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Geopolymer concrete as a cleaner construction material: An overview on materials and structural performances

Hemn Unis Ahmed [a,b,*], Lavan J. Mahmood [a], Muhammad A. Muhammad [a], Rabar H. Faraj [c], Shaker M.A. Qaidi [d], Nadhim Hamah Sor [e], Ahmed S. Mohammed [a], Azad A. Mohammed [a]

[a] University of Sulaimani, College of Engineering, Civil Engineering Department, Kurdistan region, 46001 Sulaimaniyah, Iraq
[b] Civil Engineering Department, Komar University of Science and Technology, Sulaimani, Kurdistan Region, Iraq
[c] Civil Engineering Department, University of Halabja, Kurdistan Region, Halabja, Iraq
[d] Department of Civil Engineering, College of Engineering, University of Duhok, Kurdistan Region, Duhok, Iraq
[e] Civil Engineering Department, University of Garmian, Kalar, Kurdistan Region, Iraq

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ABSTRACT

The manufacture of ordinary Portland cement (OPC) produces a lot of CO_2 in the atmosphere. Researchers have recently focused on exploring the behaviour of geopolymer concrete (GPC) as an alternative to Portland cement concrete (PCC) in micro and macro dimensions. Geopolymers (GP) are innovative cement-based materials that could totally replace OPC composites. Geopolymer composites (GC) have a reduced carbon footprint and utilize less energy than OPC. The construction industry's main concerns are material characteristics and the performance of reinforced concrete (RC) structural components. Therefore, this review paper is going to look at some important material properties, like fresh characteristics, compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity, as well as the evidence of the structural behaviour of GPC beams. According to the findings of this review, GPC offers similar or superior fresh and mechanical properties to conventional concrete composite. In addition, it was mentioned that GPC might be utilized to design GPC members securely in terms of their strength capabilities and standard codes of practice. Nevertheless, further study is suggested to include more detailed and cost-effective design methods for the potential use of GPC for large-scale field applications.

1. Introduction

Concrete is the most frequently utilized building material (Abdullah et al., 2021). Despite this, OPC remains the main cementing substance employed to bind the components of concrete composite. Nevertheless, producing OPC requires a substantial amount of raw materials and energy, which emits a significant amount of total CO_2 (approximately 7.0%) into the environment (Mahasenan et al., 2003). Nevertheless, PCC continues to be the most extensively utilized material in the worldwide construction sector (Shaikh, 2016). Thus, all governments need to consider limiting and reducing CO2 emissions (Yildirim et al., 2015). Thus, numerous studies have been conducted in order to develop an innovative material that can be utilized in the replacement of OPC (Provis et al., 2015). Professor Davidovits in France was the first to produce GP technology in 1970. (Ahmed et al., 2021a). Because of the significant utilization of waste products in various amounts, GPC releases roughly 75% less green-gas than regular concrete (Weil et al., 2009).

GPs are innovative cement-based materials that can totally substitute OPC composites while emitting less CO_2 than OPC (Ahmed et al., 2021b). The term "geopolymer" can be referred to as an alkaline liquid that could be utilized to react with silicon (Si) and the aluminium (Al) in the source material or in waste materials to produce binders (Davidovits, 1988). GPC can be produced in a polymerisation process of alumino-silicate materials including metakaolin, fly ash, rice husk ash, and ground granulated blast-furnace slag through activation using an alkaline liquid solution (Ahmed et al., 2022a). The alkaline liquids are usually potassium- or sodium-based. The most common alkaline liquid used in polymerisation is a combination of potassium hydroxide (KOH) or sodium hydroxide (NaOH) and potassium silicate (K_2SiO_3) or sodium silicate (Na_2SiO_3) (Ahmed et al., 2022b). Hence, the efficiency of making GPC depends on the alkaline liquid solution (activators) and the types of resource materials (Duxson et al., 2007). Arunkumar et al.

* Corresponding author at: University of Sulaimani, College of Engineering, Civil Engineering Department, Kurdistan region, 46001 Sulaimaniyah, Iraq.
E-mail address: hemn.ahmed@univsul.edu.iq (H. Unis Ahmed).

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Table of Abbreviations

GP	Geopolymer
GC	Geopolymer composites
GPC	Geopolymer concrete
R-GPC	Reinforced geopolymer concrete
OPC	Ordinary Portland cement
PCC	Portland cement concrete
ITZ	Interfacial transition zone
FA	Fly ash
RHA	Rice husk ash
MK	Metakaolin
GGBFS	ground granulated blast-furnace slag
CS	Compressive strength
FS	Flexural strength
PCC	Portland cement concrete
ME	Modulus of elasticity
R-GPC	Reinforced geopolymer concrete
STS	Splitting tensile strength
FE	Finite Element
BFRP	Basalt fibre reinforced polymer
RC	Reinforced concrete

(2021) used waste wood ash instead of FA as a source of binder material and waste rubber as the fibre for the production of GPC; they concluded that GPC with good mechanical properties could be produced by employing waste wood ash and 1% of waste rubber fibre. On the other hand, Arunkumar and Muthiah (2021) and Arunkumar et al. (2022a) demonstrated that substituting 30% waste wood ash for FA in the production of GPC resulted in improved setting and mechanical properties.

GPs are inorganic alumino-silicate polymers derived from the alkaline-activation of different alumino-silicate material or other by-product or agricultural wastes rich in aluminium and silicon (Sharif, 2021). The GPC is made up of alumino-silicate resources binder materials, alkaline solutions, coarse and fine aggregates, and water in various amounts. Polymerisation of alkaline solutions and resources binder ingredients results in solid concrete, similar to standard concrete composite (Omer et al., 2015). Numerous parameters impact the performance and properties of GC, such as sodium hydroxide dosages, sodium silicates/sodium hydroxide ratio, alkaline solution/binder ratio, curing ages and curing regime, water/solids ratio, type and elemental composition of source binder materials, Si/Al ratio in the GP system, blending time and rest period, fine and coarse content, and super-plasticizer dose and extra water content (Mohammed et al., 2021).

GPC is being extensively investigated and shown to be a promising alternative to PCC due to its greenness, mechanical properties, and durability (Qaidi et al., 2022a; Qaidi et al., 2022b). The number of studies on GPs has increased dramatically in this field. Despite significant studies being made in this respect, GPC needs global acceptance as a construction material. The critical issues related to GP applications can be summarized as follows (Ma et al., 2018):

- The production cost of GPC needs to be practically competitive with that of cement.
- A wide-ranging and reliable database is needed on the possibility of GPC in structural members.
- Founding new design guidelines for mixed and reinforced geopolymer concrete (R-GPC) structures is a prerequisite.

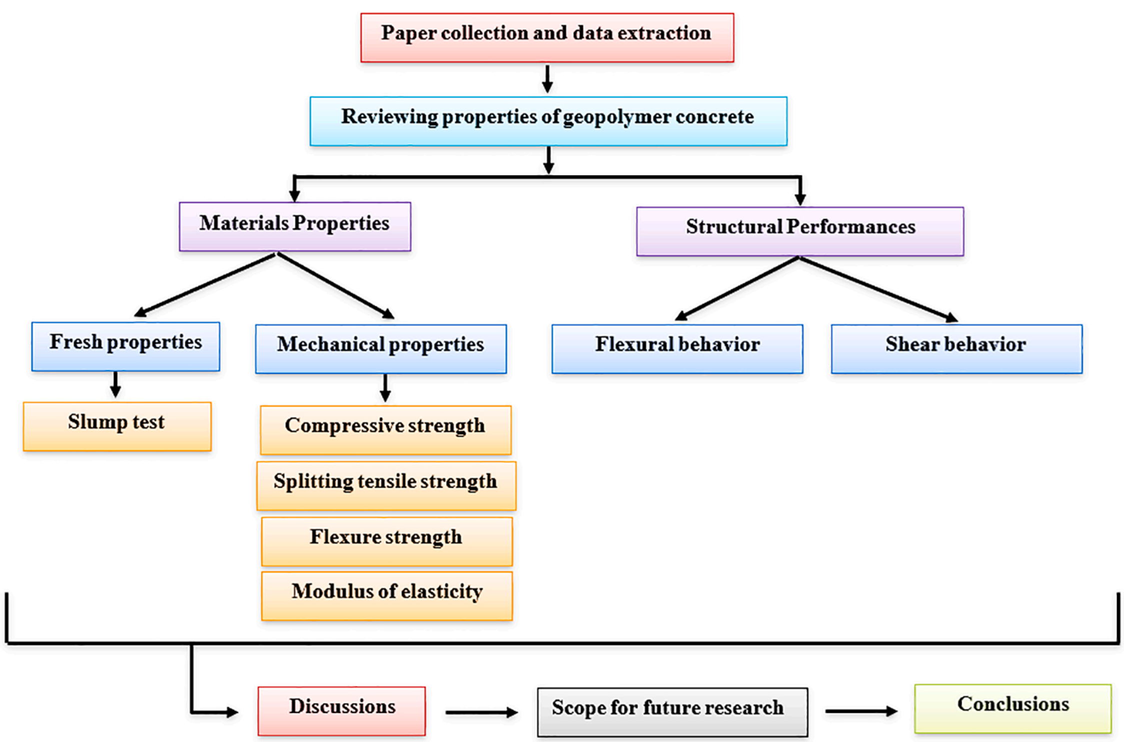

Fig. 1. The flowchart diagram describing the methodology utilized in this investigation.

While the majority of the research on GPC has focused on micro-scale materials studies, recently, a few researchers have extended the use of GPC to be tested on the structural behaviour of R-GPC members, including beams, slabs, columns, and panels (Mo et al., 2016). The performance of R-GPC elements should be ascertained with existing design codes to assess the possibility of using the concrete-cement-based design codes for GPC elements for the suitability of structural design

Table 1
Experimental and theoretical flexural moments at different stages (Dattatreya et al., 2011).

Samples ID	$M_{SL.E}$ (kN)	$M_{SL.T}$ (kN)	$M_{UL.E}$ (kN)	$M_{UL.T}$ (kN)	$M_{CR.E}$ (kN)	$M_{CR.T}$ (kN)
	As per IS-456	As per IS-456	As per IS-456	As per IS-456	As per ACI 318	As per ACI-318
C-1	39.0	21.5	13.24	11.45	2.13	1.66
C-2	48.0	30.7	17.04	16.18	2.26	1.92
C-3	56.0	35.7	17.34	18.88	2.26	2.24
GB-1	48.0	35.8	20.38	19.79	2.26	2.72
GB-2	45.0	35.4	19.25	19.40	2.26	2.62
GB-3	44.0	35.4	15.70	14.63	1.82	1.9
FB-1	26.0	20.5	8.45	10.26	1.53	0.87
FB-2	38.0	30.3	19.07	17.19	2.15	2.08
FB-3	39.0	35.2	20.22	19.23	1.98	2.47

Table 2
Crack width at the applied load of 40 kN (Dattatreya et al., 2011).

Samples ID	Total number of flexural cracks	Average crack width around service load (40kN), mm
C-1	40.0	0.124
C-2	37.0	0.22
C-3	37.0	0.24
GB-1	42.0	0.19
GB-2	40.0	0.25
GB-3	38.0	0.46
FB-1	23.0	/
FB-2	46.0	0.14
FB-3	48.0	0.29

engineers.

2. Research significance

The main purpose of this paper is to review and investigate the material properties and structural performance of GPCs. It was discovered that important research on the material characteristics and structural performance of GPCs have been conducted during the last decade. Moreover, previous review publications on GC highlighted material properties or structural properties but did not provide comprehensive information on this issue in a single paper. In addition, additional relevant study publications that had not been covered in prior review articles were recently published. Thus, this research presents a state-of-the-art review of all recent and current research on GPC materials and structural performance. Based on what the author knows, this is the first review article of this topic. It comprises a systematic review, analysis, and discussion to help researchers and the construction industry get a better understanding of the topic by giving relevant information about small and large-scale GPC samples.

3. Methodology

The authors reviewed many databases, including Scopus, Science Direct, the Web of Science, Research Gate, and Google Scholar. A large number of studies on the material properties and structural performance of GPC have been identified. The most important and frequent parameters of GC described and addressed in earlier articles are slump, compressive strength, flexural strength, splitting tensile strength, modulus of elasticity, and various structural behaviours including shear and flexural behaviour of GPC beams. Fig. 1 is a flow chart that

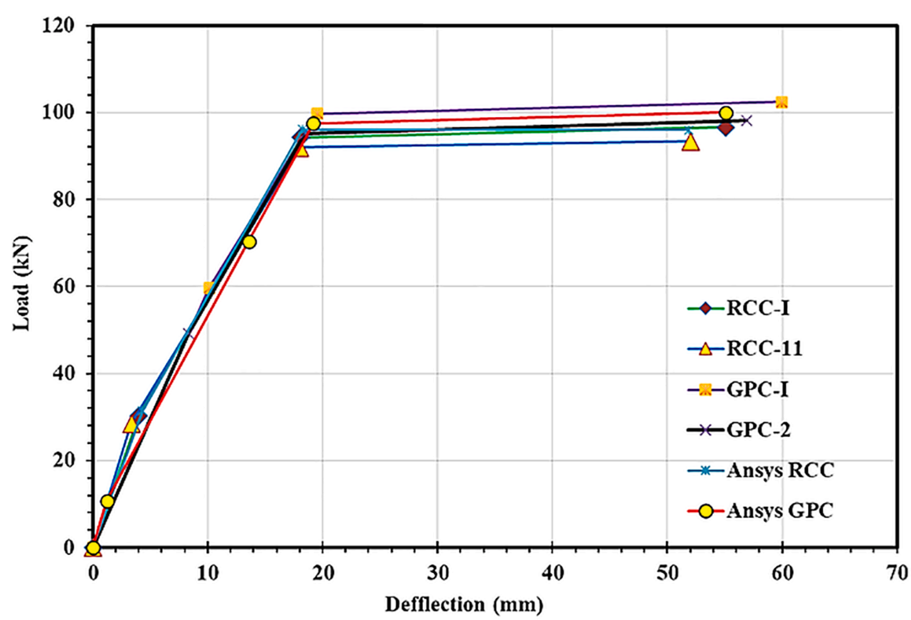

Fig. 2. Load- deflection curves ().
adapted from Kumaravel and Thirugnanasambandam, 2013a

Table 3
Summary of test and numerical results (Kumaravel and Thirugnanasambandam, 2013a).

SI. NO.	Beam code	1st crack load (kN)	Service load (kN)	Yield load (kN)	Max. deflection (mm)		Ultimate load (kN)	
					Experimental	Numerical (ANSYS)	Experimental	Numerical (ANSYS)
1	RC-I	20	64.67	95	55	53	97	96
2	RC-II	17.5	62.34	92.5	52	53	93.5	96
3	GP-I	20	68.34	100	60	55	102.5	100
4	GP-II	20	65	97.5	57	55	98.5	100

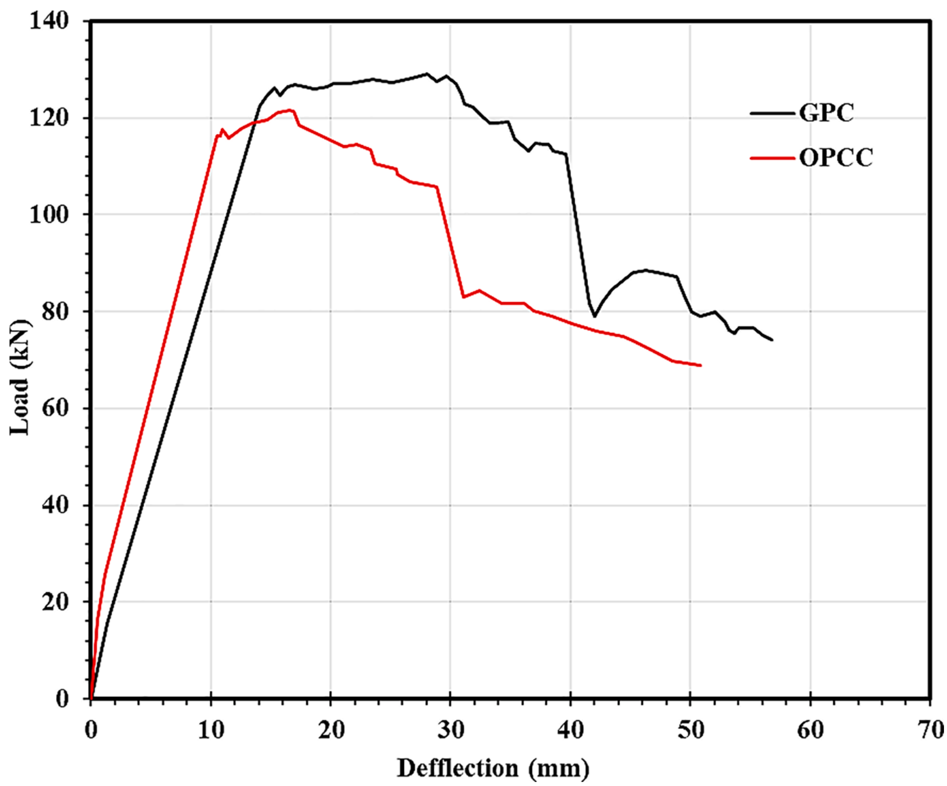

Fig. 3. Load-deflection curves ().
adapted from Pelisser et al., 2018

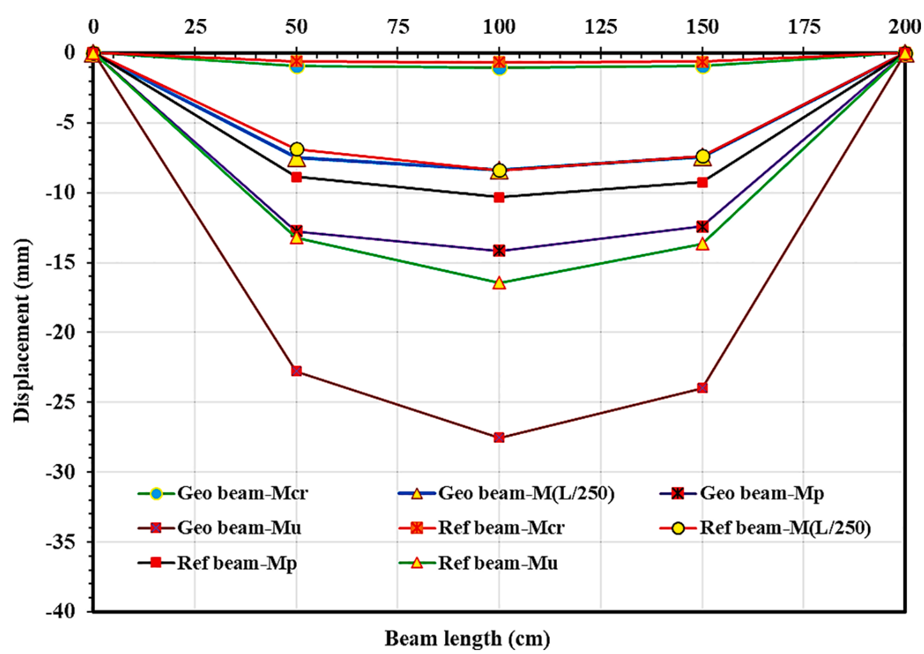

Fig. 4. Deflection-length curves at critical phases ().
adapted from Pelisser et al., 2018

summarizes further facts regarding the approach of this work.

4. Materials properties of geopolymer concrete

4.1. Fresh properties

In the field of concrete technology, the term "workability" denotes to the behaviour of fresh concrete. It is described as the useful internal work necessary to complete the compaction of the concrete (Ahmed et al., 2021c). Slump flow, slump cone, flow table, vebe, and compacting factor tests, as with conventional concrete, can be used to determine the workability of GPC.

The workability of GPC mixes varied according to the activator's molarity, superplasticizer dosages, and extra water content (Hardjito

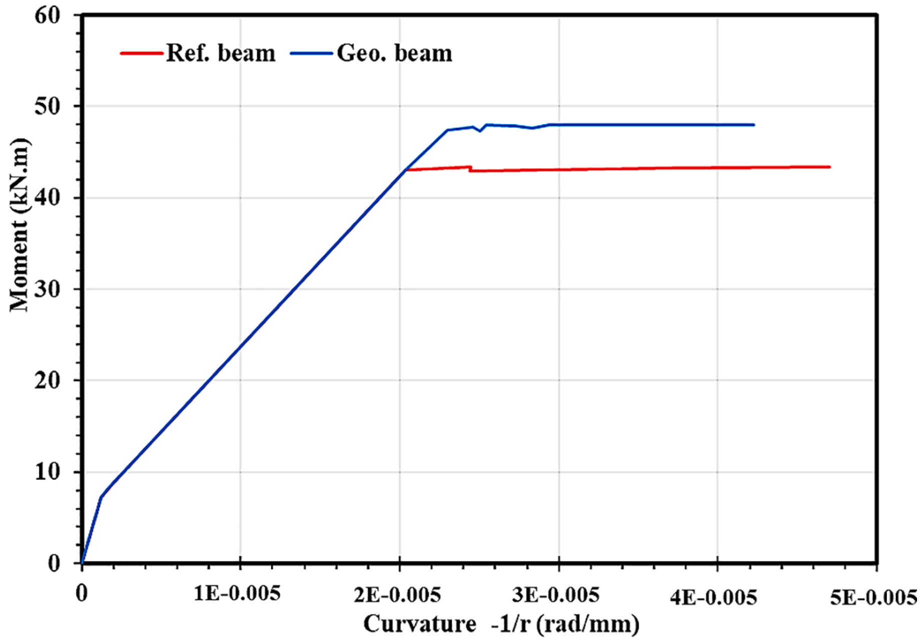

Fig. 5. Moment curvature curve ().
adapted from Pelisser et al., 2018

Table 4
Experimental Cracking moment vs. deflection (Sumajouw and Rangan, 2006).

Beam	CS (MPa)	Tensilereinforcement ratio (%)	Cracking moment, $M_{cr,}$ (kN.m)
GI-1	36	0.65	13.5
GI-2	41	1.19	13.56
GI-3	41	1.85	13.52
GI-4	36	2.68	14.32
GII-1	45	0.65	15.1
GII-2	52	1.19	16.3
GII-3	52	1.85	16.66
GII-4	45	2.68	16.06
GIII-1	75	0.65	19.2
GIII-2	71	1.19	20.1
GIII-3	71	1.85	21.1
GIII-4	75	2.68	19.2

Table 5
Experimental ultimate moment versus deflection (Sumajouw and Rangan, 2006).

Beam	CS (MPa)	Tensilere inforcement ratio (%)	Mid-span deflection at failure load (mm)	Experimental ultimate moment (kN.m)
GI-1	36	0.65	56.64	56.29
GI-2	41	1.19	46.02	87.66
GI-3	41	1.85	27.88	116.86
GI-4	36	2.68	29.23	162.45
GII-1	45	0.65	54.26	58.36
GII-2	52	1.19	47.21	90.57
GII-3	52	1.85	30.02	119.1
GII-4	45	2.68	27.48	168.65
GIII-1	75	0.65	69.76	64.85
GIII-2	71	1.19	40.68	92.85
GIII-3	71	1.85	34.03	126.75
GIII-4	75	2.68	35.86	179.94

et al., 2004). Farhan et al. (2019) studied the fresh characteristics of normal and high-strength FA- and GGBFS-based geopolymer concrete in comparison to traditional concrete. It was noticed that the workability of normal strength FA- and GGBFS-based GPC, as well as conventional concrete, was sufficient to be easily handled, placed, compacted, and finished. However, in the case of high-strength concrete, the workability of FA- and GGBFS-based GPC and traditional concrete decreased as the liquid/binder content declined and binder content increased. Furthermore, the viscosity of the alkaline solution rose as the molarity of NaOH increased, resulting in an extremely sticky mixture. Consequently, the workability of FA- and GGBFS-based GPC was diminished. Furthermore, Ghafoor et al. (2021) found that increasing the alkaline solution/binder ratio increased the workability of FA-based GPC. While a reduction in the workability of the GPC mix was observed with the increment in the molarity of NaOH (Ganesh and Muthukannan, 2019). Tests by Albitar et al. (2015) showed that the workability of the GPC mixture was enhanced by adding a superplasticizer and extra water content. Likewise, Joseph and Mathew (2012) reported that the workability of geopolymer concrete increased nearly linearly as the ratio of total water to GP solid increased. In the same vein, Aliabdo et al. (2016) demonstrated that the workability of the GPC mix increased as the content of superplasticizer, extra water content, and the alkaline solution/binder ratio increased, while increasing the molarity of NaOH and SS/SH ratio adversely affected the workability of GPC. Similarly, it was reported that the workability of GPC decreased with increasing the molarity of sodium hydroxide and total aggregate content (Chithambaram et al., 2018).

Suresh Kumar et al. (2022a) studied the utilization of different percentages (5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, and 50%) of waste glass powders as the sand replacement to enhance the behaviour of hazardous incineration bio-medical waste ash GPC. Their findings indicated that the slump value of the GPC was rose as the dosage of glass powder rose, up to a 40% replacement of fine aggregate with glass powder, and after that, a steady-state regarding the workability was reported.

Nuaklong et al. (2020) found that including nano-silica to a GPC mix reduced its rheology, particularly at high content substitution. When

Table 6
Service and failure load versus various deflections (Sumajouw and Rangan, 2006).

Beam	CS (MPa)	Tensilere inforcement ratio (%)	Service load-P_s (kN)	Δ_s (mm)	Failure load, P_u (kN)	Δ_u (mm)
GI-1	36	0.65	74	13.45	112.59	56.64
GI-2	41	1.19	116	15.26	175.29	46.02
GI-3	41	1.85	155	13.70	233.69	27.88
GI-4	36	2.68	216	15.59	325.1	29.23
GII-1	45	0.65	77	14.24	116.69	54.28
GII-2	52	1.19	120	14.37	181.09	47.21
GII-3	52	1.85	158	13.32	238.1	30.02
GII-4	45	2.68	224	16.15	337.19	27.48
GIII-1	75	0.65	86	14.09	129.79	69.76
GIII-2	71	1.19	123	12.54	185.79	40.68
GIII-3	71	1.85	168	12.37	253.59	34.03
GIII-4	75	2.68	241.5	14.87	359.88	35.84

Table 7
Experimental deflection versus ANSYS prediction (Kumar and Ramesh, 2018).

Mixes ID	$\Delta_{Exp.}$ (mm)	Δ_{Ansys} (mm)	$\Delta_{Exp}/\Delta_{Ansys}$
OPC	3.44	3.07	1.12
Mix-1	1.90	1.66	1.14
Mix-2	2.11	1.86	1.13
Mix 3	2.35	2.09	1.12
Mix-4	2.47	2.21	1.12
Mix-5	2.56	2.37	1.08
Mix-6	2.88	2.64	1.09
Mix-7	3.05	2.86	1.07
Mix-8	3.07	2.99	1.03
Mix-9	3.23	3.16	1.02
Mix-10	3.34	3.26	1.02
Mix-11	3.46	3.39	1.02

compared to the control GPC mixture, the highest decline in slump flow of the GPC was 17% at 3.0% nano-silica volume. Nevertheless, Saini and Vattipalli (2020) discovered that adding 2.0% nano-silica to the GPC mix raised the slump flow from 660 mm to 670 mm. In general, increasing the content of nanoparticles, independent of their type, affected the fresh characteristics of GC, which was associated with the increased alkaline solution and water demand. Moreover, other studies found that the workability of GC increased with rising nanomaterial quantities owing to the ball bearing affect caused by the spherical particles form of the nanoparticles. As a result, additional studies are needed to determine if nanoparticles improve the workability of GC or not.

4.2. Mechanical properties

4.2.1. Compressive strength

Compressive strength (CS) is an important property of all concrete composite, including GPC. The CS assesses the overall performance of the concrete (Ahmed et al., 2022c). The CS of concrete at 28-d, on the other hand, is crucial in building construction and structural design. The literature comprehensively investigated the CS property for different GC types with different mixture proportions, curing temperatures, and ages. Those mixture proportion factors, curing temperature, and ages that affect the compressive strength of GPC are discussed briefly here.

Based on an extensive and systematic study carried out by Ahmed et al. (2021a) on the effect of various mixture proportions, curing temperatures, and curing ages on the compressive strength of GPC; type, chemical composition, and amount of binder, alkaline solution/binder ratio, the concentration of NaOH (M), the ratio of Na2SiO3/NaOH (SS/SH), extra water content, curing temperatures, and specimen ages are those factors that directly affect the compressive strength of geopolymer concrete composites.

According to Aliabdo et al. (2016), when the Na2SiO3/NaOH ratio, molarity, chemical admixture, and extra water content were maintained at 0.4, 16, 10.5 kg/m^3, and 35 kg/m^3, respectively, the CS of GPC was increased with an increase in the alkaline solution/binder ratio up to 0.40 and then reversed, while Joseph and Mathew (2012) found that the CS of geopolymer concrete was enhanced up to the ratio of alkaline solution/binder ratio of 0.55. Likewise, Shehab et al. (2016) found that increasing the alkaline solution/binder ratio, improved the CS of GPC after specimen ages of 7- and 28-d. However, some research demonstrated that the CS of GPC decreased as the l/b ratio increased (Vora and Dave, 2013).

The molarity of NaOH is another issue that scholars have comprehensively studied. Some research studies claimed that the molarity value of 12 M gives the highest CS to GPC (Chithambaram et al., 2018), while some scholars demonstrated that the optimum molarity value is 13 M (Kumar et al., 2020; Ganesh and Muthukannan, 2019), and 14 M (Ghafoor et al., 2021). These experiments are not compatible with other research findings in which they reported that the molarity of 16 produced GPC with the highest CS (Aliabdo et al., 2016). In contrast, work by Joseph and Mathew (2012) suggested using a molarity of 10 to reach maximum CS. Typically, raising the molarity of NaOH enhances the CS of geopolymer concrete composites, which could be related to the total dissolution of silicon and aluminium particles through the polymerisation process (Ahmed et al., 2021a). Moreover, Varaprasad and Reddy (2010) asserted that increasing the molarity improved the CS. For instance, they stated that the CS of FA-based GPC was enhanced by 8.55%, 14.75%, and 19.22% at 12 M, 14 M, and 16 M, respectively, when compared to 10 M at a curing temperature of 60 °C after 28-d. As a general rule, sodium hydroxide with a higher molarity improves the CS of the GPC composites, which could be because aluminium and silicon particles are entirely broken down during the polymerisation process; Al and Si particles dissolve more quickly when the concentration of sodium hydroxide is higher. This makes GPC mixtures with more sodium hydroxide stronger (Ahmed et al., 2021a).

In addition, the ratio of Na2SiO3 to NaOH (SS/SH) is another effective factor that governs the CS of GPC. Tests by Al-Azzawi et al. (2018) demonstrated that when the ratio of SS/SH was increased in GPC mixes, the CS increased, despite FA levels ranging from 300 to 500 kg/m^3. A wide range of this parameter was examined in the literature to reveal its effects on the CS of GPC. It was found that the ratio of SS/SH can be effectively used to prepare GPC with sufficient CS in the range of 1.0 to 3.0, with 2.5 being the most frequently and effectively employed (Hardjito et al., 2004; Joseph and Mathew, 2012). However, less research indicates that the CS of GPC is reduced when the SS/SH ratio rises (Vora and Dave, 2013; Ghafoor et al., 2021).

Extra water content and superplasticizer dosages are those factors that have been dealt with by scholars in their previous research work. Hardjito et al. (2004) noticed that adding superplasticizer to the GPC up to 2% of the binder improved the fresh properties as well as the CS, while, beyond that dosage, the addition of superplasticizer adversely affects the CS of fly ash-based GPC. Also, they reported that the extra water content in fly ash-based GPC reduced the CS significantly. Similarly, it is well documented in the literature that the addition of excess water to the GPC mixture will lead to a decline in the CS property (Al-Azzawi et al., 2018; Aliabdo et al., 2016; Joseph and Mathew, 2012).

Regarding curing regimes, ambient, oven, and steam curing conditions were widely employed to cure GPC composites. Selecting the curing regime types relies on the type and chemical composition of the used source binder materials. For instance, compared to other curing conditions, most studies cured the fly ash-based GPC using oven curing conditions and then ambient curing conditions followed by steam curing conditions (Ahmed et al. 2021a). Tests by Hardjito et al. (2004) showed that the compressive strength of GPCs increased as the curing

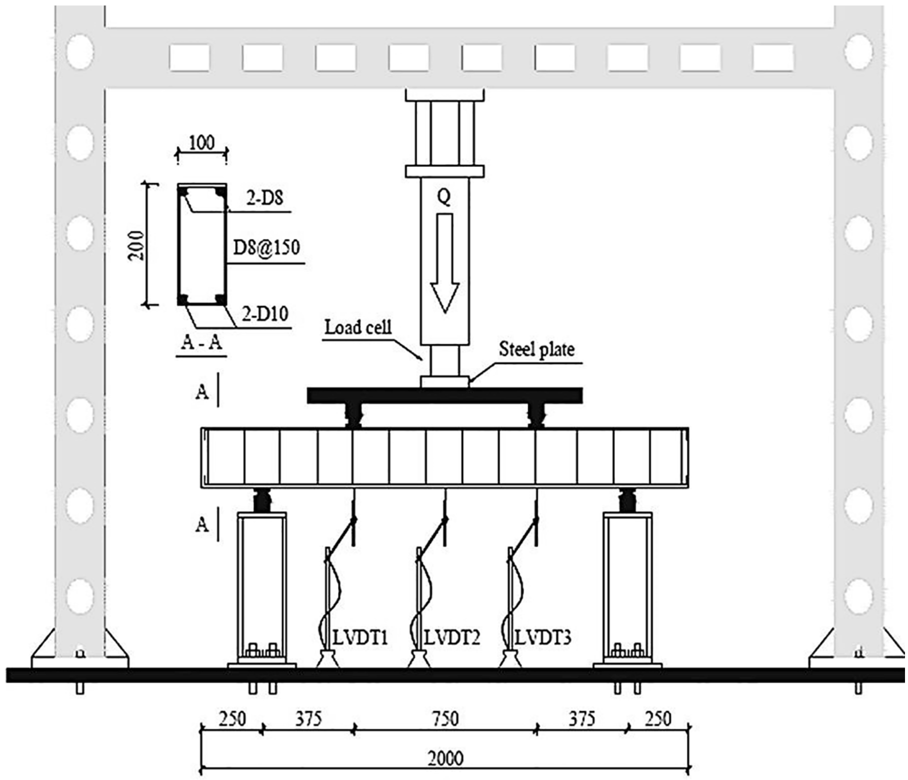

Fig. 6. Schematic test set up (Nguyen et al., 2016).

temperature increased. However, they found that beyond the curing temperature of 60 °C, this rise in CS was not substantial. According to Jindal et al. (2017), the CS of FA-based GPC samples treated in an oven is higher than those cured in ambient curing regimes. Other research has shown similar findings, although using varied ambient and oven curing conditions (Albitar et al., 2014; Hassan et al., 2019). On the other hand, various studies, on the other hand, evaluated the curing periods of GPC samples within ovens. It was discovered that curing time within ovens ranging from 24 to 48 h is sufficient for achieving the requisite CS of GPC (Hardjito et al., 2004; Joseph and Mathew, 2012). Therefore, it is suggested to use oven curing temperatures in the range of 60–100 °C and a curing time inside ovens of 24 hr to get GPC with an acceptable CS. Furthermore, ambient curing conditions were successfully used to cure GGBFS-based GPC (Hadi et al., 2017), and GPC composites incorporated nanoparticles with adequate CS (Ravitheja and Kumar, 2019).

Furthermore, it is interesting to consider the influence of various factors on the CS of GPC. The optimal total aggregate content, according to Joseph and Mathew (2012), is 70%, while the optimal fine/coarse aggregate ratio is 35%. Saini and Vattipalli (2020) observed that adding 2% nano-silica to self-compacting GPC increased its workability, mechanical characteristics, and durability. Kumar et al. (2020) observed that replacing 7% of the GGBFS source binder ingredients with biomedical waste ash raised the CS by 13.07%.

Finally, efforts have been made to correlate different geopolymer concrete mixtures, curing temperatures, and specimen ages with the CS of different geopolymer concretes. For instance, Ahmed et al. (2022d) and Ahmed et al. (2022e) developed different models like non regression, linear regression, multilogistic regression, artificial neural network, and M5P-tree models to prediction the compressive strength of blended GGBFS/FA-based GPC and GPC modified with nano silica, respectively. They used different statistical tools to evaluate their proposed models. Their findings demonstrated that the artificial neural network model predicted the compressive strength of GPC's with greater accuracy than the other models. The alkaline solution/binder ratio, sodium hydroxide concentration, molarity, curing temperature, and ages, on the other hand, were the parameters that had a substantial influence on the CS of GPC (Ahmed et al., 2022d; Ahmed et al., 2022e).

4.2.2. Splitting tensile and flexural strengths

Another essential mechanical characteristic of GC is splitting tensile strength (STS), which can be evaluated indirectly via AS EN 12390-6 or ASTM C-496 standard test procedures. The STS, also denoted to as the Brazilian test or indirect tensile test, is a technique for indirectly measuring and evaluating the tensile performance of concrete composite. Flexural strength (FS), often known as modulus of rupture, is another indirect method for determining the tensile strength of concrete. This characteristic is crucial for bending concrete elements, including sidewalks, beams, and RC slabs. The FS of GC is determined using the same standard test procedures used for typical PCC composites, such as BS EN 12390-5, ASTM C-293, or ASTM C-78. The STS and FS of GPC exhibit a similar trend to CS, and in general, increasing CS is associated with an increase in STS and FS (Mohammed et al., 2021). As a result, these two characteristics are governed by the CS parameters described in Section 3.2. Some researchers, however, have noticed some deviations from this common response.

According to Ryu et al. (2013), the rate of STS improvement was slower than the CS enhancement. In the same context, it was reported that replacing FA with GGBFS had a lower impact on both STS and FS compared to the CS (Abhilash et al., 2016). Regardless of the fact that this alteration enhances the CS of their GPC samples, investigations by Oderji et al. (2019) demonstrated a drop in FS when the FA substitution with SG rose from 15 to 20%. However, in contrast to the elastic modulus of GPC, Hassan et al. (2019) show that preheating GPC at 75 °C for 26 hrs considerably enhances both CS and FS. Saravanan and Elavenil (2018) discovered that, in contrast to CS, when 50% of FA is substituted with GGBFS, there is a considerable rise in STS. When the data from Partha et al. (2013) was compared to the other data, it was seen that using a specific heat curing improves the FS/CS ratios and, to a lesser extent, the STS/CS ratios compared to curing at ambient temperature.

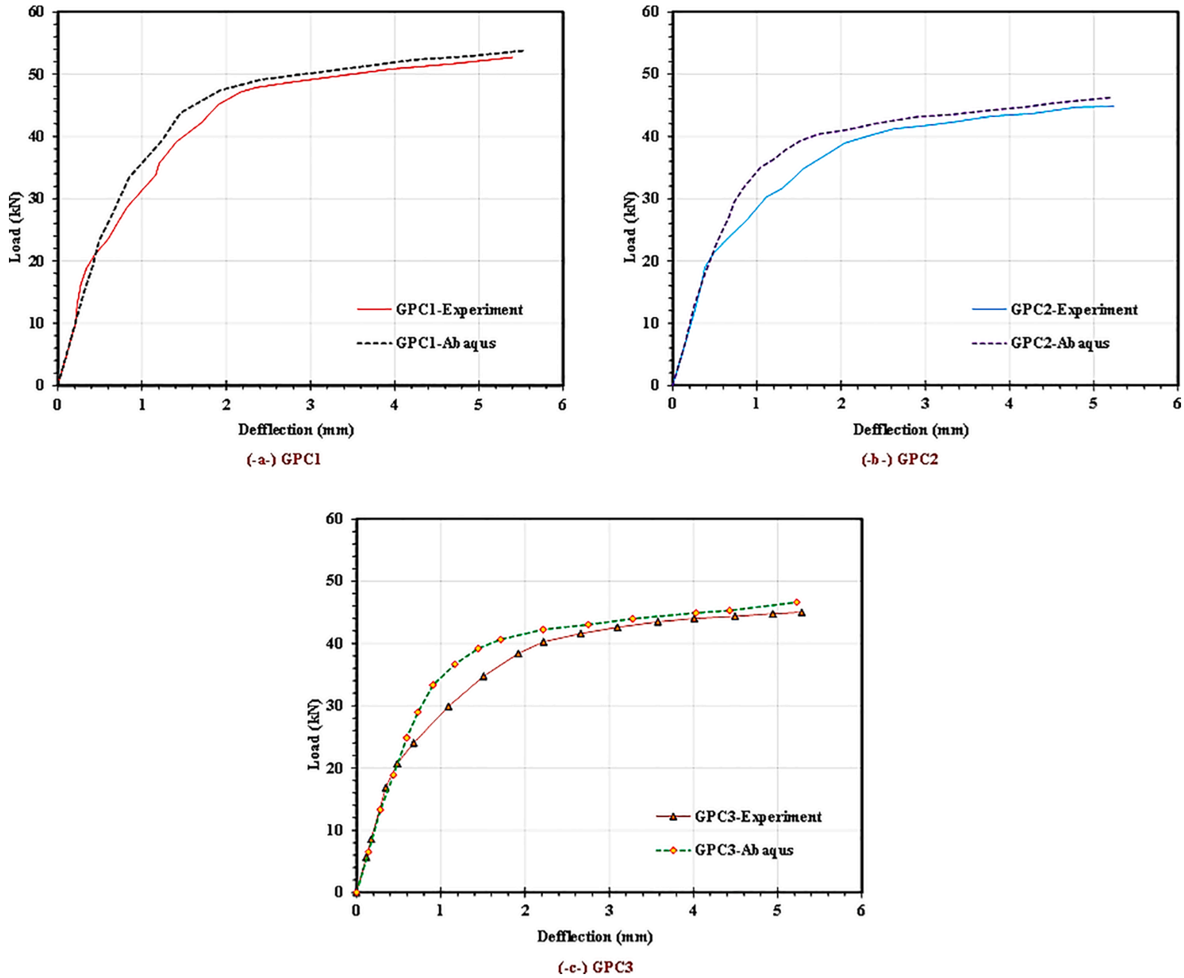

Fig. 7. Load-deflection curves ().
adapted from Nguyen et al., 2016

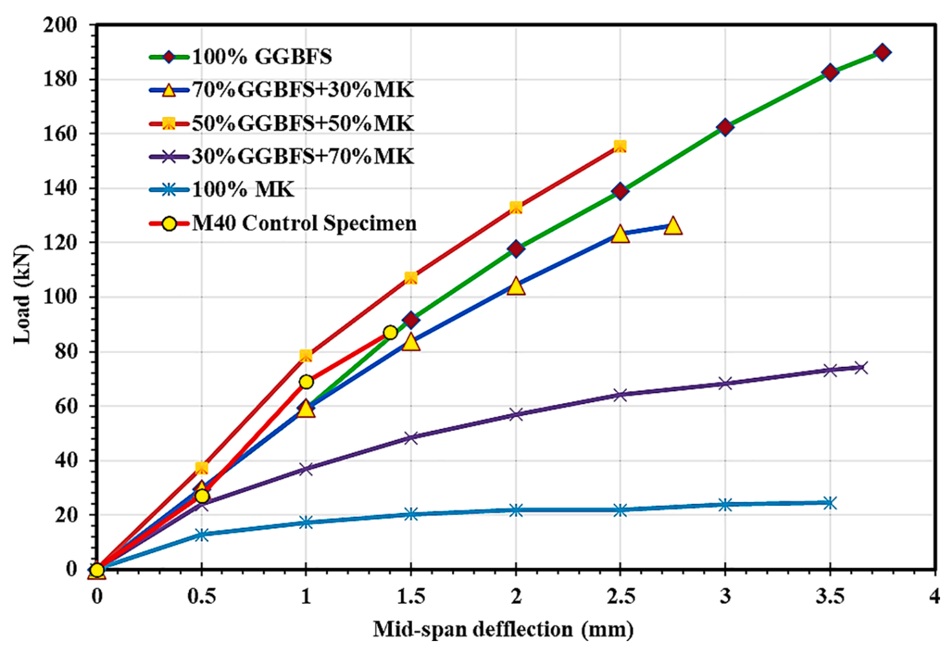

Fig. 8. Load-deflection curves ().
adapted from Kumar and Kumar, 2016

Table 8
Summary of results (Kumaravel et al., 2014).

SI. NO.	Beam code	1st crack load (kN)	Service load (kN)	Yield load (kN)	Max. deflection (mm)		Ultimate load (kN)	
					Experimental	Numerical (ANSYS)	Experimental	Numerical (ANSYS)
1	RC-I	15	48	70	71	75	72	75
2	RC-II	17.5	49.67	72.5	75	75	74.5	75
3	GP-I	20	49.34	72.5	80	80	74	77.5
4	GP-II	20.25	51	75	80	80	76.5	77.5

Rabiaa et al. (2020) demonstrated that the STS and FS of GPC were improved by adding nano-silica and nano-MK to the GPC mixture. They found that the optimum dosage of these two nanomaterials was 4% and 6% of their binder content for nano-silica and nano-MK, respectively. Other researchers have reported similar results of enhancing both STS and FS of GPC with the addition of nano-silica, despite the fact that different doses of nano-silica were utilized (Adak et al., 2017; Saini and Vattipalli, 2020). In contrast to these previous findings, fewer studies concluded that introducing nano-silica resulted in a modest drop in the STS and FS of the GPC (Nuaklong et al., 2020; Çevik et al., 2018). This finding could be attributed to improper nano-silica particle distribution, which produced weak zones within the concrete mixtures, or tensile failure can happen within the weak aggregate particles rather than the ITZ among the potent binder pastes and the aggregate particles (Nuaklong et al., 2020). Tests by Arunkumar et al. (2022b) have been done to show the effects of hybridization between different volume fractions of polypropylene (PP) and waste rubber fibres on the mechanical characteristics of GPC; they employed various percentages of PP and waste rubber fibres alone and in hybrid situations; they concluded that the maximum STS and FS were obtained with the hybridization between 0.5% of PP and 0.5% of waste rubber fibres. Similarly, the highest electrical resistivity was reported for the hybridization between 0.5% of PP and 0.5% of waste rubber fibre in waste wood ash-based GPC composites (Arunkumar et al., 2021). Furthermore, Suresh Kumar et al. (2021) highlighted that the FS of GGBS-based GPC mixtures improved by 55.81% when 30% of the GGBS was replaced with incinerated biomedical waste ash due to the good polymerisation action and the generation of CASH and CSH gels to become a pore structure.

Finally, Mohammed et al. (2021) proposed an empirical equation based on 597 data points to predict the STS from the value of the CS of GPC as shown in equation (1). In the same way, they came up with another empirical equation, shown in equation (2), to estimate the FS of GPC.

$STS = 0.222\,(CS)^{0.7436}$ ………. (1); $FS = 0.293\,(CS)^{0.7647}$ ………. (2).

Where: STS, CS, and FS are measured in MPa.

4.2.3. Modulus of elasticity (ME)

The modulus of elasticity (ME) is an important parameter for cementitious materials, particularly GC, since it indicates the stiffness of the material in the elastic stage. GC with a greater ME offers better deformation resistance. The ASTM C-469 standard test procedure is used to determine the ME value of GC.

The ME of GPC follows the same trend as the CS of GPC, and according to Hardjito's (2005) tests, the ME of GPC increases with increasing the CS. According to Nath and Sarker (2017), the curing regime has no discernible influence on the ME of geopolymer concrete. However, Saravanan and Elavenil (2018) discovered that, in contrast to CS, there is a significant ME enhancement when 50% of FA is substituted with GGBFS. Moreover, Farhan et al. (2019) studied the mechanical characteristics of normal and high-strength FA- and GGBFS-based geopolymer concrete compared to traditional concrete. They reported that the value of ME at the age of 28-d was 16.63, 16.59, and 17.98 GPa for normal strength (35 MPa) FA-based GPC, GGBFS-based GPC, and conventional concrete, respectively; while, these values were slightly increased to 19.46, 19.36, and 20.95 for high-strength (65 MPa) FA-based GPC, GGBFS-based GPC, and conventional concrete, correspondingly. In the same manner, Ghafoor et al. (2021) claimed that the ME of FA-based GPC cured at ambient conditions increased with increasing the molarity of sodium hydroxide until 14 molarity, and then it declined. The ME of GPC improved by approximately 78.9%, 41.1%, and 96.4%, respectively, when the concentration of NaOH was increased from 8 to 10 M, 10 to 12 M, and 12 to 14 M. However, minor differences in the ME were observed when the Na_2SiO_3/NaOH and alkaline activator/FA ratios were varied (Ghafoor et al., 2021).

In terms of employing nanomaterials to improve various properties of GPC composites, adding 6% nano-silica to the GPC mix raised the ME by roughly 21% compared to the reference samples (Adak et al., 2017). Furthermore, Ibrahim et al. (2018) discovered that increasing the nano-silica concentration enhanced the ME by up to 5%, but then reduced it at the curing ages of 28- and 90-d. For example, at 1%, 2.5%, 5%, and 7.5% nano-silica doses, the ME of the GPC rose by 9.6%, 24.6%, 97.5%, and 85.6%, respectively. Predicting the value of ME from the CS of GPC composites was another issue studied by Mohammed et al. (2021). They provided two empirical equations to forecast the ME of GPC composites based on the value of CS and density of the composite, as shown in equations (3) and (4).

$ME = 479.4 + 692.41\ CS$ ………. (3); $ME = 4{*}10^{-6}\,(\gamma_c)^{2.666}\,(CS)^{0.5}$ ………. (4).

Where: γc is the density of GPC in kg/m^3, while ME and CS are measured in MPa.

5. Structural performances of geopolymer concrete

5.1. Flexural behaviour of geopolymer concrete beams

Several studies have been conducted on the flexural behaviour of RC beams made with geopolymer concrete. Some researchers used reinforced normal concrete beams with the same conditions for evaluating the GPC performance in the structural beams in terms of the cracking moment, service moment, ultimate moment, and defection at different stages of loading. The following summarizes the work regarding the flexural behaviour of R-GPC beams.

Dattatreya et al. (2011) tested nine beams for flexural failure using two-point static loading tests. Three standard concrete mixtures and six GPC mixtures with goal strengths ranging from 17 to 63 MPa were utilized as a binder, using slag and FA combinations. The beams were constructed with tension reinforcement ranging from 1.80% to 3.30%. Table 1 shows the experimental and code anticipated flexural moment capacity values at cracking, service load, and ultimate load for reference and GPC beams. The comparison was poor for GPC beams, which had lower flexural strength than estimated by code recommendations. The theoretical ultimate moment capacity differed from the actual data by 0.8% to 16.95%, and they were compatible in the range of 88 to 98% of the experimental value for GPC beams, which leans towards conservatism. Table 2 illustrates the crack width for the investigation at 40 kN applied stresses. The crack widths were quite close to those of reference beams. The amount of cracking in most geopolymer concrete beams, however, was somewhat higher than in reference beams. The load-carrying capacity of most GPC beams was found to be greater than that of the comparable PCC beams. GPC beams had greater deflections at several phases, such as the service load and ultimate load stages. The ductility factor, on the other hand, was equivalent to that of PCC beams.

Table 9
Summary of flexural and shear behavior of geopolymer concrete beams.

References	variables	Findings
Sumajouw et al., 2005	Reinforcement ratio	Similar to the behavior of typical RC beams, increasing the reinforcement ratio increases flexural strength.
Sumajouw and Rangan, 2006	concrete CS, and Reinforcement ratio	In terms of flexural capacity and ductility, the affect of reinforcement ratio on GPC beams is nearly identical to that of conventional RC beams.
Dattatreya et al., 2011	FA-slag ratio	GPC beams exhibited greater deflections at distinct stages. Nonetheless, the factor of ductility was comparable to that of traditional concrete beams.
Kumaravel and Thirugnanasambandam, 2013a	Concrete types	The deflections at various phases, such as service and ultimate loads phases, are slightly higher for geopolymer concrer beams.
Srinivasan et al., 2014	Glass fiber content	With glass fiber, flexural capacity increases by roughly 35%. Overuse of fiber led to a decline in capacity.
Devika and Deepthi, 2015	Proportion of steel fiber and hybrid polypropylene	With the addition of hybrid steel-polypropylene fiber, flexural capacity increased by 30 percent.
Maranan et al., 2015	FRP bottom diameters	All examined beams exhibited the same load–deflection response, cracking pattern, deflection capacity, and bending moment, as well as strain readings identical to those obtained from normal beams.
Ferdous et al., 2015	Fly-ash; slag	In general, the strength capacities of the slag-based GPC beams were slightly higher than those of the standard concrete beams.
Kathirvel and Kaliyaperumal, 2016	Proportion of recycled aggregate	Greater number and width of cracks, but enhanced deflection and ductility
Antonyamaladhas et al., 2016	Geometry of the beam	Analysis showed that the experimental results were very close to what the ANSYS software came up with.
Kathirvel and Kaliyaperumal, 2016	Recycled aggregate dosage	It was noted that the failure of all the beams was due to the creation of flexural cracks, with no indication of shear cracks.
Kumar and Ramesh, 2018	GGBFS and Metakaolin ratio	GPC beams were found to be comparable to reinforced cement concrete beams.
Ahmed et al., 2020	reinforcement ratio, compressive strength, and concrete types	They concluded that GPC beams exhibited a modest increase in deflection and roughly the same ultimate load as conventional concrete beams, but a smaller crack width than conventional concrete beams.
Arunachalam et al., 2021	Concrete mixture	The geopolymer concrete containing 30% IBWA demonstrated high load carrying capacity, ultimate strength, stiffness, ductility, and deformation capacity.
Suresh et al., 2022	Waste glass powder dosage	Geopolymer concrete beams incorporating 50% waste glass powder as fine aggregate displayed a considerable increase in crack resistance, serviceability, and ductility when compared to ordinary concrete beams.

Table 10
Shear cracking loads (Chang et al., 2009).

Series	Beam mark	P_{si} (%)	P_{sv} (%)	fc' (MPa)	Shear cracking load (kN)
1	SH1-1	1.73	0.11	44	85
	SH1-2		0.14	44	84
	SH1-3		0.18	43	81
2	SH2-1	2.31	0.11	55	79
	SH2-2		0.14	49	87
	SH2-3		0.18	49	97
3	SH3-1	3.13	0.11	48	79
	SH3-2		0.14	48	93
	SH3-3		0.18	55	111

Table 11
Test results of shear strength (Chang et al., 2009).

Series	Beam mark	P_{si} (%)	P_{sv} (%)	fc' (MPa)	Peak load (kN)	Test shear strength (kN)
1	SH1-1	1.73	0.11	44	414	210.4
	SH1-2		0.14	44	403	204.9
	SH1-3		0.18	43	369	187.9
2	SH2-1	2.31	0.11	55	510	258.4
	SH2-2		0.14	49	518	262.4
	SH2-3		0.18	49	515	260.9
3	SH3-1	3.13	0.11	48	522	261.6
	SH3-2		0.14	48	551	276.3
	SH3-3		0.18	55	660	333.4

The review illustrates that for R-GPC flexural beams, traditional RC theory could be utilized to determine deflection, moment capacity, and crack width within acceptable limitations.

Antonyamaladhas et al. (2016) performed experimental and theoretical research on the behaviour and performance of GGBFS introduced to GPC structural components. The L-section and regular-section GPC beams were studied. The strength and weight ratio of GPC were much larger than those of traditional concrete beams in corresponding samples, according to the findings. The experimental findings closely matched the output of the ANSYS program, according to the analytical results.

Kumaravel and Thirugnanasambandam (2013a) studied the flexural behavior of GPC and reference PCC beams with CS of up to 50 MPa. Four beams were cast across a 3000 mm effective span and tested for failure under static stresses. The load–displacement response of the GPC and reference beams is obtained and compared to the numerical findings presented in Fig. 2. As can be observed, the curves have essentially identical patterns. The findings for the beams at crucial phases are

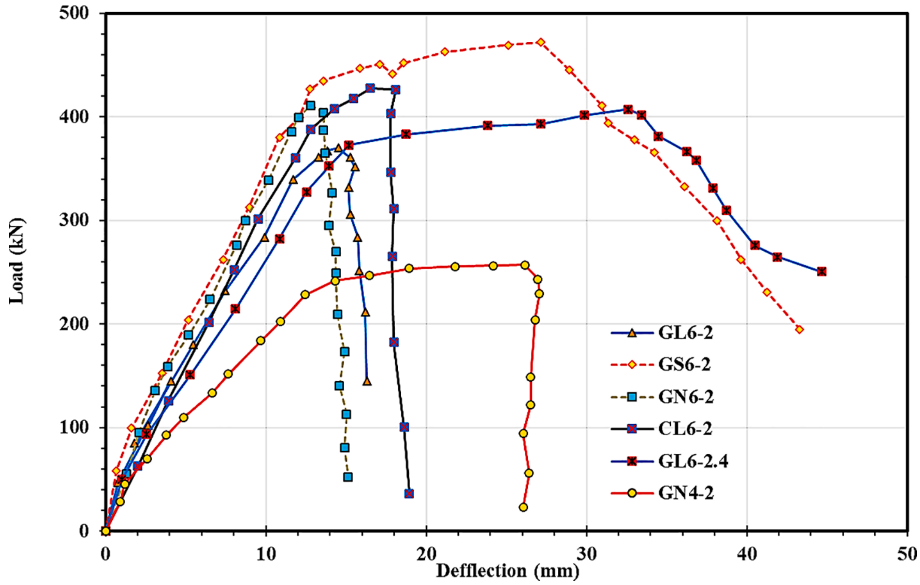

Fig. 9. Load-deflection responses ().
adapted from Yacob, 2016

Table 12
Summary of test results (Yacob, 2016).

Beam ID	Failure mode [a]	V_{test}, kN	$v_{test} = V_{test}/b_w$ d (MPa)	$v_{test}/\sqrt{fc'}$
GN6-2	Shear	209	3.94	0.64
GN4-2		127	2.39	0.44
GL6-2		213	4.04	———
GL6-2	Torsion-shear	185	3.50	———
GL6-2.4		202	3.82	———
GS6-2	Flexure-shear	236	4.47	———

Table 13
Test results of the beams (Visintin et al., 2017).

ID	fc' (MPa)	f_{ct} (MPa)	V_{st} (kN)	P (kN)
B1-T1	20	2.92	79.1	98.9
B1-T2			31.2	48.0
B2-T1	23	3.1	72.2	96.2
B2-T2			65.9	94.1
B3-T1	32	3.55	82.5	109.9
B3-T2			51.3	78.9
B4-T1	20	2.92	51.9	69.2
B4-T2			40.4	57.28

shown in Table 3. Flexural strength is enhanced in GPC beams. GPC beams have somewhat greater deflections at various phases, such as service and ultimate loads.

The flexural response of glass-fibre-reinforced polymer reinforced geopolymer concrete (GFRP-RGC) beams was studied by Maranan et al. (2015). Three full-scale beams with virtually equal longitudinal GFRP reinforcements but varied bottom diameters were strengthened (12.7, 15.9, and 19.0). Their findings showed that the load–deflection response, cracking pattern, bending moment, deflection capacity, and strain measurements recorded from all tested beams were equal to those obtained from normal beams. Further study is needed to expand the technology's acceptance in the construction sector.

Pelisser et al. (2018) investigated the mechanical performance of a GPC beam experimentally and compared it to a nonlinear finite element (FE) computer model. The reference beam was made of concrete, while the others (GP beams) were made of MK-based GPC with compressive strengths of 51 MPa and 55 MPa, respectively. The load–deflection curves of the beams for both concrete is shown in Fig. 3. The GP beam had a maximum failure load of 131.7kN (maximum bending moment, Mu = 48.9 kN.m), whereas the reference beam had a maximum failure load of 121.4kN (Mu = 45.1kN.m). The cracking loads for the GP beam and reference beam were predicted to be 17.1kN (cracking bending moment, Mcr = 6.9kN.m) and 20.4kN (Mcr = 8.1kN.m), respectively. Fig. 4 depicts the three LVDT deflections along the length of the beams. The GP beam deflected less than the reference beam. As illustrated in Fig. 5, GPC beams exhibited 11% more rotation than concrete beams. The GPC demonstrated increased tensile strength and adhesion at the cement-steel interaction.

Sumajouw et al. (2005) carried out experimental research on the flexural behavior of GPC beams. The review investigated 12 different types of GPC beams produced from FA. The test variables were compressive strength and tensile reinforcement ratio. The findings demonstrate that the failure mechanism and the load-carrying capacity of GPC beams in flexure are roughly equal to those of PCC beams. The findings of the flexural capacity and beam deflection tests were extremely well suited to the current practice codes for PCC structural components.

Sumajouw and Rangan (2006) studied reinforced beams' behaviour and flexural strength made with low calcium FA-based GPC. The test variables consist of the CS of concrete and the tensile reinforcement ratio for 12 beam specimens. The results for cracking moments are shown in Table 4. The cracking moment is significantly increased with increasing compressive strength. For instance, the cracking moment at a compressive strength of 36 MPa is 13.5kN.m, while this value increases to 19.2kN.m at 75 MPa. An increase in reinforcement also enhances the cracking moment as well. Table 5 summarizes the ultimate moment corresponding to the maximum mid-span deflection for the beams. It can be noticed that the experimental moment capacity enhanced when the strength of concrete and the flexural reinforcement ratio increased, as theoretical approaches would predict. Sumajouw and Rangan (2006) also reported the deflection at service and failure loads shown in Table 6. The ultimate moments and cracking of R-GPC beams were calculated by employing AS3600 (2001). The mean value of the experimental/ theoretical ultimate moment ratio is 1.110, with a standard deviation of 0.140. Also, the mean value of experimental/ theoretical cracking moments is 1.350, with a standard deviation of 0.090.

Ferdous et al. (2015) studied the flexural behavior of geopolymer concrete beams reinforced with FA and slag steel bars. The findings demonstrate that the strength capabilities of slag-based GPC beams were

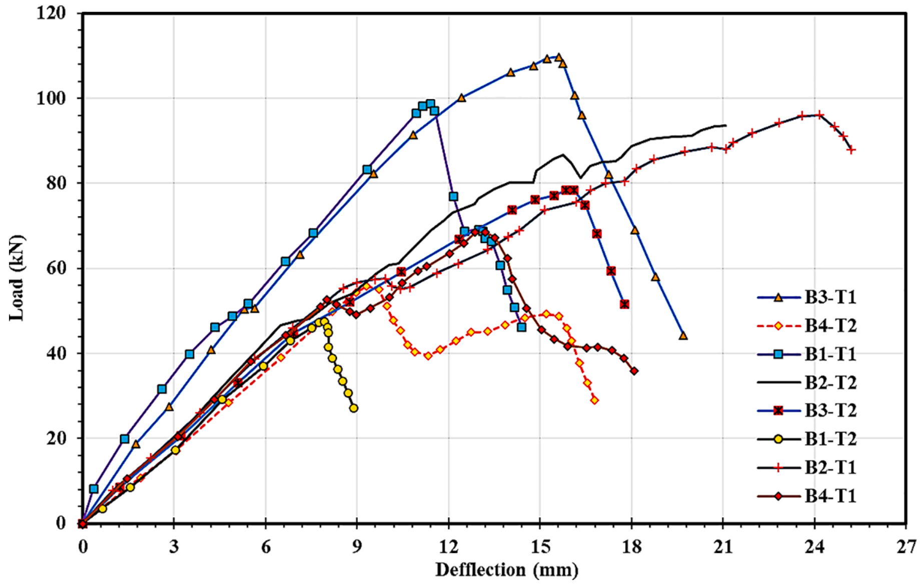

Fig. 10. Shear load–deflection curves ().
adapted from Visintin et al., 2017

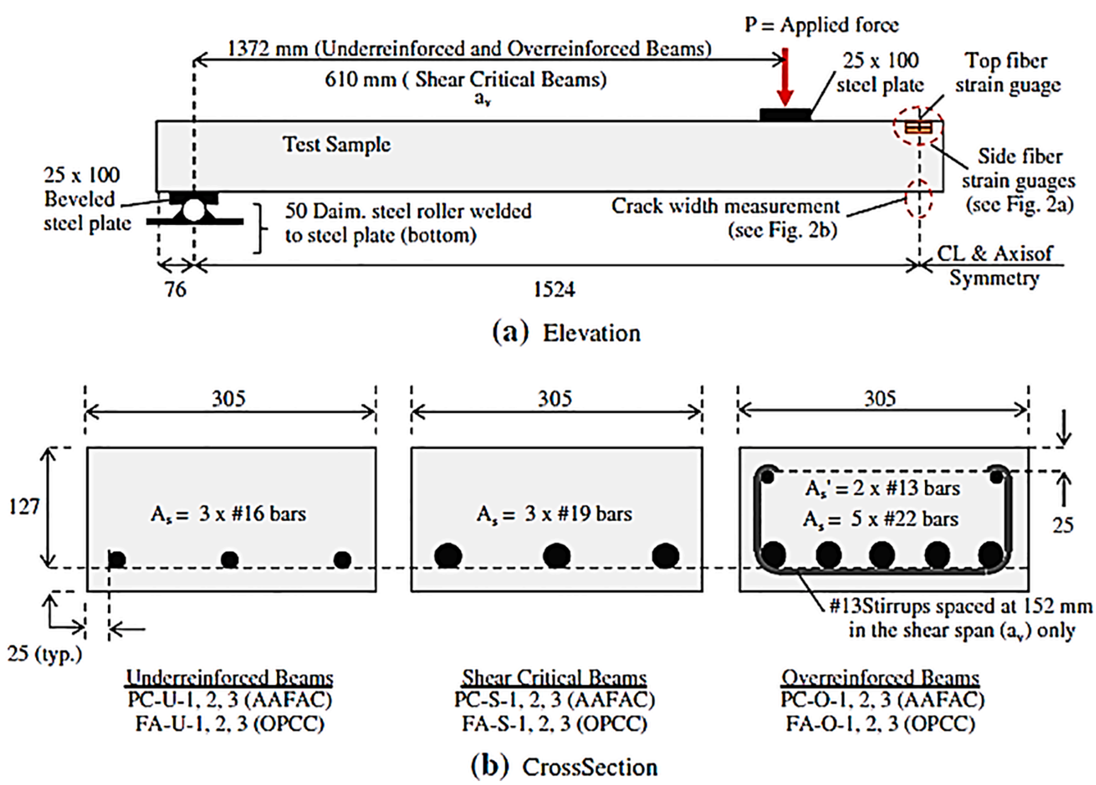

Fig. 11. Beam details (Yost et al., 2013).

slightly larger than those of standard concrete beams on average. The flexural cracks in the slag-based GPC and typical beams occurred in the same order of crack width, crack spacing, and crack number. Similar findings were reported by Kumaravel and Thirugnanasambandam (2013b).

Kumar and Ramesh (2018) studied the flexural behaviour of R-GPC beams with varying ratios of MK and GGBFS cured at room temperature with 10 M NaOH. They set twelve 700 mm × 150 mm × 150 mm beams under a two-point load. As indicated in Table 7, the ultimate deflection behaviour of the beams was determined and compared to that of finite element analysis. It was discovered that GPC beams were comparable to RC beams.

Kathirvel and Kaliyaperumal (2016) studied the flexural behavior of reinforced alkali-activated slag concrete beams with varying amounts of recycled concrete aggregates (0% to 100%). The beam samples had dimensions of 1.50 m × 0.10 m × 0.15 m and were simply supported over an effective span of 1200 mm. All beams were strengthened with two 8 mm diameter hanger bars and two 12 mm diameter tension bars, each with 6 mm diameter shear reinforcements set at 100 mm c/c. Their findings revealed that the load-bearing capability of GPC beams rises as

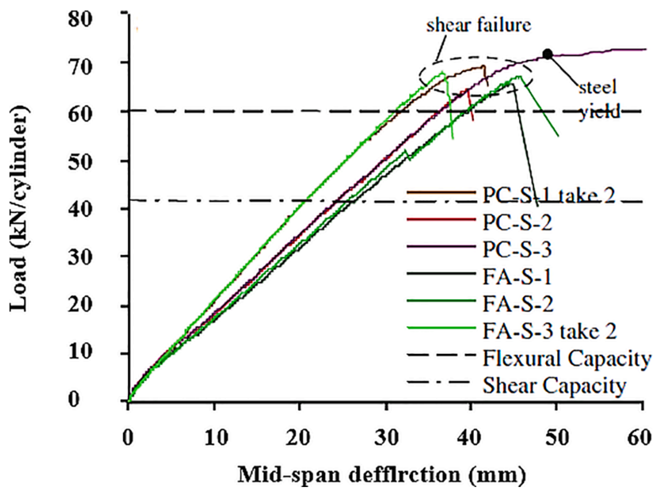

Fig. 12. Shear load–deflection curves (Yost et al., 2013).

the recycled concrete aggregate content increases; the increase was found to be optimal at 75% substitution with a 22.55% increase in loading and falls at 100% substitution. Furthermore, they observed that when the recycled concrete aggregate content increases, the GP beams' ductility and deflection are enhanced. All of the beams failed due to the development of flexural cracks, with no indication of shear cracks.

Nguyen et al. (2016) investigated and confirmed the two-point load test on three low calcium FA-based GPC beams utilizing finite element analysis ABAQUS. Fig. 6 depicts a schematic representation of the instrumental test setup. GPC has compressive strengths of 30, 25, and 20 MPa. As load–deflection curves are depicted in Fig. 7, it was found that experimental findings agreed well with those of finite elements.

Hutagi and Khadiranaikar (2016) investigated the flexural behavior of R-GPC beams using 3.0 conventional concrete and 6.0 GPC mixtures with varied FA and slag proportions as in the GPC mixes. In the majority of the testing, their findings revealed that the load-bearing capability of the GPC samples was somewhat larger than that of standard concrete samples. GPC beam deflections were larger at various stages, including service load and peak load. In contrast, the ductility factor of the GPC beam was equivalent to that of ordinary concrete samples. Furthermore, the results of this study revealed that standard RC recommendations could be utilized to determine the moment capacity, deflection, and crack size of R-GPC beams within an acceptable range.

Kumar and Kumar (2016) investigated MK- and GGBFS-based GPC with M40 grade normal concrete. Six beams were constructed and tested, utilizing two-point loading for the flexural test in an attempt to optimize the concrete's performance. Fig. 8 presents the curves for applied load vs mid-span deflection of beams built of 100% MK, 70% MK + 30% GGBFS, 50% MK + 50% GGBFS, 30% MK + 70% GGBFS, 100% GGBFS beams, and M40 grade concrete mix reference beam. It can be seen that the deflection curves varied, and that the GPC beam exhibited more ductility than the reference beams.

Andalib et al. (2014) studied the flexural strength, cracking pattern, and deflection of three forms of RC beams: FA-based GPC, POFA/FA-based GPC, and PCC beams. The experimental findings showed that reinforced POFA–FA concrete beams performed similarly to reinforced PCC beams over the 90-d curing period, as their ultimate moments and cracking were close in proximity. The ultimate moments and cracking of POFA–FA reinforced concrete, for instance, were 38.9 and 14.4kN.m, respectively, compared to 42 and 13.8kN.m for OPC-reinforced concrete. Furthermore, they reported that the behaviour and crack forms noticed for POFA–fly ash RC beams were virtually identical to those shown for OPC reinforced concrete beams in the mid-span at 90-d when compared to similar beams at 28-d.

Kumaravel et al. (2014) investigated the flexural behaviour of M40

Table 14
Summary of shear behavior of GPC beams.

References	Variables	Findings
Chang et al., 2009	longitudinal tensile reinforcement ratios; traverse shear reinforcement	The crack patterns and failure patterns could be similar to those observed in reinforced PCC beams; and for calculating the shear strength of R-GPC beams, the same code rules used in the design of RC beams are appropriate.
Mourougane et al., 2012	Different reinforcing configuration	The shear strength of GPC was observed to be greater.
Mourougane et al., 2012	Stirrup spacing	Cracks were observed in the soffit of the beams, shear cracks progressed from the centre of the shear zone toward the loading point and the support, and the beams suddenly failed.
Ng et al., 2013	Steel fiber content	Because of the fiber, shear capacity was delayed, and a finer crack was also seen.
Yost et al., 2013	Tensile reinforcement ratio	There is no substantial difference in shear behavior between GPC and conventional RC beams.
Madheswaran and Philip, 2014	stirrups	According to their findings, beams without stirrups broke owing to web crushing under diagonal compression, whereas beams with stirrups failed due to shear stress with longitudinal splitting, depending on the stirrup spacing.
Yacob, 2016	Concrete type, shear reinforcement ratio, stirrups	It was concluded that the GPC beams exhibited higher shear strength than the reference beams.
Visintin et al., 2017	Shear span ratio	The results of the direct shear tests show that the shear-friction characteristics of the GPC utilized in the test are comparable to those of PCC.
Mo et al., 2017	Steel fiber dosage	Existing formulae for steel fiber-reinforced lightweight concrete shear capacity were shown to be conservative for GPC and steel fiber-reinforced cement-based beams.
Tran et al., 2020	Hybrid fibers	The hybridization of macro-steel fibers and micro-polyvinyl alcohol fibers demonstrated an excellent synergy in terms of increasing shear capacity.

grade GPC beams and compared them to reference PCC beams. GPC with the appropriate CS was achieved by adding 25% GGBFS to FA. Two PCC (RC-I & RC-II) and two GP (GP-I & GP-II) beams were cast and tested for failure under static tow point stresses. Table 8 presents the experimental and numerical findings of the investigation. The load–deflection responses of the GP beams and reference concrete beams were obtained and compared to theoretical findings. The results show that, compared to reference beams, GP beams have higher flexural strength, peak load, and service load.

The flexural characteristics of conventional and GPC beams reinforced with carbon fibre-reinforced polymer bars were studied by Ahmed et al. (2020). Over a 2 m effective span, they prepared three traditional concrete and nine GPC beams to investigate the first cracking load, load–deflection behaviour, ultimate load, crack width, load–strain curve, the number of cracks and modes of failure as the compressive strength, reinforcement ratio, and concrete types were different. They found that as compressive strength rose, so did first cracking and deflection loads; GPC beams had a modest increase in deflection and almost the same amount of ultimate load as conventional concrete beams, and GPC beams had a lower value of crack width than conventional concrete beams.

The impact of incinerated bio-medical waste ash on the structural performance of R-GPC columns and beams was investigated by Arunachalam et al. (2021). Laboratory studies were carried out on three separate concrete types: regular concrete, 100% GGBFS as an alumino-silicate source material in R-GPC, and 30% substitution of incinerated bio-medical waste ash as an alumino-silicate source material for GGBFS in R-GPC. According to their findings, the GPC comprising 30% incinerated bio-medical waste ash had high compressive strength, flexural strength, tensile strength, ultimate strength, load-carrying ability, ductility, stiffness, and deformation capacity. Suresh Kumar et al. (2022b), on the other hand, found that the incinerated bio-medical waste ash and waste glass powder incorporated into the GGBFS-based GPC beam had the maximum fracture energy.

Suresh et al. (2022) studied the flexural behaviour of hazardous heavy metal waste ash-based R-GPC beams with varied doses of waste glass powder. The deflection, flexural strength, ductility factor, and toughness index were used to evaluate the flexural characteristics of the beams. According to the testing results, GPC beams incorporating 50% waste glass powder as fine aggregate showed a considerable increase in crack resistance, ductility, and serviceability when compared to standard concrete beams. GPC beams that did not include waste glass powder failed brittlely, but those that did contain waste glass powder failed ductility. Finally, Table 9 provides a summary of the flexural behaviour of GPC beams.

5.2. Shear behavior of geopolymer concrete beams

Dowel action, shear span/effective depth ratio, shear reinforcement ratio, concrete strength, and aggregate interlock are the key parameters influencing shear strength. Concrete strength is an important factor in determining shear load-bearing capacity in construction. Some studies on the shear behaviour of R-GPC are summarized below.

Chang et al. (2009) studied the shear behaviour of reinforced low calcium FA-based GPC beams. The compressive strength of GPC ranged between 44 and 55 MPa. The longitudinal tensile reinforcements ratio as variable parameters were 1.73%, 2.31%, and 3.13%, and the traverse shear reinforcement was 0.11, 0.14, and 0.18%. Nine GP beams were cast with the size of 200 mm × 300 mm in cross section with an effective-length of 1680 mm for shear mode failure. Table 10 shows the cracking shear loads for the beams. It can be observed that the cracking load increased with increasing traverse and longitudinal reinforcement ratios. For instance, the beam SH2-1 (longitudinal reinforcement ratio = 2.32%) reached 79 kN while the beam SH3-3 ((longitudinal reinforcement ratio = 2.32%) gained 111 kN at the same compressive strength of GPC. Table 11 shows the summary of the shear strength of the beams. It was reported that the crack patterns and failure modes could be similar to those noticed in reinforced PCC beams. As a result, code requirements employed in the design of reinforced normal concrete beams are appropriate for computing the shear strength of R-GPCs beams.

Madheswaran and Philip (2014) examined the shear behavior of geopolymer concrete T-beams with a shear span/effective depth ratio of 1.90, which are referred to as deep beams. Their findings indicated that the stirrup beams failed due to shear tension with longitudinal splitting, and web crushing under diagonal compression. GPC beams performed satisfactorily as structural elements.

Yacob (2016) observed the shear behavior of reinforced FA-based GPC beams. Six beams were cast and tested for the shear test with the dimensional size (203x305x2438mm). The beams consist of one conventional concrete beam (CL6-2) as control and five GPC beams. Among GPC beams, two beams (GL6-2and GS6-2) had various shear reinforcement ratios considering (two various stirrup spacing,s), and two beams (GN4-2 and GN6-2) had no stirrups with various longitudinal reinforcement ratios (ρw), and one beam (GL6-2.4) had higher shear span/effective depth ratio. Fig. 9 shows the shear load and shear strength obtained from beam tests. The beams performed different ductility behaviour. The toughness can be computed as the area under the load–deflection curves. The toughness factor was computed as the ratio of the toughness of the modified beam/that of the control beam (concrete beam). For CL6-2 and GL6–2 beams, the toughness factor was equal to 1.30. It denotes the normal concrete beams was more ductile than the GPC beam. Nevertheless, the toughness factor was 1.10 for the beams without shear reinforcements because the failure of both GN6-2 and GN4-2 had no ductility and was brittle. On the other hand, the toughness factor was more prominent for the beam that failed in flexure shear (namely, GS6-2 and GL6-2.4) at 3.80 and 4.20 respectively, ductile flexural failure of these beams in comparison to the control bean GL6-2. Table 12 represents the beams' shear load and shear strength with the observed failure modes. Except for two beams that failed in flexural-shear mode, the majority of the beams failed in shear; one (GL6-2.4) had a higher a/d ratio, and one (GS6-2) had a smallers. It was concluded that the GPC beams exhibited higher shear strength than the reference beams.

Mourougane et al. (2012) investigated the shear behaviour of high-strength beams made of FA and traditional concrete. GP beams are cast in two tension reinforcement series with stirrup spacings of 150 mm, 200 mm, and 230 mm. Each beam is shear tested and compared to ordinary concrete beams of the same strength under two-point loads. Cracks were observed in the soffit of the beams. Shear cracks progressed from the center of the shear zone toward the loading and the support point, and the beams failed abruptly. During the earliest phases of loading, flexure cracks formed in all of the beams. Shear cracks in the shear plane were found as the load increased. All of the beams' cracking loads were determined to be between 30 and 90kN.

Visintin et al. (2017) studied the shear performance and direct shear friction of R-GPC beams without stirrups and applied a created approach-based segmental technique for forecasting the shear strength. The test parameters used in this study were span to depth ratio, and longitudinal reinforcement ratio. The summary of the compressive strength, tensile strength, maximum shear load, and shear strength for eight R-GPC beams is given in Table 13. The load–deflection responses for the beams are shown in Fig. 10. Throughout all cases, the load increased approximately linearly until a sudden shear failure happened along the critical diagonal sliding plane. It was reported that the performance of GPC was found to be similar to that of PCC. It was concluded that the segmental mechanics could predict the shear strength of GPC beams with reasonable precision. With this segmental method, new design rules for R-GPC beams can be made.

Mo et al. (2017) conducted an experimental investigation into the mechanical characteristics and shear behaviour of steel-fiber-reinforced cement-based and geopolymer oil palm shell lightweight aggregate concrete(OPS-LWAC). Steel-fibres were introduced to the cement-based OPS-LWAC in various volume fractions (0, 0.5, and 1%), as well as the geopolymer-based OPS-LWAC (0%, 0.5%). The test findings showed that adding steel-fibres enhanced the mechanical characteristics of concrete, notably the tensile strength, while adding steel-fibres raised the flexural toughness of the cement-based OPS-LWAC more than the GPC. Steel-fibre reinforcement enhanced the shear resistance of OPS-LWAC beams, and current formulae for steel-fibre-reinforced lightweight concrete shear capacity were shown to be conservative for OPS-LWAC.

Yost et al. (2013) investigated the shear behaviour of RC beams made with cement and GPC. Six beams, three made of Portland cement (PC-S-1, 2 and 3) and the other three made of alkali-activated FA concrete (FA-S-1, 2 and 3). The beams were tested under two-point loads with a shear span of 610 mm and at the same condition shown in Fig. 11. The response is principally linear to shear failure for all three Portland cement specimens and all three FA-S specimens, as shown in Fig. 12. The stiffness of FA-S-3 take two is slightly higher than the other two alkali-activated FA specimens due to the previous take one load history. The measured loads for all Portland cement and alkali-activated FA beams were highly consistent. Average shear loads are 69.4kN and 67kN for Portland cement and alkali-activated FA beams, respectively. It was concluded that GPC beams have very similar behaviour to companion PCC beams. Hence, the shear strength of GPC beams can be determined using the same code guidelines as ACI-318 used for normal concrete.

Tran et al. (2020) investigated the impact of hybrid fibres on the shear behaviour of thirteen slender GPC beams reinforced with basalt fibre-reinforced polymer bars without stirrups in an experimental setting. To increase the shear capacity of the beams, four different fibre combinations were used: a single form of macro-synthetic polypropylene fibres or macro-steel-fibres, a hybridization of micro-polyvinyl alcohol fibres, and steel-fibres, or a hybridization of micro-carbon fibres and polypropylene fibres. Their experimental results indicated that the addition of steel-fibres considerably improved the beams' cracking behaviour, post-cracked stiffness, and shear capacity. By adding 0.5% steel-fibres to the OPC and GPC beams, the normalized shear strength was increased by 14%, and 56% respectively. The greater contributing of steel-fibres to the shear strength of geopolymer concreter can be attributed to the matrix's and fibre's superior adhesive bonding strength. Despite being less efficient than steel-fibres, adding polypropylene fibres enhances normalized shear strength by up to 34% with a fibre content of 0.5%. The hybridization of polyvinyl alcohol fibres and steel-fibres demonstrated an excellent synergy in terms of increasing shear capacity. Furthermore, the combination of carbon fibres and polypropylene fibres did not enhance the shear strength of the beams but significantly increased their ductility. Finally, Table 14 provides a summary of the shear behaviour of GPC beams.

6. Discussions and recommendations

This article provides a comprehensive review of previous investigations into this issue. The following are some of the implications that may be drawn from a detailed inspection of the study data that has been reported and evaluated:

As a result of the comprehensive systematic review of literature described in the previous section, GC can be described as cementless concrete that utilizes agricultural and industrial waste ash as the key binder in place of OPC, production it an environmentally and eco-efficient building materials. This form of concrete is influenced by a variety of mixed percentage characteristics in addition to curing conditions. Moreover, this form of concrete decreases pollution, conserves energy, and lowers construction costs.

The investigation of the various properties of GC is a burgeoning field that combines exceptional intellectual merit with broad implications. A more basic study on the possibilities of this form of eco-efficient composites is needed to extend researchers' perspectives and enable its implementation in the building sector. The goal is to develop a mechanistic knowledge of the composite's rheological, hydration, and polymerisation processes, as well as its performance in service. Comprehensive field and laboratory investigation is necessary to collect enormous quantities of data on the engineering characteristics and durability of GPC composite in a range of service conditions, in addition to preparing them for specifications and usage by practicing engineers. Geopolymerization is a complicated chemical phenomenon that we are just now beginning to understand. So, more research should be done on GC to learn more about the geopolymerisation process.

FA, MK, and GGBFS have been applied as resource materials called alumino-silicates. FA is widely used as a resource material more than other wastes. A combination of MK and GGBFS or FA and GGBFS has been tested together in different proportions. The compressive strength ranged from 17 to 63 MPa. Some of the researchers used PCC as a control to examine the performance of the GPCs. A wide range of variables was considered in both the shear and flexural tests. Steel reinforcement ratio, concrete, GP strength, and different binders are the standard parameters considered for the flexural beam tests. In addition, the test variables used for the shear beam test cover longitudinal and traverse reinforcements; the compressive strength of cement and GPC; and beams without stirrups.

Most of the structural behaviours including cracking characteristics, load–deflection, and failure mode of these R-GPC beams, were found to be similar to those of the corresponding traditional concrete beams. The majority of studies concluded that design codes designed for traditional RC elements, like ACI-318and AS-3600, are acceptable for GPC beams. Hence, these codes were generally conservative in assessing the R-GPC beams (Chang et al., 2009, Dattatreya et al., 2011, Yost et al., 2013). Considering the relatively high experimental/calculated value ratios, a more economical structural design for GPC structures could be gained by developing new codes for GPC structures or revising the current PCC-based codes.

GPC has a high potential for use in precast and prestressed RC components; such GPC can be investigated in order to accelerate GPC's future application in actual structural parts. Furthermore, GPC should be evaluated in structural elements for serviceability and durability behaviour in order to obtain reliable data on the performance of GPC structures under severe conditions including as exposure to an aggressive environment and in case of fire. When compared to cement-concrete buildings exposed to extreme conditions, GP is predicted to improve the service life of structures and perhaps save substantial repair and maintenance costs.

7. Scope for future research

Based on the comprehensive review of the fresh, mechanical, and structural characteristics of GPC that has been carried out in this study, the scope and gaps for further studies have been discussed and highlighted in the following:

- Detailed investigations, including those relating to the derivation of reaction kinetics and modeling under different treatment and production circumstances of the developing class of GP raw materials, such as blended GPs and biomass ash GPs, are needed.
- GP binders need a high pH and heat curing condition. As a result, efforts are required to create a room-temperature cured one-component GP system that uses solid activators rather than alkaline solutions in order to gain widespread acceptability in the field.
- More investigation is needed to evaluate the cost of GPC compared to that of standard concrete. Furthermore, contradictory findings regarding GPs' embodied energy and carbon footprint compared to OPC must be addressed. Appropriate instructions for the selection of fine and coarse aggregate content in GPC should be It is also critical to develop design procedures for each significant predecessor.
- There is not enough research on the life-cycle sustainability of GPC from all three perspectives of sustainability, which are social, environmental, and economic. This means that more investigations are needed to evaluate the sustainability of GPC fully, and a life-cycle assessment process is recommended. You would have to think about the raw materials selection procedure, the curing system, the production process, etc. You would also have to think about the construction process, the maintenance system, etc.
- To gain a better understanding of GPC's structural behaviour, we need to look into the serviceability of the concrete, especially crack propagation. We also need to look into full-scale structural elements made of GPC, and we need to look into the brittle behaviour of GPC with a dense and compact microstructure; the behaviour of GPC in multi-axial stress states, stiffness degradation, and recovery are those important issues that should be investigated for further understanding of the structural behaviour of GPC.
- Additional extensive study of the shear strength of geopolymer concrete is needed to establish the accuracy of the shear capacities of geopolymer concrete structural components.

- GPC made by the manufacturing industry should be checked for long term creep and shrinkage characteristics since it may differ from the laboratory findings.
- There are limited studies on other structural elements like columns, slabs, foundations, column-beam connections, and walls. Therefore, more extra research in these areas is necessary.
- Lastly, it is recommended to study the properties of GPC by consuming other different waste materials like waste plastics, as well as trying to find more natural and economically alkaline activators.

8. Conclusions

Based on a comprehensive review of relevant literature, the following conclusions can be drawn:

I. GPC is a cementless concrete that uses agricultural and industrial waste ashes as the primary binder rather than OPC, making it an environmentally and eco-efficient building material. GPC saves energy, gets rid of waste, cuts building costs, and lowers the effects of CO2 emissions.
II. Many factors influenced the fresh and mechanical characteristics of GPC, such as the concentration of sodium hydroxide, the ratio of sodium silicates/sodium hydroxides, water/solids ratio, curing ages and curing regime, elemental composition, the alkaline solution/binder ratio, blending time and rest period of the GP mixture, type of source binder materials, superplasticizer concentration, aggregate contents, and extra water content.
III. Regarding the structural properties of R-GPC beams, it was concluded that the specification codes for GPC beams, such as ACI 318 used for traditional RC structures, could be predictably developed.
IV. In most cases, the majority of codes offer an approximation of the ultimate load capacity of GPC beams.
V. R-GPC beams behaved and failed in the same way as conventional reinforced cement-based concrete beams. These comparable results should improve the usage of existing codes of practice for designing structural elements utilizing GPC.
VI. Many design equations for GPC structures have been proposed. However, they are still fairly limited. As a result, there are still chances to explore the structural behaviour of GPC in order to develop a standard design procedure that might be cheaper and more dependable for R-GPC members.
VII. Finally, eco-friendly, sustainable, and structurally sound GPC with acceptable properties can be produced by consuming a variety of waste-source binder materials in their mixed proportions instead of OPC, which may eventually replace OPC-based concrete.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clema.2022.100111.

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