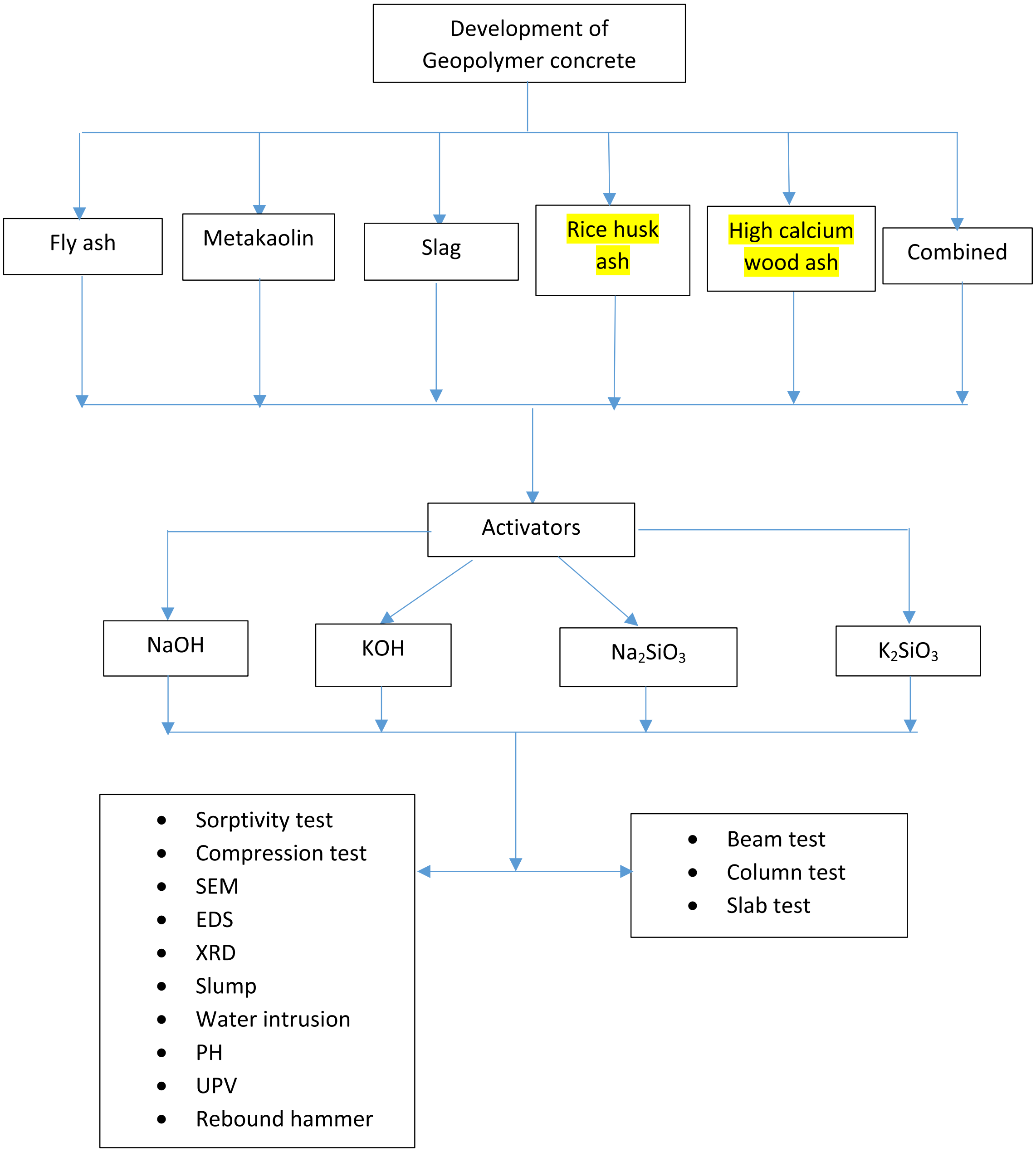

Fig. 3. Taxonomy on the studies of geopolymer concrete.

any activators to assess the capability of HCWA in activating the geopolymer.

The methods used to evaluation the reactivity of activators includes sorptivity test, compression test, SEM, EDS, XRD, slump test, water intrusion test, pH test, UPV and rebound hammer test for geopolymer concrete material, whilst in structurally, column, beam and slab tests were performed. According to Table 2, it can be revealed that cylinder compression test is to be often adopted as assessment. It was found that forty-seven (47) authors used this test. In addition to compression test, seventeen (17) used sorptivity test, six (6) used water intrusion test, nine (9) used UPV, eight (8) used pH tests, twenty-one (21) used SEM/EDS, thirteen (13) used XRD, fourteen (14) used slump tests, three (3) used rebound hammer test and one (1) used impact test. Meanwhile, eleven (11) authors used beam test, six (6) authors used column test and two (2) used slab tests. It should be noted that different tests were performed to identify to efficiency of each group of activators in affecting the mechanical properties, fresh properties, durability and structural performances of geopolymer concrete.

4. Performance assessment methods

Most of the studies measured the performances of geopolymer concrete by compressing cylinder specimens to obtain their ultimate compressive strength and analogize with the capacities of the control specimens. They can be either conventional concrete cylinder or specimens made with other geopolymer concrete group. It was found that the paramount approach in assessing the performances of geopolymer concrete. Cylinder monotonic compression tests, sorptivity test, SEM, EDS, XRD, slump test, water intrusion test, pH test, UPV, rebound hammer test, column test, beam test and slab test were among the methods normally used.

As presented in Table 3, it can be observed that various aluminosilicates resources have been adopted in producing geopolymer concrete. These resources are FA, MK, SG, RHA, HWCA or combination from two or three of these resources. Various activators have been tested over FA-based geopolymers. Based on the analysis, it can be seen that FA is the most commonly used aluminosilicates in geopolymers concrete and the reactivity is the most promising. The influencing variables on the performance of geopolymer concrete are summarized in Table 3. For FA-based, the variables include proportion of additional cement, mix proportion, proportion of nano material, effect of silica fume, effect of glass fiber, effect of additional cement, proportion of $Ca(OH)_2$ and SG, effect of adding PVA fiber, effect of adding recycled aggregate, NaOH-Na_2SiO_3 ratio, liquid-ash ratio, curing time, proportion of steel fiber activator types, curing procedure, elevated temperature, molar ratio, types of aggregate used, effect of superplasticizer and effect of curing condition. For MK-based, the variables tested are considerably lesser compared to FA-based. These variables include the effect of source material, effect of immersion time, sample mass-volume value, aggregate-mass ratio, molar ratio, effect of temperature and superplasticizer, effect of adding limestone and effect of additive. For SG-based geopolymer concrete, the variables tested are proportion of $Ca(OH)_2$ and SG, different environment condition, different mix proportion and superplasticizer, liquid-solid ratio and the effect of different activators. For the combined aluminosilicates group, test variables include the effect of bio-additives, effect of PVA fiber, concentration of activators, molar ratio, size distribution, mix proportion ratio and solution concentration ratio. RHA and HWCA-based groups are the least tested groups, the variables tested include curing duration and condition, concentration of acti-

Table 2
Matrix of frequency analysis of different geopolymer concrete.

Sources	Aluminosilicates						Activators				Testing approaches												
											Cylinders										Structural elements		
	Fly ash	Metakaolin	Slag	Rice Husk Ash	High calcium wood ash	Combination	NaOH	KOH	Na_2SiO_3	K_2SiO_3	Sorptivity	Water intrusion	UPV	pH	Compression	SEM/EDS	XRD	Slump	RH	Impact test	Beam	Column	Slab
[20]	■						■		■						■	■	■						
[21]		■					■					■			■			■					
[22]	■						■								■								
[23]	■						■		■						■								
[24]	■					■	■		■		■	■	■	■	■				■				
[25]	■						■			■					■								
[26]						■	■		■		■		■		■	■		■	■				
[27]						■	■		■						■			■		■			
[28]	■						■		■						■								
[29]	■						■		■		■	■		■	■	■	■						
[30]	■						■		■		■			■		■	■						
[31]						■	■		■					■	■								
[32]	■		■			■	■		■						■								
[33]	■						■		■						■								
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[39]	■						■		■		■				■								
[40]	■		■				■		■		■	■	■		■	■							
[41]	■						■		■						■								
[42]	■						■		■		■								■				
[43]						■	■		■		■				■	■							
[44]						■	■		■		■		■		■	■		■					
[45]	■	■				■	■	■							■	■							

Table 2 (*continued*)

[46]	■						■		■		■				■			■					
[47]	■						■		■						■	■	■						
[48]						■	■		■		■		■		■	■	■						
[49]						■	■		■		■				■	■							
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[104]	■			■		■	■		■						■	■							
[105]	■					■	■		■				■		■	■		■					
[106]			■		■	■									■			■					
[107]	■				■	■					■	■	■		■			■					
F	45	7	6	2	2	19	64	7	55	4	17	6	9	8	47	21	13	14	3	1	11	6	2

Note: F = Frequency; RH = Rebound hammer.

Table 3
Taxonomy of aluminate resources in geopolymer concrete research, covering different variables.

Aluminosilicate	References	Activators	Independent variables
FA	[20,22–25,28–30,32,33,36,37,39,40–42,46,47,57,62,105]	NaOH + Na_2SiO_3	Proportion of additional cement, mix proportion, proportion of nano material, effect of silica fume, effect of glass fibre, effect of additional cement, proportion of $Ca(OH)_2$ and slag, effect of adding PVA fiber, effect of adding recycled aggregate, NaOH-Na_2SiO_3 ratio, liquid-ash ratio, curing time, proportion of steel fiber, activator types, curing procedure, elevated temperature, molar ratio
	[38]	Na_2SiO_3	Types of aggregate
	[45,55,104]	NaOH or KOH	Effect of temperature and sp, effects of different curing condition and activators
MK	[51,52]	KOH + K_2SiO_3 or NaOH + Na_2SiO_3	Effect of source material, effect of immersion time, sample mass-volume value
	[21,45,54,61]	NaOH or KOH	Aggregate-mass ratio, molar ratio, effect of temperature and sp effect of adding limestone, effect of additive
SG	[32,35,40,60]	NaOH + Na_2SiO_3	Proportion of $Ca(OH)_2$ and slag, different environment condition, different mix proportion and sp.
	[59]	NaOH	Liquid-solid ratio, different activators
FA + SG	[31,32,43,63]	NaOH + Na_2SiO_3	Effect of bio-additives, effect of PVA fiber, concentration of activators, molar ratio
	[34]	K_2SiO_3	Slag content, silica fume size distribution
FA + MK	[49,50]	NaOH + Na_2SiO_3	Proportion of FA and MK.
MK + SG	[53]	NaOH + Na_2SiO_3	MK-Sl ratio, solution concentration ratio
RHA	[102]	NaOH	Curing duration, concentration of NaOH, RHA particle size
RHA + FA	[103,104]	NaOH + Na_2SiO_3	Proportion of FA and RHA, FA and RHA particle size, curing duration, concentration of NaOH
FA + SG + HCWA	[105]	NaOH + Na_2SiO_3	Proportion of FA, mix proportion, molar ratio
HCWA + SG	[106]	–	Proportion of SG and HCWA
HCWA + FA	[107]	–	Proportion of FA and HCWA, curing duration and condition

vators, particle size, mix proportion. The variables have been proven to affect the reactivity and mechanical properties as well as durability of geopolymer concrete.

5. Assessing variables and assessing approaches

Various testing methods have been attempted to establish the performance of geopolymer concrete. Performance of geopolymer concrete can be influenced by many variables. The most frequent were the type of aluminosilicates, activators, proportion of additional cement, mix proportion, molar ratio and etc. Table 4 summarized and analysed dependent variables, and results assessed by various studies. The dependent variables studied are durability, mechanical properties, fresh properties and microstructure. The table shows that twenty-four (24) authors focused on the durability of geopolymer concrete using various tests, whilst forty-seven (47) authors studied on the mechanical properties such as compressive strength, tensile strength and impact resistance of geopolymer concrete. Thirteen (13) and twenty-three (23) studies were performed on fresh properties and microstructure, respectively. Furthermore, Table 4 also showed the testing methods adopted for measuring the independent variables. It was found that geopolymer mortars expanded less than the corresponding OPC with regards to alkali-silica reaction [64]. Comparison between FA-based and SG-based geopolymer concrete shown that SG-based is has higher expansion due to the formation of sodium calcium silicate hydrate [65]. For FA blends with SG geopolymer concrete, increasing SG content will result in higher alkali-silica reaction [66]. Acid and alkali resistance of geopolymer concrete is generally higher than ordinary concrete. The durability can be further enhanced by incorporating additional cement as FA replacement, silica fume or bio-additives. Studies also proven that FA-based geopolymer has negligible influence under sea water and sodium sulphate [67]. FA-based geopolymers has least resistance with Na_2SO_4 + $MgSO_4$ solution [68]. The deterioration was examined based on visual appearance, loss in terms of weight and reduction in strength. No significant effect was observed when geopolymer concrete was immersed in Na_2SO_4 solution after approximately 3 months after [69]. Approximately 30% reduction in compressive strength when geopolymer concrete is immersed in $MgSO_4$ for 3 months [70]. In carbonation, it was reported by Bernal et al. [71] that the loss in capacity in geopolymer concrete is affected by many parameters, especially porosity.

The workability of geopolymer concrete is highly dependent on the activator molarity, superplasticizer and water content. It was reported by Laskar and Bhattacharjee [72] reported that the concentration of NaOH and the proportion of silicate to hydroxide solution affects the workability of fresh geopolymer concrete. On the other hand, setting time of the geopolymer concrete could be improved up to 3 h with the addition of naphthalene based admixtures [73]. As the water-solid ratio improved, the compressive strength of geopolymer concrete decreased relatively. It was also reported that the geopolymer concrete was brittle due to the dense framework [74,75]. The fracture energy of geopolymer concrete was reported to be low due to its stronger bond with aggregates than conventional concrete [76].

The addition of OPC improved the microstructure of the geopolymer concrete. This is due to the co-existence of hydration products and polycondensation products. Hence, this resulted in the reduction in water absorption, porosity, sorptivity, and chloride permeability of geopolymer concrete. The addition of OPC results in a more compacted and dense microstructure in which the fibres-matrix interfacial bond is observed to be better through SEM analysis [29] (See Fig. 4).

The other parameters that affect the performance of geopolymer concrete are summarized and tabulated in Table 5. From Table 5, it can be seen that all the testing variables has been tested for FA-based geopolymer concrete. It also can be seen that among the other geopolymer concrete types, MK-based, SG-based, RHA-based, HWCA-based and combination based geopolymer concrete are not regularly, indicating the lack of research. Most of the past research mix design, ratio between activators and aluminosilicates and effect of additional fibers as variables. However, the effects of

Table 4
Dependent variables in geopolymer concrete research, covering different measurable parameters, measurement methods, and results.

References	Dependent variables	Tested parameters	Testing method	Remarks
[20,21,24,26,29–31,36, 38–40,42–44,46,48–51,57,59,60,105,107] Frequency = 24	Durability	• Sulphur acid resistance • Water absorption • Sorptivity • Sodium Chloride resistance • Atmospheric carbonation • Alkali-silica reaction • Freeze-thaw attack • Permeability	• Sorptivity test • Water intrusion • UPV • pH test	The addition of OPC in FA-based geopolymer concrete did not have effect on resistance to sulfuric acid. It is shown that sodium sulphate has the greatest impact on geopolymer concretes, with no erosion in the case of geopolymer concrete containing 20% silica fume when exposed to 2% H_2SO_4 and 5% NaCl solution. Magnesium sulphate solution for sulphate resistance test showed negligible impact on geopolymer concrete due to the intrinsic nature of aluminosilicate gels in geopolymer materials. Rate of chloride ingress in fly ash based geopolymer concrete is high in aggressive environment. Geopolymer concrete shows less carbonation resistance compared to Portland cement concrete. The addition of Bio-additives was observed to increase durability properties of geopolymer concrete when compared to control ordinary geopolymer concrete. Comparison between fly ash-based and slag-based geopolymer concrete shown that slag-based is has higher expansion due to the formation of sodium calcium silicate hydrate. The addition of HCWA into geopolymer concrete increases the water absorption rate
[20–29,31–41,43–53, 55–63,102–107] Frequency = 47	Mechanical properties	• Compressive strength • Split tensile strength • Impact resistance	• Compression test • Flexural test • Toughness test • Rebound hammer tests • Tensile strength test • Impact test	The results indicate that the inclusion of OPC (as fly ash replacement) improves the compressive strength of fly ash-based geopolymer concrete. Nano materials such as nano silica and titanium di-oxide can be added with low calcium fly ash based geopolymer concrete to get satisfactory amount compressive strength. The addition of 0.5% steel fibers enhanced the splitting tensile and flexural strength of POFA-SG based geopolymer concrete by about 19%–38% and 13%–44%, respectively compared to the non-fibrous geopolymer concrete. There was substantial increase in tensile strength of geopolymer concrete due to the addition of glass fibres. Split tensile strength increased by 5–10% in glass fibre-reinforced geopolymer concrete. Fine Silica Fume was also being found to has improved compressive strength while coarse silica fume results in a reduction of strength. The use of undensified silica fume results in geopolymer concrete with the highest tensile strength. The usage of high SG and fine SF improved the tensile behaviour of geopolymer concrete. The optimum silica to alumina ratio was found to be 16 for RHA-FA geopolymer. Higher proportion of HCWA to SG ratio improved the compressive strength of hybrid geopolymer concrete. 60% and more HCWA content in HCWA-FA geopolymer results in a lower compressive strength
[21,26,27, 36–38,44,46,57,59, 60,105,106] Frequency = 13	Fresh properties	• Workability • consistence	• Slump test	Fresh state of geopolymer concretes has shown that the consistency classes used to determine the possible applications of traditional Portland cement are applicable to geopolymers. Sodium silicate and sodium hydroxide solutions which are more viscous and sticky in nature compared to water and create cohesive and viscous geopolymer concrete. The inclusion of HCWA increases the water required for desired mix consistency
[20,26,29,30,34,40, 43–45,47–52,54,55, 61,102–105,107] Frequency = 23	Microstructure	• Porosity • Chemical characterization	• SEM • EDS • XRD	The addition of OPC improved the microstructure of the geopolymer concrete. This is due to the co-existence of hydration products and polycondensation products. Hence, this resulted in the reduction in water absorption, porosity, sorptivity, and chloride permeability of geopolymer concrete. The addition of OPC results in a more compacted and dense microstructure in which the fibres-matrix interfacial bond is observed to be better through SEM analysis. The inclusion of HCWA in geopolymer concrete results in a higher porosity

different types of aluminosilicate which is an important parameter have not been commonly tested.

6. Structural tests for performance of geopolymer concrete

Evaluation approaches were performed on two scale levels to establish the performance of geopolymer concrete, namely small and full scale. For small scale test, unreinforced cylinder specimens were used while structural elements were used for full scale test. The taxonomy in research construct according to scale of test are presented in Table 6. Findings show that majority of tests were on small scale tests. In contrast, only few full scale tests were conducted. Apparently, this could hinder the use of geopolymer concrete in practical.

Although many studies had been carried out to study a wide range of variables in small scale tests, it was found that most of

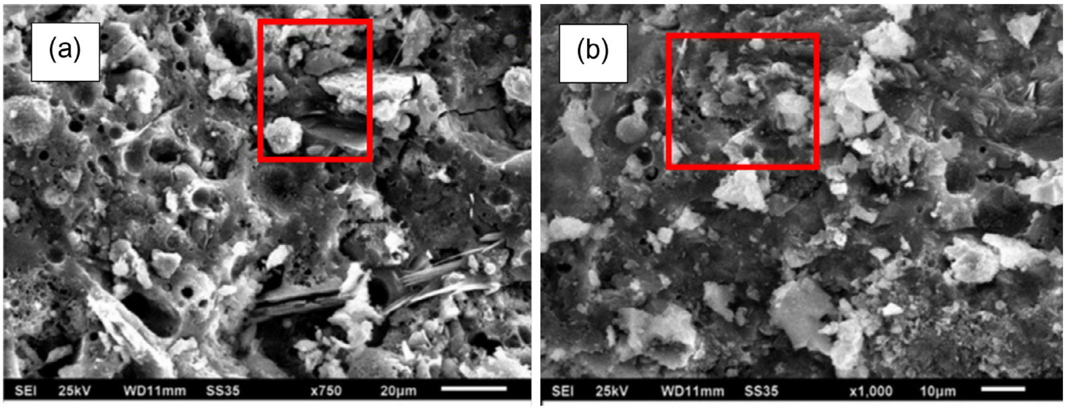

Fig. 4. SEM analysis of geopolymer concrete: (a) without OPC; (b) with OPC [29].

Table 5
Testing variables and methods.

Testing variables	Method	Concrete type	Sources
Proportion of additional cement	Cylinder	FA	[20,29,41,42]
Mix proportion	Cylinder	FA/FA + SG/RHA/FA + RHA/FA + SG + HCWA/HCWA + SG/HCWA + FA	[22,102–107]
Proportion of nano material	Cylinder	FA	[23]
Effect of silica fume	Cylinder	FA	[25]
Effect of glass fibre	Cylinder	FA	[28]
Proportion of OPC and fly ash	Cylinder	FA	[29]
Effect of adding PVA fiber	Cylinder	FA/FA + SG	[33]
Effect of adding recycled aggregate	Cylinder	FA	[36,39]
Molar ratio	Cylinder	FA/MK/FA + SG/FA + SG + HCWA	[62,105]
Liquid-ash ratio	Cylinder	FA	[30]
Curing time and condition	Cylinder	FA/ RHA, FA + RHA	[32,42,102,104]
Proportion of steel fiber	Cylinder, beam	FA	[46,80,85]
Activator types	Cylinder	FA/SG/MK + SG	[24,57]
Elevated temperature	Cylinder	FA/ MK	[62]
Aggregate types	Cylinder	FA	[37,38]
Effect of sp	Cylinder	FA/MK/SG	[45,55]
Reinforcement ratio	Beam/column	FA	[77,78,82,88]
Concrete compressive strength	Beam/column	FA	[78,87]
Fly ash/ slag ratio	Beam	FA	[79]
Different reinforcing configuration	Beam	FA	[81]
Glass fiber content	Beam	FA	[84]
Proportion of recycled aggregate	Beam	FA	[86]
Shear span ratio	Beam	FA	[93]
Load eccentricities	Column	FA	[88,94]
Aspect ratio	Column	FA	[89]
Effect of confinement	Column	FA	[90]
Slenderness ratio	Column	FA	[94]
Volume fraction of reinforcement	Slab	FA	[91,92]
Types of reinforcement	Slab	FA	[91,92]

these studies were focused on FA-based geopolymer concrete. This can lay a groundwork in further development of research in this field. From Table 6, it can be clearly seen that almost all the affecting parameters have been tested for small scale tests.

The tests on full scale specimens were carried out by a number of researchers. These tests have shown that geopolymer concrete is suitable to be used as structural elements. However, it was found that full scale specimens test on other types of geopolymer have not been conducted to assess their structural performance. Hence, the structural performances of geopolymer concrete are still needed to be further clarified as the tests conducted in this field are comparatively limited.

7. Performance design of geopolymer concrete

Geopolymer concrete can become a sustainable alternative for conventional OPC concrete if the environmental issues are concerned. Hence, it is important that the design aspects, such as load carrying, flexural strength and bond-slip are studied and assessed to ensure the applicability and suitability of geopolymer concrete as structural element. This section highlights the main considerations in designing geopolymer concrete structural elements. The design capabilities of geopolymer concrete are explored together while the inadequacy in the design consideration is highlighted.

An acute assessment of the performance of geopolymer concrete is necessary before it can be used practically. Good understanding on the deformability of concrete will be required especially in the estimation of deflections, stress-strain relationship or to develop the constitutive laws for finite element modelling. Owing to different material properties and behaviour, geopolymer concrete can act differently compared to conventional OPC concrete. Hence, it is necessary to develop the stress-strain of geopolymer concrete for design and simulation purposes [95]. As we generally known, the stress-strain of OPC concrete is relatively

Table 6
Different scales of studies in geopolymer concrete.

Scale of test	Specimen	Testing variables	Geopolymer type	Sources
Small	Cylinder	Proportion of additional cement; mix proportion; proportion of nano material; effect of silica fume; effect of glass fiber; proportion of $Ca(OH)_2$ and slag; effect of adding PVA fiber; effect of adding recycled aggregate; molar ratio; liquid-ash ratio; curing time and condition; proportion of steel fiber; activator types; elevated temperature; aggregate types; effect of SP	FA/MK/SG/FA + SG/MK + SG/ FA + RHA/RHA/FA + SG + HCWA/HCWA + FA	[20,22–25,28–30,32,33, 36–39,41,42,45,46,55,57,62, 80,85,102–106]
Full	Beam; column; slab	Reinforcement ratio; concrete compressive strength; FA/SG ratio; different reinforcing configuration; glass fiber content; proportion of recycled aggregate; shear span ratio; load eccentricities; aspect ratio; effect of confinement; slenderness ratio; volume fraction of reinforcement; Types of reinforcement	FA	[77–79,81,82,84,86,88–92,94]

well established [96,97]. However, the understanding in stress-strain behaviour of geopolymer concrete is still comparatively limited. A study conducted by Noushini et al. [95] proposed a stress-strain model as follows:

$$\frac{\sigma_c}{f_{cm}} = \frac{n\left(\frac{\varepsilon_c}{\varepsilon'_c}\right)}{n-1+\left(\frac{\varepsilon_c}{\varepsilon'_c}\right)^{n}} \qquad (3)$$

$$n = n_1 = \left[1.02 - 1.17\left(\frac{E_{sec}}{E_c}\right)\right]^{-0.45}, \quad if\ \varepsilon_c \leqslant \varepsilon'_c \qquad (4)$$

$$n = n_2 = n_1 + (\omega + 28 \times \xi), \quad if\ \varepsilon_c \geqslant \varepsilon'_c \qquad (5)$$

$$\omega = C\left(12.4 - 0.015 f'_c\right)^{-0.5} \qquad (6)$$

$$\xi = 0.83 e^{(-911/f_{cm})} \qquad (7)$$

$$C = \begin{cases} 15, & \text{water and internal curings} \\ 7, & \text{heat cured OPC concrete} \\ 17, & \text{heat cured geopolymer concrete} \end{cases} \qquad (8)$$

$$E_{sec} = \frac{f_{cm}}{\varepsilon'_c} \qquad (9)$$

where σ_c is the concrete stress, f_{cm} is the mean compressive strength of concrete, n is the material parameter that depends on the shape of the stress-strain curve, ε'_c is the strain corresponding to the maximum stress f_{cm}, n_1 is the modified material parameter at the ascending branch, n_2 is the modified material parameter at descending branch, E_c is the modulus of elasticity, E_{sec} is the secant modulus of elasticity, ω and ξ are the coefficients and C is the curing parameter. Comparison of the proposed stress-strain model with the experimental tests conducted by Hardjito et al. [98] is presented in Fig. 5 and it is evidenced that the model can sufficiently predict the behaviour of geopolymer concrete.

For flexural strength of geopolymer concrete, a modification to the equivalent stress block for geopolymer concrete is proposed by Prachasaree et al. [99] by introducing several terms, k_1, k_2, and k_3 geopolymer concrete. By using the standard design procedures for flexural members, the flexural design of geopolymer concrete can be conducted by using the following equations for the proposed terms:

$$k_2 = 0.384 - \left(\frac{f'_c}{1000}\right) \qquad (10)$$

$$k_1 k_3 = 1.070 - \left(\frac{f'_c}{76.3}\right) + 9\left(f'_c\right)^2/100000 \qquad (11)$$

where k_1 and k_3 are the equivalent stress block parameter and k_2 is the centroid of the compressive force.

Generally, performance of geopolymer concrete in terms of structural is highly dependent on the bond behaviour. Due to the difference bonding reaction and microstructure of geopolymer concrete compared to conventional OPC concrete [100], the bond properties should be clearly clarified because the reliability in terms of bond behaviour could ensure safety in the design. Few investigations have been conducted and estimation of bond strength for geopolymer concrete has been proposed by Kim and Park [101].

$$\sigma = f'_c\left(2.07 + 0.2\left(\frac{c}{\phi}\right) + 4.15\left(\frac{\phi}{l_d}\right)\right) \qquad (12)$$

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).

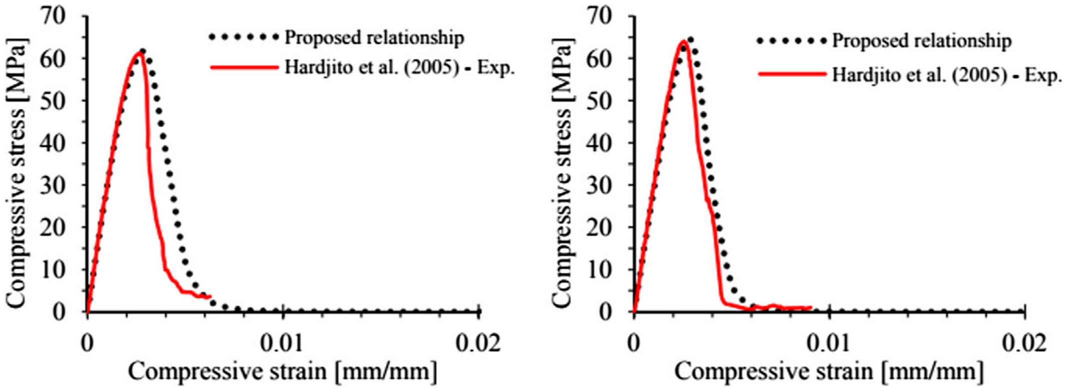

Fig. 5. Verification of proposed model with Hardjito et al. [98] (reproduced from [95]).

It was found that there is no close-form design equation for the direct estimation of load carrying capacities for both short and slender geopolymer concrete columns, indicating the lacking in the design of geopolymer concrete structural columns. Besides, all of the above-mentioned design equations have been development based on one particular type of geopolymer concrete, for instance, FA-based geopolymer concrete only. For the convenience use of the practical structural engineer, it is suggested that unified design equation, which covered all geopolymer concrete types should be proposed.

8. Conclusions and remarks

The paper assessed the performance of geopolymer concrete, both in material and structure. It was found that there are about 6 groups of geopolymer concrete based on alumina silicate sources. They are FA-based, MK-based, SG-based, RHA-based, HCWA-based and combination of either two of the earlier mentioned aluminosilicates. Among these types, FA-based geopolymer concrete is the most popular and widely tested. Few findings can be summarized as follows:

a) The performance was normally assessed by analogized the strength or load capacities of geopolymer concrete with conventional OPC concrete using cylinder, beam, column and slab tests. Cylinder compression test and beam test were the most frequently adopted assessing approaching.
b) Previous investigation covered a large number of variables including the proportion of additional cement, mix proportion, proportion of nano material, effect of silica fume, effect of glass fiber, proportion of $Ca(OH)_2$ and slag, effect of adding PVA fiber, effect of adding recycled aggregate, molar ratio, liquid-ash ratio, curing time and condition, proportion of steel fiber, activator types, elevated temperature, aggregate types and effect of SP for material performance. In terms of structural performance, the parameters including reinforcement ratio, concrete compressive strength, FA/SG ratio, different reinforcing configuration, glass fiber content, proportion of recycled aggregate, shear span ratio, load eccentricities, aspect ratio, effect of confinement, slenderness ratio, volume fraction of reinforcement and types of reinforcement. The lack of tests in investing the effect of different aluminosilicates was also underlined.
c) In general, two tests scales were used: small and full scale tests. Majority focused on small scale approach. It was found that geopolymer is suitable as structural elements. It was also found that the full scale test are still lacking especially for non-FA based geopolymer concrete.

The above findings were obtained based on the current state of research in geopolymer concrete. Other studies are required to fill in the gaps before the material can be widely used in the site.

8.1. Recommendations and research gaps

This paper has highlighted the gaps in the research of geopolymer concrete. Below are the suggestions on the future research direction.

- Experimental investigation on the serviceability, especially in crack propagation.
- Experimental investigation on full scale structural elements for non-FA based geopolymer concrete.
- Experimental investigation on applicability of HWCA in replacing the needs of alkali activators for geopolymer concrete.
- Future research should address the brittle behaviour of geopolymer concrete with compact and dense microstructure.
- Behaviour of geopolymer concrete in multi-axial stress states, stiffness degradation and recovery should be investigated for further understanding of structural behaviour of geopolymer concrete.
- Practicality and cost effectiveness in using geopolymer concrete in the industry should be further investigated.

Conflict of interest

No conflict of interest.

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