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Geopolymer Concrete (GPC) as a Suitable Green Solution for Building and Construction Material

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ABSTRACT
Geopolymer Concrete (GPC), an innovative material characterized by long chains or networks of inorganic molecules, is made from by-product materials rich in Silicon (Si) and Aluminium (Al). Si and Al are chemically activated by a high alkaline solution to form a matrix that binds the loose, coarse and fine aggregates, as well as other un-reacted materials in the mixture. GPC depends on thermally activated natural material, it can be industrial by-products materials, such as fly ash or ground granulated blast furnace slag, or kaolinite, to provide a source of silicon and aluminum. They are, in turn, dissolved in an alkaline activating solution, and polymerizes into molecular chains to create the hardened binders. This process is also referred to as alkali activated cements. On the last decades, extensive researches on this topic have been conducted all over the world. According to Geopolymer Institute in 2014, the worldwide advancement in geopolymer research has an exponential growth in the number of scientific and technology publications in peer-reviewed journals. More than 400 publications were recorded in 2013 only, published by Science Direct, SpringerLink, Wiley and ACS. Initially, most researchers studied the geopolymer chemistry; afterward research trend is shifting to study the physical and mechanical properties of fresh and hardened geopolymer pastes and concrete, as well as the structural member performance of GPC for engineering applications and commercialization. Many studies revealed that GPC has better physical, mechanical and structural member performance compared to that of OPC concrete. This review paper looks over and examines both the scientific advancements aswell as the utilization of GPC as an alternative material to OPC concrete for building and infrastructure construction.

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I. Introduction

OPC concrete is a conglomerate of hydraulic cement, aggregate, sand, and water. OPC concrete is conventionally produced from local materials using simple methods.. It is the most widely used building material around the world because of the availability of raw materials, the simplicity in preparation and the molding into different shapes. One of the main ingredients in an OPC mixture is Portland cement, and recent literature reveals that cement industry accounts for approximately 8% of the current man made carbon dioxide (CO2) emission worldwide. This is due to the production of each ton of Portland cement introduce one ton of CO2 into atmosphere. In the year 2013, the global production of Portland cement was about 3.75 billion tons annually [1]. The expected growth of cement demand and production worldwide is approximately 4.4 billion tons (high estimate) by the year 2050, meaning that about 4.4 billion tons CO2 will also be released to the atmosphere. Because of the large CO2 emissions of making OPC, there is a need to find other binders to make concrete.

The effort to produce more environmentally friendly concrete is to replace the amount of OPC in concrete with by-product materials such as fly ash [2]. An important achievement in this regard is the development of high volume fly ash (HVFA) concrete that utilizes up to 60 percent of fly ash, and yet possesses excellent mechanical properties with enhanced durability performance. Another effort to make environmentally friendly concrete is the development of inorganic alumina-silicate polymer, called Geopolymer, synthesized from materials of geological origin or by-product materials such as fly ash that are rich in silicon and aluminium [3].

Fly ash (FA), one of the source materials for geopolymer binders, is available abundantly worldwide, but to date its utilization is limited. The global coal ash production was more than 390 million tons annually, but its utilization was less than 15%. In the USA, according to ACI the annual production of fly ash is approximately 63 million tons, and only 18 to 20% of that total is used by the concrete industries (ACI 232.2R-03). In addition to FA, geopolymer technology can also utilize

other by-product materials such as ground granulated blast slag (GGBS), palm oil fuel ash, rice husk ash, and mining wastes. Other resources may include natural reactive aluminosilicate powders or thermally activated alumino-silicates.

II. A Review On Geopolymer Research

Geopolymer, an inorganic alumina-silicate polymer, is synthesized from source materials that rich in amorphous forms of Silicon (Si) and Aluminium (Al), involving those processed from natural mineral and clay deposits (e.g., kaolinite clays) or industrial by-products materials such as low calcium oxide Class-F FA or GGBS. The chemical composition of geopolymer materials is similar to zeolite, but they reveal an amorphous microstructure [3]. During the synthesized process, Si and Al atoms are combined to form the building blocks that are chemically and structurally comparable to those binding the natural rocks.In the case of geopolymer material made of FA, the role of calcium in the systems is very important, because its presence will result in flash setting, and therefore must be carefully controlled [4]. The source material is mixed with an activating solution that provides the alkalinity - sodium hydroxide or potassium hydroxide is often used - needed to liberate the Si and Al and possibly with an additional source of silica (sodium silicate is most commonly used). The temperature during curing is very important, and depending upon the source materials and activating solution; heat is normally applied to facilitate polymerization. Though, the test results from several studies reported that GPC cured at room temperature also gave comparable result to that of heat curing [5-8].

II.1 Geopolymer Pastes

Initially, most of the literature available on this material deals with geopolymer pastes. Davidovits and Sawyer [9] used ground blast furnace slag to produce geopolymer binders. This type of binders patented in the USA under the title Early High-Strength Mineral Polymer was used as a supplementary cementing material in the production of precast concrete products. In addition, a ready-made mortar package that required only the addition of mixing water to produce a durable and very rapid strength-gaining material was produced and utilized in rapid restoration of concrete airport runways, aprons and taxiways, highway and bridge decks, and for several new constructions when high early strength was needed.

Davidovits [2] studied and examined the properties of Geopolymer cements. This paper focused on Geopolymer paste that has excellent properties and is well suited to manufacture precast concrete products usually needed in rehabilitation and retrofitting of structures after a disaster. It was reported that introduced geopolymeric cements, are not only for environmental aspects, but also in construction for civil engineering that would reduce CO2 emission caused by the production of cement by 80%. Geopolymer has also been used to replace organic polymer as an adhesive in strengthening structural members.

II.2 Geopolymer Concrete

The early work on fly ash-based GPC was introduced first by Hardjito, et al. [10]. In this study, it deals with the manufacturing process and salient parameters that affect the compressive strength. Low-calcium Class-F FA was used as the base material. The Silicon and the Aluminium in the FA are activated by a combination of sodiumhydroxide and sodium silicate solutions to form a paste that binds the aggregates and other un-reacted materials. The manufacture of GPC is carried out using the usual concrete technology methods. It was reported that the compressive strength is influenced by several factors such as curing time, curing temperature, water content in the mixture, and sodium silicate-to-sodium hydroxide liquid ratio by mass. It was also found that curing at 60oC for 24 hours was sufficient to achieve the required compressive strength.

The Young's modulus of fly ash-based geopolymer concrete was measured at a stress level equal to 40 percent of the compressive strength [11]. The test results given in Table 1 are similar to those of OPC concrete. Concrete with a higher compressive strength has a higher Young's modulus. These values are at the lower end of those calculated using the expression given in the Australian Standard AS 3600.

TABLE 1 Young's modulus and Poisson's ratio

Compressive strength (MPa)	Young's modulus (GPa)	Poisson's ratio
89	30.84	0.16
68	27.29	0.12
55	26.05	0.14
44	22.95	0.13

Earlier, Hardjito et al. [11] have reported the stress-strain relations of fly ash-based GPC for various compressive strengths. These test data have shown that the stress-strain relations of GPC are similar to that of OPC concrete. Sarker [12] investigated the suitability of using an existing stress–strain model originally proposed by Popovics for OPC concrete. It is found that the equation of Popovics can be used for GPC with minor modification to the expression for the curve fitting factor, to better fit with the post-peak parts of the experimental stress–strain curves. The slightly modified set of stress–strain equations was then used in a non-linear analysis for reinforced concrete columns. It is also found that a good correlation is achieved between the predicted and measured ultimate loads, load–deflection curves and deflected shapes for 12 slender test columns. It was suggested a modified model to properly predict the post-crack portion by introducing a new expression for the curve fitting value (n) using the same equations for the high strength concrete proposed by Thorenfeldt et al. [13].

Manjunatha, et. al. [14] studied the mechanical behavior of ambient cured GPC. Various mechanical properties such as compressive strength, split tensile strength, shear strength, impact and bond strength were investigated. This was also including investigation on the stress-strain behavior. The test results were compared between GPC and OPC concrete. It was found that many properties of ambient cured GPC were superior when compared with OPC concrete. It was concluded that GPC can be used as high performance concrete in place of OPC concrete for structural application with many advantages. The new model gave good predictions correlated well with the measured values. The peak strain for the different mixtures of GPC was recorded in the range of 0.0015-0.0026 [15, 16]. This is less than the 0.003 strain that is usually used in the OPC concrete design equations.

II.3 Short Term Properties

Similar to OPC concrete, the short term properties of GPC are influenced by many factors mainly due to mix proportion of sand, aggregates, water and liquid solution. The experimental test data of short term properties had been revealed from several researches implemented by Hardjito et. al. [17-19] as stated bellows:

- Higher compressive strength is resulted from high concentration in terms of molar of sodium hydroxide solution; in other words, higher the ratio of sodium silicate-to-sodium hydroxide ratio by mass, higher is the compressive strength. GPC mortar does not show any exothermic action, as shown by metakaolin-based geopolymer paste or mortar. In spite of this, the GPC yields high compressive strength.
- The effect of the Na2O-to-Si2O molar ratio on the compressive strength of GPC is not significant. But, As the H2O-to-Na2O molar ratio increases, the compressive strength of GPC decreases. It was also find that as the ratio of water-to-geopolymer solids by mass increases, the compressive strength of GPC decreases.
- As the curing temperature in the range of 30oC to 90oC is increase, then the compressive strength of GPC is also increase. Longer curing time, in the range of 4 to 96 hours (4 days), produces higher compressive strength of GPC. However, the increase in strength beyond 24 hours is not significant.
- The addition of naphthalene sulphonate-based super plasticizer up to approximately 4% of fly ash by mass, improves the workability of GPC; nevertheless, there is a slight degradation in the compressive strength of hardened concrete when the super plasticizer dosage is greater than 2%.
- The slump value of the fresh GPC increases with the increase of extra water added to the mixture. It was also found that the fresh GPC is easily handled up to 120 minutes without any sign of setting and without any degradation in the compressive strength. While, Prolonged wet mixing time of up to sixteen minutes increases the compressive strength of GPC.
- The rest-period, defined as the time taken between casting of specimens and the commencement of curing,of up to 5 days increases the compressive strength of hardened GPC. The increase in strength is substantial in the first 3 days of rest-period.
- The average density of GPC is similar to that of OPC concrete, and the measured values of the modulus elasticity of GPC with compressive strength in the range of 40 to 90 MPa were similar to those of OPC concrete. The measured values are at the lower end of the values calculated using the current Design Standards due to the type of coarse aggregate used in the manufacture of GPC.
- The indirect tensile strength of GPC is a fraction of the compressive strength, as in the case of OPCconcrete. The Poisson's ratio of GPC with compressive strength in the range of 40 to 90 Mpa falls between 0.12 and 0.16. These values are similar to those of OPC concrete. The stress-strain relation of GPC in compression is similar to that of OPC concrete, with the strain at peak stress in the range of 0.0024 to 0.0026.

Compressive strength is one of the most important characteristics of concrete. Compressive strength of GPC depends on different factors such as curing temperature, mixing ratio and the molarity of alkaline activator solutions. GPC can develop high strength in the earlier age under elevated curing temperature [11, 15, 20-23] and it gains target 28 days strength under ambient temperature when slag or OPC material is added to the mix [24-26]. The improvement in physical properties is related to the intrinsic structure developed due to enhanced geopolymerisation [24, 27]. Curing at 60oC for 24 hours produces very rapid strength gain which gives a compressive strength at one day ranging between 47 and 53 MPa [23]. This system makes GPC is suitable for precast applications.

Even though GPC has higher tensile strength compare to OPC, its structural performance still depends on the bonding between concrete and steel bars. Bonding strength between the reinforcement and surrounding concrete is an essential factor to examine the structural performance of the material. GPC shows higher bond strength to the reinforcement because of its higher tensile strength [28-30]. Due to the similarity of failure behavior for GPC specimen compared to OPC, the existing design equations for the bond strength of OPC concrete with steel reinforcing bars can still be applied for GPC [28-30].

Olivia and Nikraz, [31] conducted splitting tensile strength test by using standard cylinder specimens of size 150x300mm. It was found that splitting tensile strength of GPC increases with the increasing of concrete age. It was observed that the tensile strength of GPC was 8- 12% higher than OPC after 28 and 91 days. This study shows that there is an effective bond between GPC matrix and aggregate. They also studied the flexural strength by using blocks of dimension of 100x100x400mm and observed that the flexural strength of GPC increases with increase in age of concrete. It was found that the flexural strength of GPC was 1-1.4 times higher than that of the OPC. They also found that the compressive strength of GPC increases with its age. The cylindrical specimens of 100 mm diameter and 200 mm length were used for testing the compressive strength. The influence of aggregate content, alkaline solution/fly ash ratio, sodium silicate/sodium hydroxide ratio, and curing method over the compressive strength of GPC had been examined. Test results shown an increase in strength over 28-day period after curing for aggregate contents of 1800, 1848 and 1896 kg/m3. Among these, the greatest strength was developed on the mixture containing 1800kg/m3 aggregates. High alkaline solutions also increased the strength in 28-day. But, maximum strength was achieved from low alkaline solutions. It was also found that high amounts of sodium silicate solutions have significant positive effect on the compressive strength. High curing temperature also increases the strength of GPC.

Joseph, and Mathew [32] studied the effect of different factors on the compressive strength of GPC. After seven days test data showed that up to the value 10 of molarity of NaOH, the increase in molarity influence the increase in compressive strength of the GPC. However, after the value 10 it starts decrease. They also examined the effect of curing on compressive strength, and the results showed that compressive strength was proportional to curing till 24 hours after which there was no significant effect of curing on the strength. Also, they found that compressive strength enhances with increase in sodium silicate to sodium hydroxide ratio. Anuar et. al., [33] also tested the effect of NaOH molarity of 8M and 16M on the compressive strength of geopolymer concrete at different ages. The resultof his study showed that compressive strength increases with the increase in molarity of NaOH. The result of this study is also get along with experimental test data of short term properties conducted by Hardjito et. al. [10, 11, 17, 18].

Sarker et. al. [34] used cylinder specimens with dimensions 100mmx200mm for testing the influence of fracture energy on the compressive strength of GPC. It was observed from their result of test data that fracture energy increases with the compressive strength in both types of concrete. Similarly, it can be observed that the fracture energy of GPC increases at a higher rate with compressive strength than OPC.

II.4 Long Term Properties and Durability

Durability issue on the reinforced concrete structures is one of important factor affecting the lifetime of buildings. For example, the penetration of destructive substances into the concrete will damage concrete and corrode steel reinforcement; therefore, understanding the long term performance of the GPC is essential to be able to construct real structures with the confidence. Many researches have shown that GPC has better resistance against aggressive environments. Wallah et al. [35-37] reported the experimental data on the durability of GPC related to sulphate and acid resistance. From results of test conducted up to one year period, it was concluded that GPC has an excellent resistance to sulphate attack. All specimens soaked in 5% sulphate solution showed no change in the appearance compared to the condition before they were exposed and no degradation in compressive strength. Furthermore, there was no sign of surface erosion, cracking or spalling on the specimens. In the case of exposing GPC to sulphuric acid solution, it was found that the concentration of the solution plays an important role. Exposing GPC to 2% of sulphuric acid solution for one year caused significant degradation in compressive strength but in the case of exposing GPC to 1% and 0.5% of sulphuric acid solution the effects were significantly less.

H. S. Shankar and R. B. Khadiranaikar, [38] investigated the durability of GPC and compared with OPC concrete specimens. Both GPC and OPC specimens were immersed in 10% sulphuric acid solution after 7 days of casting. The specimens were kept fully immersed in the solution, having four times the volume of specimens for the duration of 45-day exposure. The effect of sulphuric acid solution on both specimens was regularly observed through visual inspection by quantifying the compressive strength and weight change. It was concluded that the compressive strength loss for the specimens exposed in sulphuric acid was in the range of 10 to 40% for OPC, whereas it was about 7 to 23% for GPC. Furthermore, all specimens showed a decrease in mass loss up to 1% for OPC, but negligible weight change for the case of GPC.

Long term properties such as creep and shrinkage are also important aspects affecting long term performance of structures. Past studies showed that geopolymer concrete also has excellent long term properties. As reported by Wallah and Rangan [37], Wallah [39] and Wallah and Hardjito [40],GPC undergoes very low creep. Based on the test results, the creep coefficient, defined as the ratio of creep strain-to-elastic strain, after one year of loading for GPC with compressive strength of 40, 47 and 57 MPa is between 0.6 and 0.7, while for GPC with compressive strength of 67 MPa, the value is between 0.4 and 0.5. The specific creep, defined as the creep strain per unit of sustained stress values, is about 50% of the values predicted by the method as proposed in the AS3600.

Wallah, [41] also studied the drying shrinkage of heat-cured fly ash-based GPC. Four series of GPC specimens with different compressive strength were used. The test specimens were prims with dimension 75mm x 75mm x 285mm. In this experimental, two types of heat curing, i.e. oven dry curing and steam curing were applied to the test specimens. The test results were compared with the results predicted by Gilbert method as in AS3600. It was found that the heat cured concrete samples have very low drying shrinkage.

Gao et. al. [42] conducted study on the shrinkage and creep properties of GPC. It was found that 33% to 40% reduction in the shrinkage and expansion strain for GPC.

II. 5 Fire Resistance

All types of concrete are inflammable, but exposing concrete to extreme heat may create a very unsafe condition. Concrete members start to spall when it is subjected to high temperature and in the long run this condition drastically reduces the structural member performances. GPC is considered as a fire resistant material compare to OPC. At early part of the curing cycle, high temperature improves the compressive strength of Sapute et. al. [43]. Additionally, Mane and Jadhav [44] observed that even when exposed to high temperature of 500o C, geopolymerspecimen show less reduction about 29% in the capacity than that for OPC concrete about 36%. This reduction results from the differential thermal expansion between the aggregate and paste [44, 45]. In general, GPC shows a good fire resistance compared to OPC when exposes more than 800o C [45-48].

III. BEHAVIOR OF GPC STRUCTURAL MEMBERS

GPC has a different mechanism for the strength development compared to OPC concrete. Therefore, the available methods for analysis and design of GPC structural members should be scrutinized and verified with available code/standard before using GPC in building and infrastructureapplications. Available literature and research of GPC coped with much on mix design, physical and mechanical properties, and durability. There is not much attention given to reinforced GPC structural member behavior until a research group at Curtin University, Australia, initiated the works on the structural behavior of fly ash-based GPC structural [49-51]. A total of twelve under-reinforcement concrete beams with various reinforcement ratio between 0.64-2.69 were tested for flexural failure. As expected, the test results showed that the flexural load-carrying capacity increased with increase the tensile reinforcement ratio. The test results was also compared to the design provisions given in Australian Standard and the test to prediction ratio were 0.98 and 1.28 with the majority of the predicted values are conservative. Over all, it was reported that the behavior of reinforced GPC beams were similar compare to conventional OPC concrete beams in terms of effect of tensile reinforcement ratio and concrete compressive strength on flexural capacity and ductility index.

The research works were also carried out on slender fly ash-based GPC columns under load eccentricity by Curtin University research group Sumajouw et. al. [51-55]. A total of twelve slender GPC columns were cast and tested under load eccentricities. The slender columns have longitudinal reinforcement ratios of 1.47% to 2.95% with targeted concrete strength grades of 40 MPa to 65 MPa. The column specimens were tested at specified various load eccentricities from 15mm to 50mm. It was reported that the slender GPC columns failure mode was characterized by crushing of concrete in the compressive face near the mid-height, and brittle failure mode was observed for the columns with smaller load eccentricity, higher concrete strength and higher reinforcement ratio. Furthermore, it was also noted that the load-carrying capacity were increased with the decrease in load eccentricity, increase in concrete compressive strength and increase in longitudinal reinforcement ratio. On the other hand, the mid-height deflection of GPC columns increased with the increase of load eccentricity, decrease in concrete compressive strength and increase in reinforcement ratio. The test results showed that the load-carrying capacity of slender GPC columns were comparable with the result predicted by design provisions from AS 3600 and ACI 318. Over all, it was found that good correlation is existent as the average test to prediction ratio is 1.03 for the case of AS 3600 and 1.14 for the case of ACI318. It is suggestion. Therefore, test data showed that the design provision used to predict the behavior of slender OPC concrete columns can be applied for slender GPC concrete columns. Further studies on the behavior of GPC structural members are out line bellow.

Chang et. al. [56] investigated the shear behavior of the reinforced GPC beams. Nine GPC beams with dimensions of 200x300x1680 mm were cast using the fly ash-based GPC. It was found that the failure modes and the cracking patterns were similar for both the GPC and OPC beams. The shear capacity of the GPC beams was also recorded to be dependent on the longitudinal reinforcement ratios. The shear cracking load and the shear strength of the GPC beams were predicted using the ACI 318 code provision for shear calculations and gave conservative results. The VecTor2 programme was used to simulate the cracking patterns, the failure modes and to predict the shear strength. The predicted results showed a very good correlation with the experimental data.

Sarker [12] studied the GPC slender columns under the combined stress of compression and uniaxial bending. It was suggested that Popovics' equation for OPC concrete can be used to predict the stress-strain curve of fly ash-based GPC with some modifications suggested for a proper stress-strain relationship. It was also found that the analytical methods for calculating values of the ultimate loads using the described non-linear method available for the OPC concrete column could be conservatively used for the analysis of the GPC columns. The mean value of test to prediction ratio is 1.03, and standard deviation is 5% for the all specimens. Over all, the predicted results of the ultimate loads, mid-height deflections, load deflection curves, and deflected shapes correlated well with the experimental data. Therefore, the analytical method for conventional OPC concrete columns can be applied tp GPC columns with appropriate stress-strain relationship of GPC.

Rahman and Sarker [57] investigated the behavior of GPC columns under combined axial compression load, and biaxial bending using twelve reinforced fly ash-based GPC slender columns. The tested parameters includedconcrete grade, reinforcement ratio, and eccentricity. It was recorded that the failure mode for all columns was by the spalling of the concrete cover followed by the concrete crushing. For the small eccentricity, the failure was in brittle manner with a shorter post-peak on the load-deflection diagram. Increasing the eccentricity distance increased the measured deflection at the mid-height of the columns. Moreover, the deflection increased for a higher reinforcement ratio and higher compressive strength. Generally, the failure modes and load-deflection behavior are comparable to that of observed for the reinforced OPC columns under the same loading conditions. Bresler's reciprocal load formula, and the stress block formulas provided by the Australian standards were used to predict the column load capacity. The predicted results were found to be conservative and comparable to the experimental results. However, these formulas give higher accuracy in the case of columns with smaller eccentricities.

Dattatreya et. al. [58] studied the behavior of reinforced GPC beams. The beams were cured under ambient conditions. The total number of 18 GPC beam were tested in flexure. The dimensions were 100x150x1500 mm, and the tensile reinforcement ratio varied between 82-110% of the balanced reinforcement ratio. It was recorded that the first crack load was 9-11% for the GPC beams and 13-16% for the OPC beams as a percentage ratio of their ultimate loads. All the specimens were tested under two-point load static loading. It was reported that the average service loads were reduced by 12% for the GPC beams compared to the OPC beams. The cracking patterns were observed including the crack number, spacing, and width, and the failure modes. All gave almost the same results with OPC beams. Even though it was not identical for the all aspects, test data showed a good correlation between test results and standard equations provided by ACI 318 code to predict the cracking moment, ultimate moment, and maximum deflection.

Sujatha et. al. [59] investigated the loading behavior of the reinforced GPC slender columns with reference to the reinforced OPC columns. Totally 12 specimens GPC slender columns were fabricated. Six specimens of fly ash-based GPC columns and the other six for OPC reinforced columns. The column shape was circular cross-section and 1800 mm height, and tested for axial compression loading. Test results showed that the reinforced GPC columns had higher load carrying capacity by 30% over the reinforced OPC columns. Conversely, low mid-height deflections were observed for the reinforced GPC columns compare to reinforced OPC columns, and the mean value of predicted ultimate load is 1.27. Furthermore, by comparing the performance of GPC columns to OPC columns it is important to point out that there is a promising scope in the applicability of GPC as structural elements in building and infrastructure.

Ganesan et. al. [60] investigated the behavior of the fly ash-based reinforced GPC panels in one-way direction, and made comparison to the reinforced OPC concrete panels. Similar cracking patterns and failure modes were observed. The failure modes were by crushing of the concrete near the edges associated with large lateral deflections at mid span. The load-deflection curves showed linear response until the appearance of the first crack, afterwards it showed a nonlinear response. The reinforced GPC concrete panels showed sharper curves compare to reinforced OPC panel, which indicated the higher ductility of the OPC panels. This was referred to the softening behavior due to the existence of more fine particles in GPC mixes, which resulted in a less ductile behavior. It was found that the current available ACI 318 code provision gives conservative results in predicting the ultimate load of the GPC panels. However, the predicted results were always lower that of the experimental results. The error ranged from 20-35% depending on the aspect ratio and slenderness ratio. It may suggest the need to apply additional safety margins for predicting the ultimate load of reinforced GPC panels.

Madheswaran et. al. [61] investigated the shear behavior of thin webbed T-beams produced using the FFA+GBFS-based geopolymer concrete. The test results showed that both the reinforced GPC and the OPC beams had similar shear behavior, where the shear capacity was affected by the stirrups' spacing and the shear span to effective depth ratio. The beams failed by the typical diagonal tension shear failure mode. The flexural cracks in the shear span developed an inclined crack that extended toward the loading and supporting points after which a sudden brittle shear failure occurred. The load-deflection diagrams showed a linear relationship before cracking, then the post cracking portion also showed a linear relationship as well. The experimental values for the deflections were higher than the predicted values using the available ACI 318 code equations for the reinforced OPC beams. This may attribute to the lower modulus of elasticity of the reinforced GPC. It was reported that the available ACI 318 code provision for the shear design of the reinforced OPC beams is valid and can be safely applied for the reinforced GPC beam design. The upper limit provided by the code is also conservative.

Madheswaran, et. al. [62] conducted a study to examine the shear behavior of reinforced GPC rectangular beams. The overall dimensions of the GPC beams are 250 mm×300 mm×2200 mm. Twelve reinforced GPC beams were cast with a span of 1600 mm and designed as shear deficient beams. Experiments are conducted on 12 GPC beams and four OPC control beams. The specimens were produced from a mix incorporating fly ash and ground granulated blast furnace slag, which was designed for a compressive strength of 40 MPa at 28 days. The reinforced concretespecimens are subjected to curing at ambient temperature under wet burlap. The parameters being investigated include shear span to depth ratio (a/d = 1.5 and 2.0). The strain compatibility method was used to determine the ultimate moment carrying capacity of the beams, and the non-linear stress-strain relationship was applied to estimate the complete load-deflection diagram. These methods showed an excellent correlation between the experimental test results for both the reinforced GPC the OPC beams.

Laskar et. al. [63] reported the better capacity of the reinforced GPC beams under cyclic loading effects over reinforced OPC beams. It was reported that the reinforced GPC beams had an increased capacity by almost 30% over the reinforced OPC beams. Moreover, the reinforced GPC beams exhibited a lower degradation in stiffness over time. The test results showed that the reinforced GPC beams have higher capability for energy dissipation by about 45% over the reinforced OPC beams. This fact infers that the reinforced GPC beams have higher ability to sustain earthquakes compare to reinforced OPC beams.

IV. APPLICATIONS OF GPC FOR BUILDING CONSTRUCTIONS

Lloyd and Rangan [64] studied on GPC with fly ash as based material. It was suggested that GPC has excellent properties and is suitable to manufacture precast concrete products. Furthermore, Aleem and Arumairaj [65] conducted a review surveying on GPC. It was recommended that due to the high early strength; the GPC shall be effectively used in the precast industries, so that huge production is possible in short duration, and the damage during transportation shall also be minimized. It was also informed that the characteristics of GPC could be used in place of OPC. Several GPC applications in constructions are outline bellow.

IV.1 GPC Precast Products

GPC precast products and cast in-situ structures have been developed and constructed in many places. GPC has been manufactured and successfully trialed on sewer pipes, railway sleeper, cemetery crypts, box culverts, and wall panels [66]. One of the earliest fully structural applications of GPC was the Murrarie Plant site bridge. This is a composite bridge structure made from pultruded fibreglass girders acting compositely with a Grade 40 GPC bridge deck. The bridge was prefabricated at Wagners Toowoomba CFT factory and brought to site for installation in 2009 [67].

Wagners in Australia is supplying a brand-named GPC for both precast and in-situ applications successfully utilizes in field applications such as precast girder, precast bridge deck, light pavement, retaining wall, water tank, and boat ramp [68]. Additionally, Wagners EFC Team have designed, tested and supplied Grade 40 GPC precast floor beam-slab elements for the production of 33 large floor beams that form suspended floor plates of the new innovative Global Change Institute (GCI) building at the University of Queensland St. Lucia Campus deck [67]. This is the first application of modern GPC into the structure of a multi-storey building. Moreover, the Bundaleer Road Bridge, located at West Moggill, Brisbane, was made and installed between May - June 2012. This project is another example of a composite pultruded girder with Grade 40 GPC precast deck bridge structure. The GPC deck acts as the compression flange to the bridge as well as providing a serviceable wearing deck [67]. In addition, GPC's chemical resistance enlarges their use in marine applications, sewage pipes and in mine tailings deck [67].

In Australia, the Brisbane West Well Camp Airport (BWWA) has been fully operated. It is believed that the BWWA become the greenest airport in the world, because more than 40.000 cubic meters of the world's lowest carbon, cement free GPC was used for the turning node, apron and taxiway pavement. Wagners EFC was used, and it saved more than 6.600 tonnes of CO2 gas emission into atmosphere. To date, the pavement project at BWWA is considered to be the largest commercial application of GPC in the world [69].

The precast GPC house was designed to accommodate a small family living in an urban environment. The concrete components include floor plate cast integrally with grade beams and structural insulated wall panels. This structure was completed in about two weeks and was assembled into three pods that were shipped to California from North Carolina [70].

IV.2 GPC for Other Constructions

A typical light pavement with size of 900 metres long by 5.5 metres wide, was cast using Grades 25 MPa and 40 MPa. In addition, the pavement slab for a weighbridge at the Port of Brisbane was cast in November 2010 using GPC Grade 32 MPa [67].

A total over fifty Grade 40 MPa GPC precast panels were used for retaining wall for a private residence. The panels were up to 6 metres long by 2.4 metres wide, and were designed to retain earth pressure of 3 metres. The GPC precast panels were cast in Toowoomba and cured under ambient conditions before being sent to site for installation [67].

Two in-situ water tanks with the diameter of 10 m and 2.4 m high were cast in March 2011. The first water tank was built using a Grade 32 MPa concrete with blended cement consisting of 80% OPC and 20% FA, while the second tank is constructed with a Grade 32 MPa GPC. Both water tanks were used a maximum aggregate size of 10 mm. These water tanks were constructed to investigate the authogenous healing behavior of GPC [67].

V. BENEFITS, LIMITATION AND CHALLENGES OF GPC

The benefits, limitation and challenges should be comprehensively analyzed, and proposed the development for the future work of this material. By doing this, the design engineers can use the GPC in large volumes with greater confidence and less risk.

GPC shows significant benefits to be a construction material for the future; because it is not only environmentally friendly but also possesses excellent physical and mechanical properties. The physical and mechanical properties of GPC are comparable or even better than that of OPC concrete. Similar to OPC, aggregate takes up about 85% of the material. Interactions among alumino-silicate framework, alkali cations, additives and aggregate in GPC are important factors that influence the overall mechanical performance. The solid interfacial interactions between the aggregate and the GPC matrix in a large zone contributes to the high splitting tensile strengths between GPC and steel reinforcements [71]. Compressive strength of the GPC depends on molarity of NaOH, sodium silicate to sodium hydroxide ratio, curing time and curing temperature. Other properties of GPC such as low drying shrinkage, low creep, greater tensile strengths, sulphate resistance and acid resistance, and density are comparable to OPC concrete.

For each developed technology, there are always several limitations over its acceptance. Main limitations associated with the acceptance of GPC in the construction field are the high cost of alkaline solution which depends on its alkalis content, the mixing method prior to use which takes 24-hour to prepare the alkaline solution, some health hazards due to the high alkalinity environment prossess, and the brittle behavior of GPC [65].

Notwithstanding with the enormous researches globally implemented, the GPC faces many challenges that need to be addressed. One of the main challenges is the absence of the standards or specifications. The adaption of GPC as a new material will be limited by lack of standards or specifications, rather than the obstacles of the technical issues. Heidrich et. al. [72] performed a survey to respondents, a wide range of the concrete industry stakeholders in Australia, observing the obstacles that could be facing for the utilization and acceptance of GPC. Most of the respondents (more than 60%) found that the absence of standards was the first main challenges for GPC to be utilized and accepted in concrete industries. In the second position came the concerns about the long term properties. The productivity and safety issues came in the third position; conversely, cost and liability were found to be lower concerns. Thus, appropriate standards that consider the performance as a base for GPC evaluation may be the most suitable solution for the adaptation of such a new material. On the other hand, the term of geopolymer covers a wide range of base materials that may confuse to design engineers in concrete industry. Therefore, a correct category of the base materials should be well selected and standardized for use in the concrete industry. The creation of new standards or specifications will be very complicated and expensive; hence collaboration of governments, industries, and researchers in global community is a must.

Other ***challenge*** faced by GPC is that commercialization is more likely to be limited to the high-performance applications, including chemical, heat and fire resistance and hazardous waste management. The long term performance aspects create another issue for the acceptance of GPC because the available durability tests resulting from many investigations give only indications about the expected performance. In fact, most of the design engineers require more time field application of GPC in real world verification before such a new material isadapted in the construction industries. Therefore, practical recommendations for long term performance aspects for the utilization of GPC technology in building and infrastructure constructions need to be developed. Further ***challenge*** to be encountered is particularly related to the variation in the physical and mechanical properties that are associated with the irregularity of the compositions of the base materials [73]. This circumstance creates some difficulties to relate the results of the available test data to other research. Adaptation of GPC requires the predictability and reproducibility of the fresh and hardened properties. Therefore, acceptance of GPC in various application of concrete industries may require a new chemical and engineering point of view in which the chemical composition and rheological properties form the base for the evaluation of the product.

VI. FUTURE DEVELOPMENT

Based on aforementioned discussion, there are many issues and concerns that need to be addressed for future development of GPC. Of these, development of standard and specifications, development of new codes specific to GPC that include performance requirements, safety, and provision for constructions are considered the highest priority.

In this review paper, the advanced preparation for the fresh and hardened GPC is look over and examine. Though last decades or so have witness the remarkable advance in the science, the preparation technology, and the insights into the performances of GPC, there are several issues exist for future development on this material. Attention should therein be paid to have more understanding on how several issues for development on GPC such as further enhancing mechanical performance, scaling up production and exploring new applications are accepted. It is also required a deeper understanding of the physicochemical description of the geopolymerization process. Also, this may contribute to more understanding for the role of the other ingredients that may exist in the source materials for making GPC.

In most case, GPC's are simply produced at laboratory scale with experimental test data, and empirical formulation with the comparison to the predicted values using codes or standards for OPC concrete. In the near future, by learning some GPC application outlined above, the manufactures of GPC are being realized on a large-scale. For field application, it is important to consider and address other identified problems. In the short term, it is more likely that the greatest volume uses for GPC will be precast and non-structural applications, footpaths and shared paths, pipes and fire or chemical resistant purposes.

For the near future, the extensive use of GPC in building and infrastructure construction seems to come true; therefore there is a need to have new codes and specifications. To facilitate GPC on concrete code and provisions, there is also an essential to have extensive investigation required to decide the shape and parameters of the stress block and maximum compressive strain in GPC in order to provide more accurate prediction.

VII. CONCLUDING REMARKS

This review paper has looked over and examined the scientific advances on the utilization of GPC as an alternative material to OPC concrete for use in building and infrastructure constructions. The concluding remarks summarized several important issues are listed below:

Geopolymer binder offers a possible solution for several problems that are facing by the current OPC binders. These binders exhibit similar or even better physical and mechanical properties compared to OPC binder. Alkali solutions influence the porosity of GPC structure. The porosity effects the migration of alkali of GPC into the ion solutions, the moisture and then has a consequence on the mechanical strength and durability. GPC with compact and denser structure shows better mechanical performance, and provides good resistance to chloride, sulfate and acid solutions.

Compared to the OPC concrete, the stress-strain curves of the GPC showed similar behavior up to the ultimate strength, after which a rapid decline in stress occurs during the post-peak strain softening. However, the GPC displays a more brittle behavior comparing to the OPC. The peak strain for the different mixtures of GPC was recorded low (in the range of 0.0015-0.0026) compare to OPC concrete (less than 0.003). In addition, an extensive investigation still required determining the shape and parameters of the stress block and maximum compressive strain of GPC.

Regardless of available literature of GPC, there is still a significant gap concerning the engineering properties and the structural behavior of the reinforced GPC. It is required to clearly determine the relationships between the different properties of the GPC including elastic modulus, Poisson's ratio, tensile strength, flexure strength, compressive strength, shear strength, and bond strength. More study is required regarding these issues.

Many researchers reported that the structural behavior of the reinforced GPC members is similar to the known behavior of the reinforced OPC concrete members. Therefore, reinforced GPC structural members such as beams, columns, and slabs could provide physical and mechanical properties that are comparable or even better than reinforced OPC concrete.

The existing design provision available in the ACI 318 code and the AS3600 code standards are reported to be applicable for the analysis and design of the reinforced GPC structural members, and in most cases give conservative results for analysis and designing of reinforced GPC members. However, it is recommended to apply an additional safety factor to adjust for the unexpected long term behavior.

The unavailability of the standards makes the major challenge for the acceptance of the GPC in industries. Therefore, for the time being, evaluation of the GPC based on its physical and mechanical characteristics including test result over GPC structural member performances seems to be the best way for acceptance of such a new material for industrial applications.

Even though the currently available standards of OPC concrete have been conservatively used for analysis and designing of reinforced GPC members, the main obstacles facing to the spread out of GPC is the absence of standards. In the future, therefore, it is strongly suggested to form a committee to generate code provision for GPC. Other issues that need to be studied more are related to the safety, cost and liability.

The conclusion of this reviewed paper is that there is significant potential of growth for GPC as a suitable green solution in Building and Construction material.

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