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High-Strength Geopolymer Concrete- Properties, Advantages and Challenges

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Abstract: Geopolymer is a noble material, made from reaction between aluminosilicate compounds and alkali solution which owns a good binding property. In last decades, lots of research and development works have been carried out globally to investigate the engineering, thermal, micro-structural and durability properties of geopolymer concrete as a sustainable alternative to Portland cement. Results from previous works indicated that geopolymer concrete exhibited better mechanical strength and durability properties than ordinary Portland cement (OPC) concrete. Nowadays, high-strength concrete is increasingly used in major civil construction works, such as high-rise buildings and bridges because of its structural and economic benefits over normal-strength concrete. This paper reports the experimental results on engineering properties of high-strength geopolymer concretes of 65 and 80 MPa using geopolymer binders at ambient curing conditions. High-strength concrete produced in this study was able to set quickly in ambient conditions therefore can attain sufficient strength at early days as well as exhibited higher tensile and flexural strength than concrete from OPC. High-strength geopolymer concrete can be produced with very simple mix design; however, it has some limitation for commercial applications. This paper discusses about the advantages and limitations of geopolymer high-strength concrete for its application in concrete industry.

Keywords: Geopolymer, High-Strength Concrete, Workability and Mechanical Strengths

1. Introduction

Manufacturing of Portland cement is responsible for around 7% of greenhouse gas emission globally [1] which poses a significant threat to the global climate changes. Geopolymer arrives as an alternative material to Portland cement which was firstly reported by Davidovits [2]. Geopolymer can be produced by reaction between aluminosilicate materials such as, metakaolin, fly ash and ground granulated blast furnace slag (slag) and alkali activator. This reaction produces an alkali aluminosilicate compound which works as a calcium silicon hydrate (C-S-H) to bind the aggregate materials. Geopolymer technology utilizes industrial waste materials to convert them into a noble binding material, thus it has been branded as a sustainable cementitious material [3].

In recent decades, studies have been carried out to investigate mechanical, microstructural and durability properties of the geopolymer binder and concrete as well as the effects of source materials on geopolymers as a sustainable alternative to OPC [4-9]. It has been reported that geopolymer made from fly ash or metakaolin struggled to set at normal temperature because of slow reaction rate, hence most experiments in the past were done in higher temperature curing [5, 10-12]. In normal construction practice, concrete elements are leaved in normal temperature after casting for curing instead of curing at high temperature. When slag is added in source materials as a partial replacement of fly ash or metakaolin, it makes geopolymer able to set in normal temperature as well as develop higher strength at early age as well as later age [13-15]. This is due to the stimulation of polymerization reaction by calcium presence [16] as well as partially formation of C-S-H gel in very early days [17, 18].

ACI-363R [19] defines high-strength concrete as concrete having a compressive strength of 55 MPa or higher; however,

AS-1379 [20] classifies concrete having a compressive strength higher than 50 MPa as special class concrete. High-strength concrete offers a lot of advantages over normal strength concrete, such higher strength at early days and higher mechanical strengths at later age, better durability and lower permeability of concrete. Because of these advantages a slim section of high-strength concrete can replace bigger volume of concrete, thus reducing structural self-load and cost and duration of construction. Nowadays, high-strength concrete is widely used in major structures where concrete strength is an important factor, such as high-rise buildings, bridges and pre-stressed concrete structures.

Mix design of high-strength concrete is not easier as normal-strength concrete. Partial replacing of Portland cement by supplementary cementitious materials (SCMs), such as fly ash, slag and silica fume up to 20-30% is inevitable to achieve desired workability and durability of concrete [21, 22]. However, addition of SCMs can result in significant loss of strength at early days [23]. In order to improve the workability and compensate higher water demand, a significant amount of high range water reducing admixture or super-plasticizer should be added into high-strength concrete mix [24].

Generally high-strength concrete contains very low water/binder ratio and significantly higher amount of binder which can make concrete sticky and give a sudden loss of workability [19]. High heat of hydration in the early age is another issue of high-strength concrete which can result in thermal cracking. In order to control this, a significant amount of SCMs with set retarder should be added in the concrete mix. Instead, high-strength geopolymer concrete can be prepared by simply adding water without any chemical admixtures.

In this study, the engineering properties of high-strength geopolymer concrete (Grades 65 and 80 MPa) of were investigated and the results were compared agaiant the same grades OPC (control) concrete. Major concrete properties, such as workability, mechanical strengths, elastic modulus and shrinkage were measured using relevant testing methods. Applicability of some correlation equations of mechanical properties in geopolymer concrete is also discussed.

2. Experimental Procedures

2.1. Ingredients of Concrete

Two types of geopolymer binders; Geopolymer GP and Geopolymer HE made by Cement Australia, Pty Ltd, Qld were used to produce concrete in this experiment. Unlike to use of alkali liquid, these geopolymer binders consist of solid alkali activators (sodium silicate and alkali compounds) in powder form. The source material is a combination of low calcium (Class F) fly ash and slag in different proportions. Geopolymer GP has 70% amount of fly ash and 30% slag; Geopolymer HE consist of 60% slag amount and 40% fly ash. Portland cement (type GP) was used to make control high-strength concrete. Chemical compositions of fly ash, slag cement and are shown in Table 1.

Table 1. Chemical compositions of fly ash, slag and GP.

	LOI	CaO	SiO$_2$	Al$_2$O$_3$	Fe$_2$O$_3$	MgO	SO$_3$	Na$_2$O	K$_2$O	Others
Fly ash	0.7	3.2	52.7	26.0	12.8	1.4	0.2	0.52	0.79	2.05
Slag	0.2	42.6	33.5	13.9	0.9	5.2	1.7	0.26	0.36	1.35
GP	3.5	64	19.2	4.96	3.07	1.14	2.5	0.14	0.41	1.08

Note: Others: TiO$_2$, Mn$_2$O$_3$ and P$_2$O$_5$; LOI: loss of ignition.

River sourced coarse aggregates (mainly greywacke sandstone rock) of maximum 20 mm size were used in both, OPC and geopolymer concretes mix design. Same sourced medium and fine graded sands were used as fine aggregates.

Concrete from all binders were designed as conventional method [25]. Necessary adjustment were made in water and binder content in geopolymer concrete in order to achieve a comparable characteristic strength and workability to OPC concrete. To keep the lower water/cement ratio and good workability in OPC concrete, high range water reducer (HWR) was used. Geopolymer concrete, instead did not need a chemical admixture. The mix compositions of concrete from different binders are presented in Table 2.

Table 2. Mix compositions of concretes of different grades.

Binders	Grades (MPa)	Binder amount (kg/m^3)	Aggregates (kg/m^3)				Water (kg/m^3)	Slump (mm)	Admixture (litre/m^3)
			20 mm	10 mm	Medium sand	Fine sand			
GP	65	500	610	420	490	180	179	105	1.75
GP	80	555	605	425	495	180	161	140	2.50
Geopolymer GP	65	360	705	480	565	190	109	110	-
Geopolymer GP	80	480	650	455	520	190	115	160	-
Geopolymer HE	65	360	705	475	565	190	112	120	-
Geopolymer HE	80	455	660	460	535	185	117	160	-

2.2. Preparation and Testing of Specimens

Concrete cylinders having 100 mm x 200 mm size and beams having 100 mm x 100 mm x 350 mm size were cast to determine the mechanical properties of concrete. All concrete specimens were cast and cured at 23°C till testing. Geopolymer concrete specimens were sealed cured as shown in Figure 1; they were sprayed with small amount of water before sealing

by impervious plastic. Specimens from OPC concrete were conventionally immersed cured. In case of shrinkage prism, they were stored inside 23°C temperature and 50% relative humidity after completion of 7 days curing period.

Figure 1. *Curing of geopolymer concrete specimens (a) cylinders (b) flexural beams.*

Relevant Australian standards [26-31] were followed to measure the engineering properties of both geopolymer and OPC concretes of different states and ages. Concrete properties of 28 days were determine by testing 5 samples, properties of other ages were based on results of 3 samples.

3. Results and Discussions

3.1. Workability

As summarized in Table 2, geopolymer concrete requires around 30% less amount of water than OPC concrete of same workability level despite OPC concrete consists of chemical admixture.

Rapid loss of workability is one of the major issues in commercial application of high-strength concrete due to early setting of concrete. Obviously, high-strength concrete consists of lower water/binder ratio and significantly high binder content which results of shorter setting time and rapid workability loss. Figure 2 shows the loss of workability (slump loss) of different concretes for 2 hours. In this Figure, high–strength geopolymer concrete suffers lower workability loss then OPC concrete. However, in Grade 80 MPa, both types of concrete show similar trend of rapid decrease of workability within 90 minutes. The workability loss in high-strength OPC concrete can be controlled by adding significant amount of SCMs or admixtures, such as set retarder and hydration stabilizer. However, addition of these SCMs and admixtures results in reduction of early days strength of concrete due to prolonged setting time of cement [32].
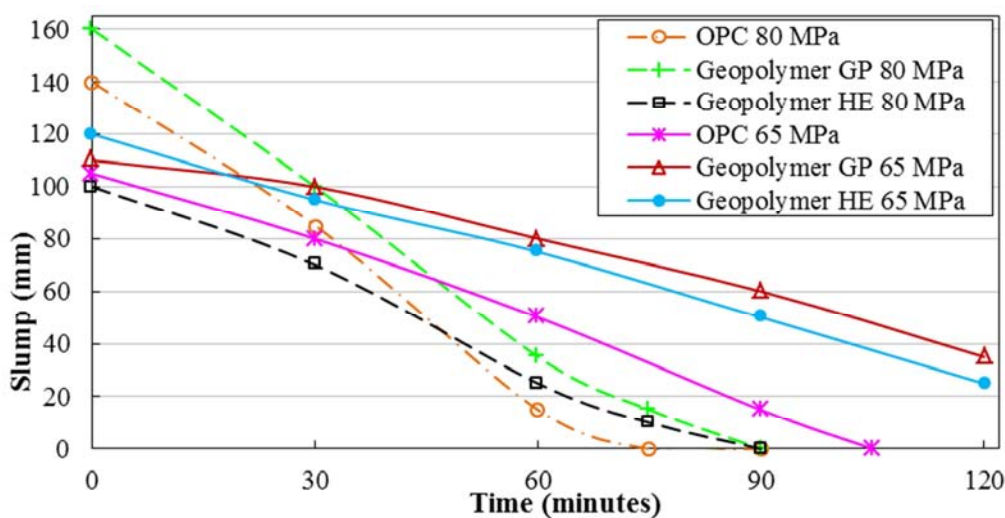

Figure 2. *Slump loss in high-strength concretes.*

In case of high-strength geopolymer concrete, the setting time cannot be substantially delayed by adding commercially available admixtures because of the difference in chemistry between geopolymers and Portland cement and particularly

the high level of alkalinity in geopolymer system [33, 34]. This is one of the major issues for application of high-strength geopolymer concrete in commercial practice. Geopolymer high-strength concrete was found to be stickier than normal-strength and OPC concrete which can results in some difficulties in mixing and placing of concrete as well as higher entrapped air pockets in harden concrete. This effect is due to higher volume of paste and higher cohesiveness of geopolymer concrete. Deb, Nath [13] also reported higher

cohesiveness of geopolymer concrete due to its difference in rheology and chemistry with OPC. This higher entrapped air increase the porosity of concrete, hence reduces the concrete strength. Figure 3 illustrates the visible air pockets inside the harden concrete.

In order to overcome these issues, a further research is necessary to develop chemical admixtures which are applicable in geopolymer concrete to improve the fresh concrete properties.

Figure 3. Fracture surface of hardened high-strength geopolymer concrete.

3.2. Compressive Strength

Growth of compressive strength of high-strength geopolymer and OPC concretes is present in Figure 4. It has been widely suggested that geopolymer concrete generally attains lower strength at early days (1-3) under normal temperature because of slow rate of reaction [7, 35, 36]. However, results of high-strength geopolymer concrete

showed that there was a substantial early age strength growth which was comparable with same grade OPC concrete. This may be due to lower water/binder ratio as well as higher amount of binder available for polymerization. In addition, a considerable growth (around 18%) in compressive strength from 28 days to 90 days can be noticed in geopolymer concrete compare to 4 % in OPC concrete for same period.
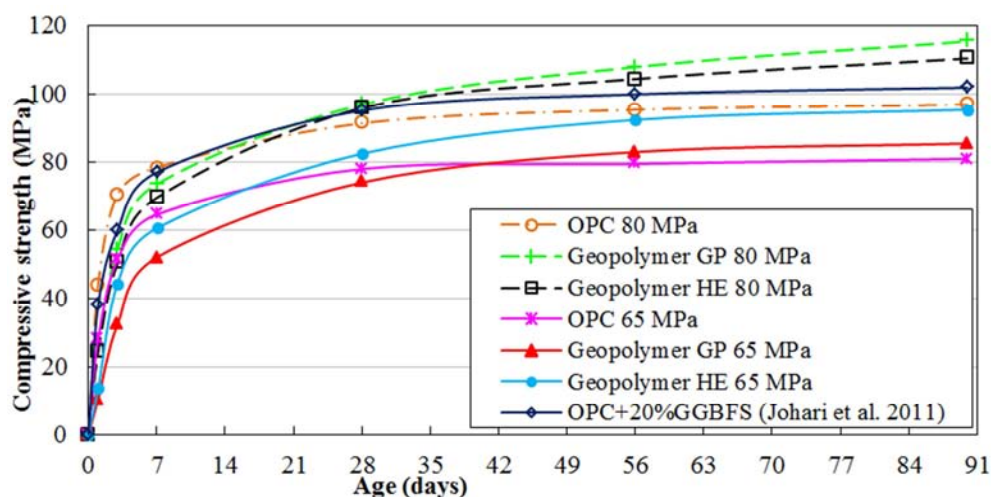

Figure 4. Growth of compressive strength.

Table 2 shows that geopolymer high-strength concrete requires 20-25% less binder then OPC concrete for the same characteristic strength. This can compensate the slightly higher cost of geopolymer binder compared to Portland cement.
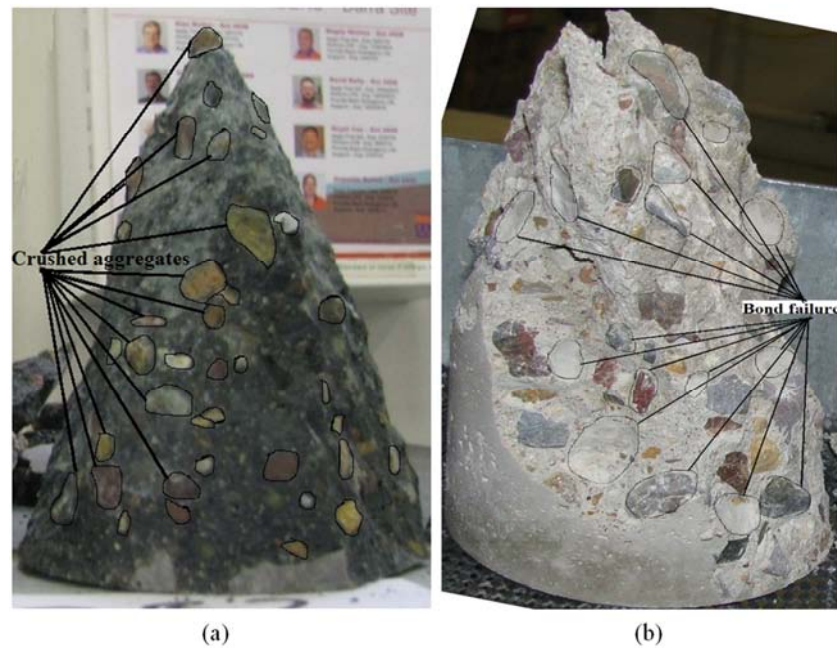
3.3. Mode of Failure under Compression

Figure 5. *Mode of failure of high-strength concrete (a) geopolymer concrete (b) OPC concrete.*

Figure 5 visualizes the mode of failure of high-strength geopolymer as well as OPC concrete (Grade 80 MPa) under compression. Where high-strength geopolymer concrete undergoes a different mode of failure (crushing of aggregates) in a perfect conical shape than in OPC concrete (mostly bond failure). The difference in mode of failure may be the result of stronger aggregate-paste interfacial transitional zone (ITZ) in geopolymer concrete due to higher bond strength. It indicates that an even higher strength geopolymer concrete would be produced from the same mix-design (same amount of ingredients; binder, water and aggregates) if stronger rock aggregates (quartz or granite) were used instead of greywacke sandstone (used in this experiment).

3.4. Indirect Tensile Strength

Experimental results of indirect tensile strength growth in geopolymer high-strength concretes are illustrated in Figure 6. In this figure, high-strength geopolymer concrete develops a similar tensile strength to OPC concrete for early age and relatively higher tensile strength at later age. At the age of 7 days, geopolymer concrete developed about 90% of its 28-day tensile strength. There was considerable growth in tensile strength from 28 days to 90 days (around 12%) in geopolymer concrete and while only 3% in OPC concrete for same period.
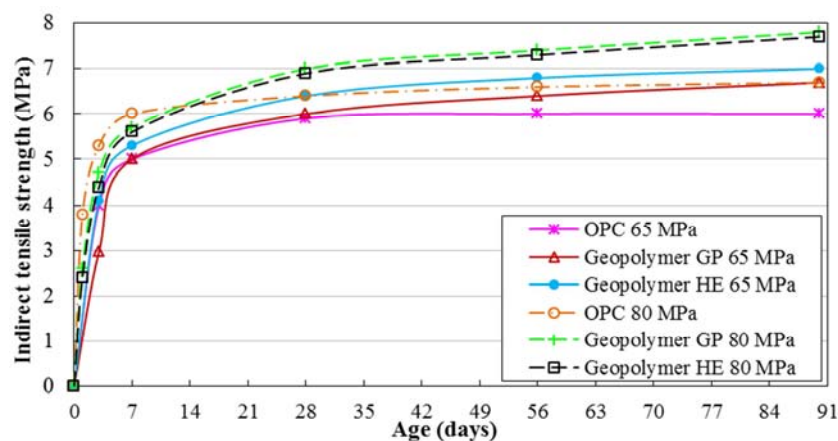

Figure 6. *Growth of indirect tensile strength.*

Following equations are suggested to calculate indirect tensile strength of high-strength concrete in some concrete standards and in publish papers.

ACI-363R [19] recommends an equation high-strength concrete as:

$$f'_{sp} = 0.59 \ \sqrt{f'_c} \ \text{MPa} \qquad (1)$$

AS-3600 [37] recommends a same equation for all strength-grades concrete as:

$$f'_{sp} = 0.36 \ \sqrt{f'_c} \ MPa \quad (2)$$

Carrasquilio, Nilson [38] suggested an equation high-strength concrete as

$$f'_{sp} = 0.54 \ \sqrt{f'_c} \ MPa \quad (3)$$

where, f'_{sp} = characteristic indirect tensile strength of concrete
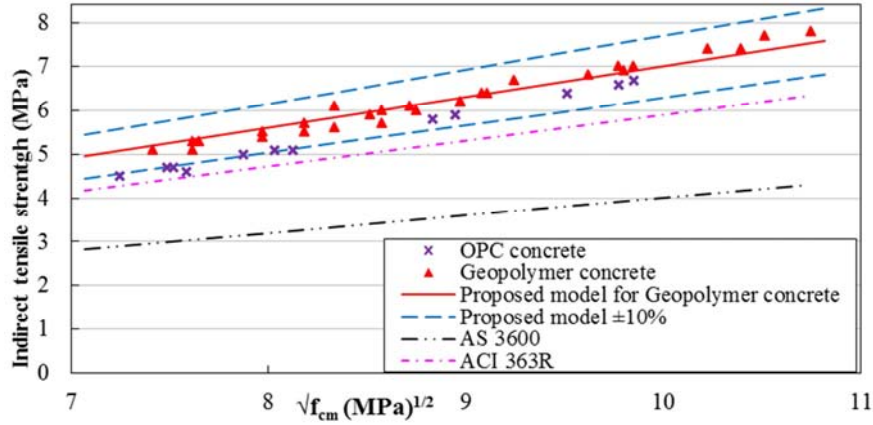
f'_c = characteristic compressive strength of concrete.

Figure 7. *Indirect tensile strength vs compressive strength.*

Indirect tensile strength of high-strength concretes are shown in Figure 7 with compressive strength in the abscissa. Data points shows that indirect tensile strength of high-strength geopolymer concrete is higher than predicted by ACI 363R [19] and AS3600 [37]. A best fit model can be proposed for high-strength geopolymer concrete as in Equation (4).

$$\text{Indirect tensile strength } (f'_{sp}) = 0.7\sqrt{f'_c} \quad (4)$$

A careful observation in Figure 7 suggests there is a marginal difference in trends of indirect tensile strength below and above compressive strength of 80 MPa. Data points of compressive strength from 50 to 80 MPa seems to be located below the proposed model line, whereas data points of concrete above 80 MPa are slightly above this line. The increase in indirect tensile strength of high-strength geopolymer concrete may be due to the improved and denser microstructure of this concrete.

3.5. Flexural Strength

Experimental results of flexural strength growth in geopolymer high-strength concrete are plotted in Figure 8. Similar to indirect tensile strength, the flexural strength was developed rapidly in 7 days and then it was increase slowly with age. Data points show that geopolymer concrete developed relatively higher flexural strength than OPC concrete.

In geopolymer concrete, increase of flexural strength after 28 days was around 13% when compared with 3% in OPC concrete in same duration. Geopolymer HE concrete developed slightly higher flexural strength than Geopolymer GP concrete in both strength grades.
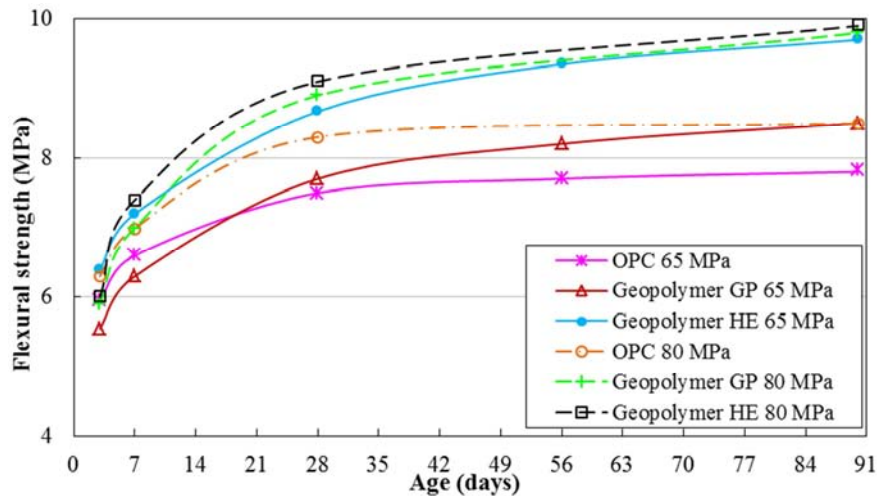

Figure 8. *Experimental results of flexural strength.*

Some standards of concrete structures suggest the equations to estimate flexural strength of high-strength concrete as following.

$$\text{ACI 363R [19]: } f'_r = 0.94\ \sqrt{f'_c}\ \text{ MPa} \qquad (5)$$

$$\text{AS 3600 [37]: } f'_r = 0.6\ \sqrt{f'_c}\ \text{MPa} \qquad (6)$$

where,
f'_r = characteristic flexural strength

Iravani [39] proposed a relationship as,

$$f'_r = 0.97\ \sqrt{f'_c}\ \text{MPa} \qquad (7)$$

Figure 9 shows the correspondence between flexural and compressive strengths for high-strength concretes. It can be clearly seen that AS 3600 [37] estimates lower flexural strength for high-strength geopolymer concrete. On the other hand, ACI 363R [19] predict marginally higher values; however, this equation seems to be suitably fitted above 80 MPa level.

Nath and Sarker [40] proposed a higher value of flexural strength of normal strength geopolymer concrete as:

$$f'_r = 0.89 * \sqrt{f'_c} \qquad (8)$$

Based on experimental results, an equation is proposed to estimate the flexural strength as following.

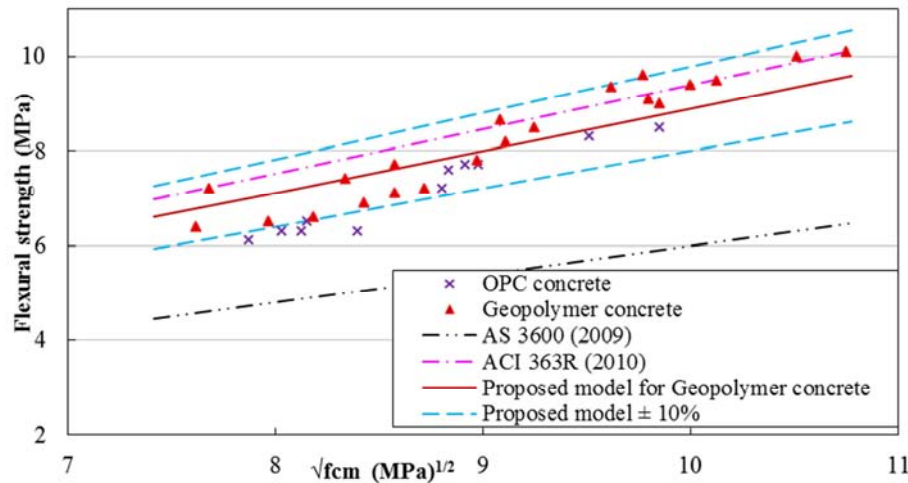$$\text{Flexural strength } (f'_r) = 0.89 * \sqrt{f'_c} \qquad (9)$$

Figure 9. Flexural strength vs compressive strength.

A careful observation in Figure 9 suggests there is clear difference in trends of flexural strength of high-strength concrete below and above of compressive strength of 80 MPa. Data points of compressive strength from 50 to 80 MPa are located below the proposed model line, whereas data points of concrete above 80 MPa are above this line. The increase in flexural strength of high-strength geopolymer concrete may be due to denser microstructure of this concrete. A similar trend can also be observed in OPC concrete.

Mechanical properties of material, such as compressive strength, tensile strength and flexural strength are the function the constituent materials. Geopolymer and Portland cement are based on different chemistry. Chemically, geopolymer binders are formed by the polymeric structure resulting from cross linking of poly-sialate chains having a strong covalent bond [41]. As a result, geopolymer concrete retains higher tensile strength than OPC concrete of same level of compressive strength.

3.6. Modulus of Elasticity

Modulus of elasticity is a serviceability property of concrete which governs the deformation of concrete structures. Higher elastic modulus results on lower deformation of structures. Past studies reported a lower elasticity modulus of geopolymer concrete when compared with OPC concrete of similar strength level [5, 10, 40].

Table 3 summarizes the 28 days results of elastic modulus of high-strength concretes where geopolymer concrete possesses a comparable elastic modulus to OPC concrete.

Table 3. Modulus of elasticity high-strength geopolymer concrete at 28 days.

Binder ID	Grade 65 MPa		Grade 80 MPa	
	f_{cm} (MPa)	E_c (GPa)	f_{cm} (MPa)	E_c (GPa)
OPC	78.0	37.0	90.5	41.0
Geopolymer GP	73.5	37.0	91.5	39.0
Geopolymer HE	82.5	39.0	90.0	40.0

Some standards of concrete structures suggest following empirical equations to calculate the elastic modulus of high-strength concrete.

$$\text{ACI 363R [19]: Modulus of elasticity } (E_c) = 3320\ \sqrt{f'_c} + 6900 \text{ MPa} \qquad (10)$$

$$\text{AS 3600 [37]: } E_c = \rho^{1.5}\,(0.024\ \sqrt{f_{cm}} + 0.12)\,\text{MPa} \qquad (11)$$

where, ρ = concrete density (kg/m^3)
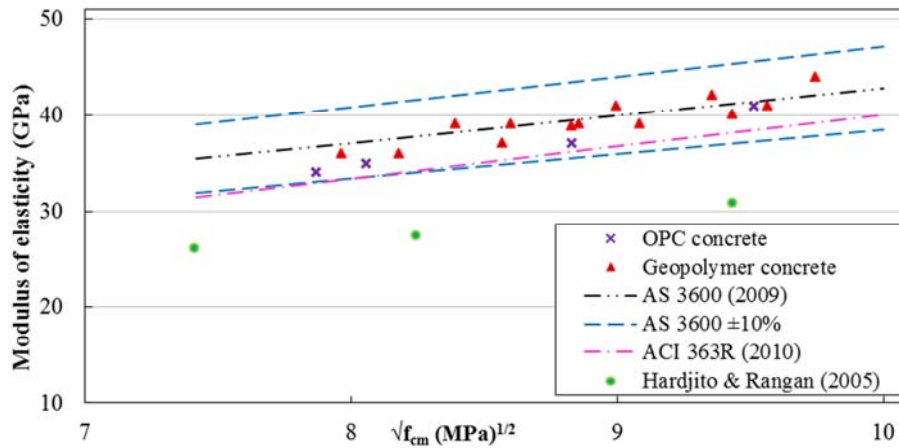f_{cm} = average 28 days compressive strength (MPa)

Figure 10. Modulus of elasticity vs compressive strength.

As shown in Figure 10, the measured elastic modulus of geopolymer concrete are closely located with AS 3600 [37] model. A separate calculation found the ratios of measured/predicted figures using this equation ranged from 0.94 to 1.02 with an average of 0.98. As, the experimental results of geopolymer concrete are located within the ±10% range of AS 3600 model, the existing model is applicable in case of geopolymer concrete as well as OPC one. Data points of OPC concrete are also positioned in the same range.

3.7. Shrinkage

Shrinkage is the process of contraction of concrete volume due to loss of water from capillary pores which occurs in two stage; autogenous shrinkage and drying shrinkage. Autogenous shrinkage is the result of consumption of interior water by cement hydration. In contrast, drying shrinkage is caused by the escaping of water from capillary pores of concrete to the unsaturated outside air. Although, autogenous shrinkage results a very small strain (40 to 50 microstrain) [42] it is not applicable in geopolymer concrete because geopolymerization reaction recycle water molecules [41]. Shrinkage strain can cause of curling and axial shortening of

concrete element and initiates shrinkage cracking. Some earlier studies on fly ash and or slag base geopolymer concrete advised higher drying shrinkage of geopolymer concrete cured at ambient conditions [43, 44]. However, Deb, Nath [45] reported a smaller drying shrinkage of ambient cured geopolymer concrete from fly ash and slag which was 482 micro-strains at 180 days compared to 562 micro-strains in OPC concrete of similar grade. Experimental results of drying shrinkage of high-strength geopolymer are plotted in Figure 11. Results show that high-strength geopolymer concrete undergoes drying shrinkage in the same range to the OPC concrete.

According to ACI-363R [19], high-strength concrete may suffer higher drying shrinkage because of having substantial amount of binder than in normal-strength concrete. A detailed investigation of drying shrinkage on powder-activated geopolymer concrete of different grades found that drying shrinkage of geopolymer concrete gradually decreases with ratio of water to binder and independent of paste amount. And therefore, high-strength geopolymer concrete were found to be suffered significantly lower drying shrinkage than normal-strength one [35].
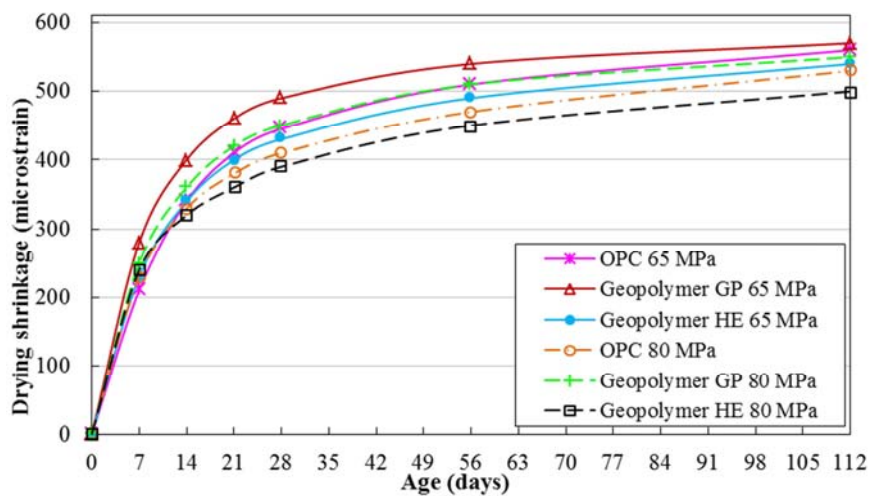

Figure 11. Drying shrinkage of high-strength-geopolymer concrete.

4. Heat of Hydration

Sometimes high heat of hydration in the early age may be a serious problem in application of high-strength concrete specially when concreting in hot weather conditions and can result in thermal cracking. This effect can be reduced by adding set retarder chemical admixture and substantial amount of SCMs, such as fly ash and slag [19, 46]; however, addition of SCMs not only decrease the early age strength but also increase drying shrinkage strain of high-strength concrete [47, 48].

Geopolymer binder does not have C_3A and C_3S compounds (responsible for heat of hydration) as in Portland cement, therefore it emits significantly low heat of hydration when compared with OPC concrete. A detail investigation in thermal behaviour of geopolymer concrete using the same binder of this experimental concluded that geopolymer concrete emitted less than one third of heat of hydration of OPC concrete [49].

5. Durability

Durability is claimed to be one of the strongest agvanteges of geopolymer concrete over the OPC one because this binder system does not rely on calcium compounds and is free from C_3A and CaO which are very vulnerable in acidic and sulpahtic attact [50]. Lots of experimetal results from the past prooved that geopolymer concrete has lower permeability, higher ressistance againt agessive environments, such as acidic and sulphate water as well as very less or nil corossion in reinforcing steel under marine environments [51-53].

Formation of hydrated sulphoaluminate (ettringite) in the later age; delay ettringite formation (DEF) is one of the serious durability problems in OPC concrete structures, it is more subjectable when they are cured at elevated temperature at early age [54, 55]. Ettringite is an expansive compound which is a product of reaction between sulphate and calcium aluminate during hydration of Portland cement. When ettringite form in an already hardened cementitious system, the volumetric expansion of concrete paste creates tensile stresses which results in cracking and failure of concrete structure [54]. On the other hand, there is no presence of sulphate and calcium aluminate in the geopolymer binder system, hence there is no possibility of DEF in the normal temperature or heat cured geopolymer concrete in later age [56].

6. Conclusions

High-strength geopolymer concrete offers a lot of advantages over conventional OPC based high-strength concrete, such as higher mechanical strengths, lower shrinkage and superior durability with environmental sustainability. Because of having higher tensile and flexural strength, this concrete will be more beneficial in high-rise buildings and bridge structures where flexural strength is more important. It eliminates the problem of high heat of hydration in early age in high-strength concrete. Unlike to normal-strength concrete, it attains a significant strength at early days as well as retains a comparable elastic modulus to OPC concrete. High-strength geopolymer concrete do not need any mineral or chemical admixtures to develop sufficient workability level in lower water/binder ratio which facilitates a simpler mixing process. Geopolymer concrete requires 20-25% less binder than conventional concrete of comparable characteristic strength. These various factors can make high-strength geopolymer an economical structural material.

Fresh high-strength geopolymer concrete suffers considerable workability loss due to rapid setting which is similar to OPC high-strength concrete. Green geopolymer high-strength concrete seems more sticky and cohesive than OPC one which can results in higher entrapped air pockets in harden concrete. Addition of commercially available chemical admixtures, which are effective in OPC based concrete, cannot be used effectively to alter the properties of fresh geopolymer concrete. This can limit the commercial application of high-strength geopolymer concrete. Further research and development of chemical admixtures which can be applicable in geopolymer concrete is needed.

Conflicts of Interest

The authors declares no conflict of interest with any parties or persons

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