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Review Research

STRUCTURAL BEHAVIOR OF GEOPOLYMER REINFORCED CONCRETE BEAMS: A SHORT REVIEW

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Abstract: The significant CO_2 emissions that can be associated with cement manufacture is the primary cause of global warming. Thus, the authors and research groups are motivated by many factors to find long-term solutions to this problem. Geopolymer concrete is such type of concrete in which the primary binder is resulted from alkali activation of some source materials like fly ash, metakaoline, rice husk ash, and ground granulated blast furnace slag. Commonly, geopolymer concrete gives comparable mechanical strength properties to conventional concrete. The use of this type of concrete is restricted by the properties of the used source materials and the molar concentrations of the alkali activator. As a consequence, making investigations to the relevant structural behavior as a result of these variables are rich sources of scientific research. The goal of this work is to provide a brief overview to the recent contributions that have dealt with the structural behavior of geopolymer concrete. The context of this paper was obtained to illustrate the main findings as well as the used source materials and some additional considerations.

Keywords: *Flexural strength; shear strength; fly ash; Metakaoline; slag; Carbon Dioxide*

1. Introduction

The construction industries are consuming high energy and disposing large quantities of waste materials. This represents a huge problem regarding global warming due to the negative environmental effects. Within this context, the cement industry has a major share within these problems due to the high Carbon Dioxide (CO_2) emissions [1-5]. In this way, seeking for other alternatives that can compensate cement is a serious task for the authors in the civil engineering scientific field [6-10].

"Geopolymer" are such materials that can be synthesized by the alkali activation of any suitable alumino-silicate materials such as slags, metakaoline, fly ash and red mud [11-14].

The resulted matrix of the "Geopolymerization Process" is a hardened matrix that can play the same role of ordinary Portland cement (as the primary binder). To manufacture adequate and stable geopolymer, the source materials must be highly reactive, easy to release aluminum, and have moderate water consumption [15-22]. Many materials can be used as alkali activators such as Sodium Hydroxide (NaOH), Potassium Silicate (K_2SiO_3), Sodium Silicate (Na_2SiO_3), and Potassium Hydroxide (KOH) [23-30]

Since the geopolymer hardened matrix has good mechanical strength, stiffness, and durability properties [30-34], geopolymer concrete can be reinforced to play the same role of conventional

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reinforced concrete that wholly used in civil engineering applications.

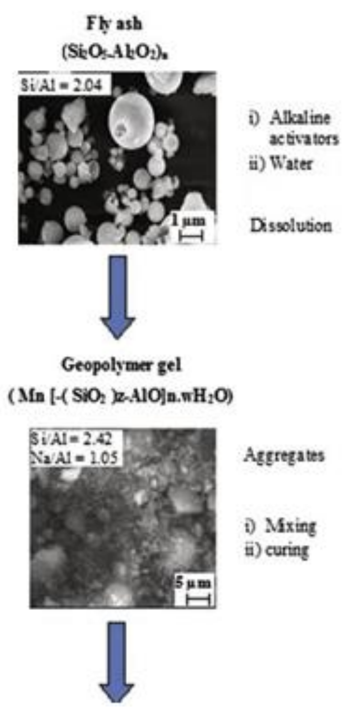
2. Geopolymerization

In normal cases and circumstances, SiO_4 and AlO_4 tetrahedral units become free after the dissolving of alumino – silicate reaction. Then after that, such units are usually attached to the polymeric precursor and Oxygen atoms are released accordingly. As a result, the bonding structure of Si–O–Al–O are formed. The following chemical formulas describes the chemical reactions of geopolymerization [14].

$$(Si_2O_5.Al_2O_2)_n+H_2O+OH^{-}\text{-->}Si(OH)^4+Al(OH)^{4-}$$

$$Si(OH)_4+Al(OH)^{4-}\text{--}(\text{-}\underset{\underset{O}{|}}{\overset{|}{Si}}\text{-}O\text{-}\underset{\underset{O}{|}}{\overset{|}{Al}}\text{-}O\text{-})_2+4H2O \qquad (1)$$

The released water during the intended reaction plays a good role for workability and facilitates handling [36-44]. However, these opposites the role of ordinary Portland cement where high level of water consumption can be noticed during the entire process of hydration [45-49]. Figure 1 illustrates this process schematically.



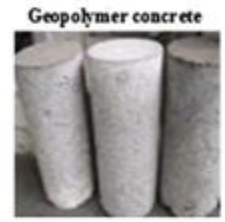


Figure 1. Geopolymerization process, schematic representation [14].

3. Importance of the Study

Collecting reliable data about the structural behavior of reinforced geopolymer beams is a very crucial issue for any researcher. This is necessary to understand the relevance of the inherent mechanical properties of geopolymer concrete and know how to build a reasonable starting point for the intended research program. In this way, the current paper presents a short review about the structural behavior of reinforced geopolymer beams.

4. Previous Studies on Geopolymer Reinforced Concrete Beams

The following are the most important previous studies that included the structural behavior of geopolymer RC beams :

Chang, (2009) [50] Conducted an experimental program to investigate the bond and shear behavior of Geopolymer Concrete (GC) beams. The source material that used to produce the GC is the low – calcium fly ash. To study the shear behavior of fly – ash based geopolymer RC beams, the effect of longitudinal reinforcement ratio was selected as a variable. The results showed that the observed cracks pattern and the relevant failure mode of the geopolymer RC beams were similar to the known in beams that made by traditional concrete. Within that study, the "Disturbed Stress Field Model" proposed by Vecchio (2000) [51] was detected against the test results and a good correlation was gained. In addition, it is stated that the known code provisions regarding shear capacity of traditional RC beams are valid for geopolymer RC beams.

In contrast, to study the bond behavior, the included variables were bar diameter, concrete compressive strength and concrete cover with respect to bond stress. It was also reported that the failure mode was also similar to traditional concrete. The validity of the model proposed by Canbay and Frosch (2005) [52] was also detected with respect to the resulted tensile strength of GC as well as the relevant bond behavior and good correlation degrees was gained. However, it is stated that the common predictive equations that used for traditional concrete can be applied for GC beams. Figure 2 shows the test setup of that research.

Figure 2. Test setup and beam model of Chang, (2009) [50].

Ambily et al., (2011) [53] Investigated the shear behavior of geopolymer RC beams experimentally and numerically. The source material used during that study were fly ash and ground granulated blast slag (GGBS). Three mix designs were proposed for GC and one for ordinary concrete. The first GC used GGBS only as a source material, the second used 75% of GGBS and 25% of fly ash while the third used 50% GGBS and 50% of fly ash. In addition, a numerical modeling was also performed using the Finite Element (FE) approach by the Analysis System (ANSYS) software. Figure 3 shows the experimental setup of that study.

Figure 3. The experimental setup of Ambily etal., (2011) [53]

The results of the study stated that the load – deflection behavior of GC beams is somewhat similar to that of ordinary RC beams but GC beams showed slightly more deflections for the same level of load as shown in Figure 4.

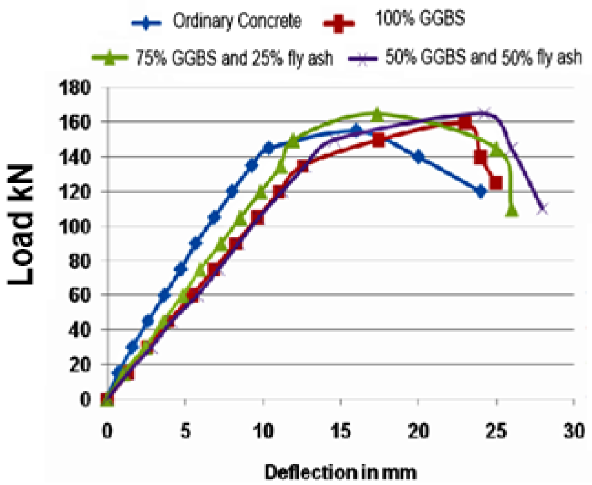
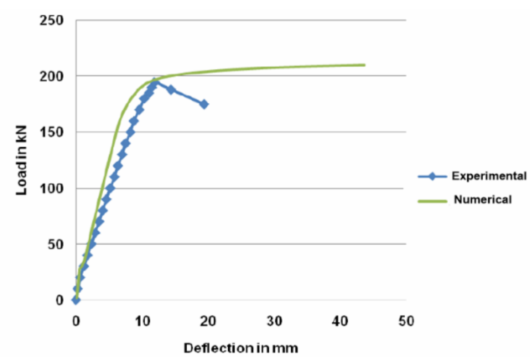


Figure 4. Load – deflection response of Ambily et al., (2011) [9].

Furthermore, the comparisons between experimental and three-dimensional numerical modeling showed an acceptable agreement between the experimental and numerical results. Figure 5 showed such accord for ordinary and GC beams.



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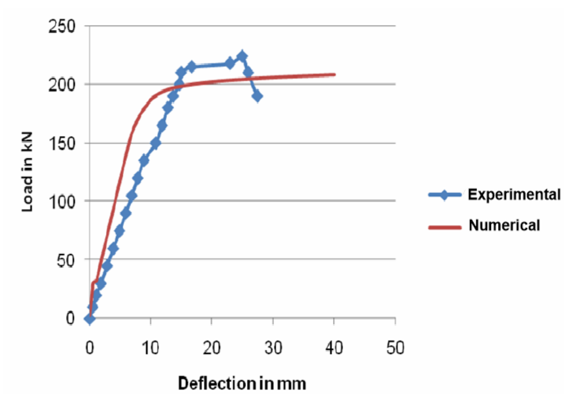

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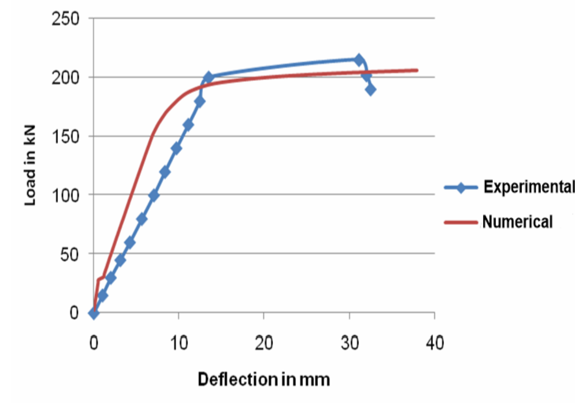

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Figure 5. Experimental versus numerical results of Ambily etal., (2011) [53].

Jeyasehar et al., (2013) [54] conducted an experimental program to investigate the feasibility of using fly ash based RC geopolymer beams as "precast units". The study was focused on taking the effect of liquid over fly ash ratio. During that study, the structural behavior of specimens was characterized by the load deflection and moment curvature diagrams and the GC beams were compared with reference ordinary RC beam specimen. The test setup of beams that conducted throughout that study is shown in Figure 6.

Figure 6. Experimental setup of Jeyasehar etal., (2013) [54].

In addition, the procedure of Park and Paulay (1975) [55] was followed to build the theoretical moment curvature diagrams for the desired comparisons .

The results of the study showed that the optimum L/F is 0.5 with respect to structural behavior as shown in Figure 7. Finally, Table 1 shows the load carrying capacity of the beams of this research.

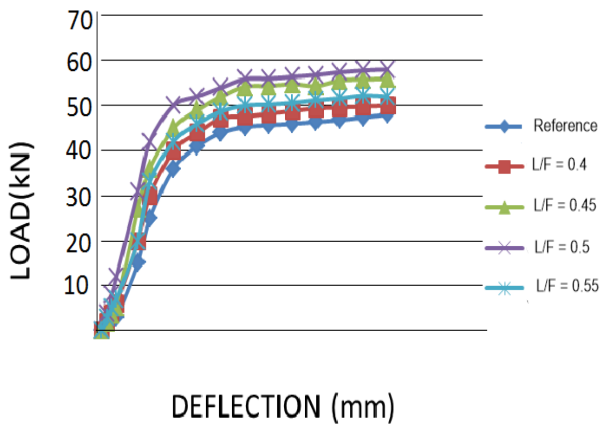


Figure 7. Load deflection response of Jeyasehar etal., (2013) [54].

Table 1. Load carrying capacity results of Jeyasehar etal., (2013) [54].

Beam Description	Load Caring Capacity kN	Increase in Load Caring Capacity %
Ordinary concrete	42.75	/
$\frac{Activator}{Fly\ ash} = 0.4$	62.50	46.20
$\frac{Activator}{Fly\ ash} = 0.45$	61.75	44.44
$\frac{Activator}{Fly\ ash} = 0.5$	61.00	42.69
$\frac{Activator}{Fly\ ash} = 0.45$	61.50	43.86

Hutagi and Khadiranaikar. (2016) [56] Conducted an experimental program to investigate the flexural behavior of fly ash based GC beams. Three levels of compressive strength and steel reinforcement were taken as study variables. The structural performance throughout the study was represented by the first cracks load, service load, ultimate load and the relevant load deflection diagrams . The test setup is shown in Figure 8.

Figure 8. Experimental setup of Hutagi and Khadiranaikar. (2016) [56].

The results of the study showed that the first cracking load, service load and ultimate load increased by increasing the longitudinal steel ratio for all proposed compressive strength levels.

It was stated that changing the compressive strength from 50 MPa to 70 MPa increased first cracking load between 69.32% to 113.53%, the service load increased between 27.80% to 57.89% while the ultimate load increased between 40.33% to 47.38%. The effect of increasing steel ratio from 0.75% to 1.89% at nominal compressive strength of 50 MPa with respect to load deflection response is shown in Figure 9. Table 2 shows the change of service load versus the steel ratio within the study.

Table 2. Load carrying capacity results Hutagi and Khadiranaikar. (2016) [56].

Percentage Tensile Reinforcement Ratio	Service load kN	Increase in Load Caring Capacity %
0.75%	70.0	/
1.34%	90.1	28.71
1.89%	105.0	50
0.75%	85.0	21.43
1.34%	92.0	31.43

1.89%	110.0	57.14
0.75%	110.5	57.86
1.34%	115.2	64.57
1.89%	140.3	100.43

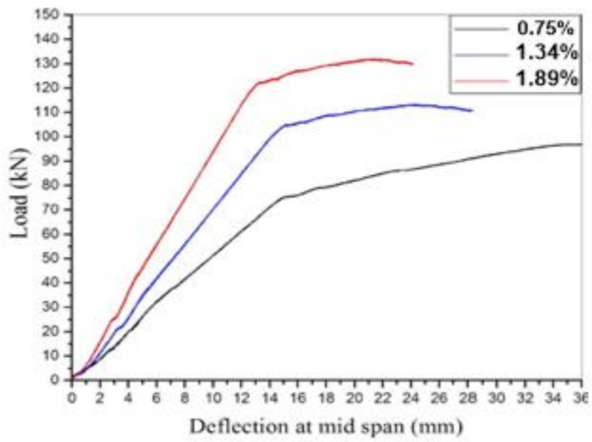


Figure 9. Effect of longitudinal steel ratio within Hutagi and Khadiranaikar. (2016) [56] experimental work.

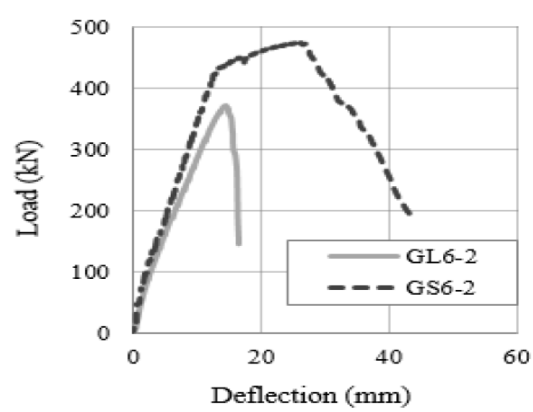
Yacob, (2016) [57] studied the shear behavior of geopolymer RC beams to include the effect of shear span-to-effective depth ratio, longitudinal steel ratio and level of shear reinforcement. The structural behavior of the tested beams was represented by load-deflection response, load carrying capacity, failure mechanism, failure strain of steel reinforcement

The results of the study showed that the ductility of GC beams that drawn from load deflection response is some - what similar to traditional RC beams. In addition, when increasing shear span-to-effective depth ratio and spacing of stirrups, the mode of failure can be changed from “pure shear” to “flexural-shear”.

Furthermore, it was reported that the crack propagation was identical for GC beams that fail in “shear” while those that fail on “flexural-shear” showed concrete crushing at extreme fiber of compression “between the two point loads .”

It was stated throughout the study that the code provisions of Load Resistance Factor Design (LRFD) equation that used to predict the shear strength in code of American Association of State Highway and Transportation Officials (AASHTO) was applicable to geopolymer RC beams. The load deflection response of GC beams that failed in “flexural-shear” against the reference traditional RC beam is shown in Figure 10.

Kumar and Poluraju, (2017) [58] Conducted an experimental program to investigate the flexural behavior of geopolymer RC beams. The source materials that used to produce GC were the GGBS and metakaoline (MK). Table 3 showed the mix proportions variation and the relevant specimens designation. The structural performance in the research was categorized by the load deflection diagrams, moment curvature diagrams, the relevant ultimate load carrying capacity, service load and the first cracks load. The test setup of that study is shown in Figure 11.



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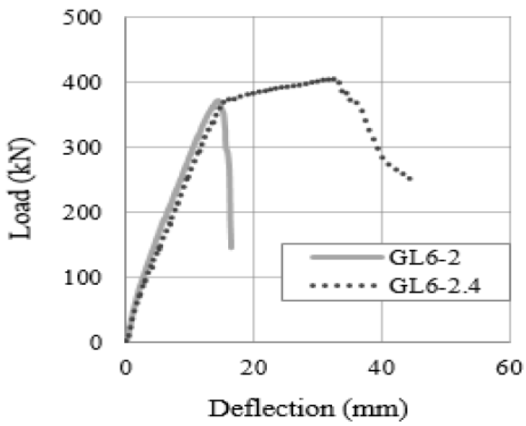


(b)

Figure 10. The load deflection response of Yacob, (2016) [57] flexural – shear geopolymer RC beams: (a) GC with excessive stirrups. (b) GC beam having high shear span to effective depth ratio.

Figure 11. Experimental setup of Kumar and Poluraju, (2017) [58].

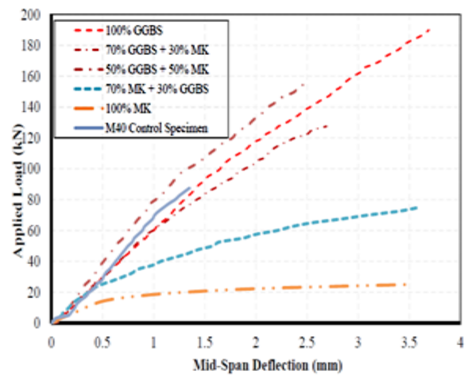
The results of the study showed that the increasing the GGBS from 0% to 100% increases the relevant first cracks load by 412.49%. It is also state that the general load deflection response of GC beams are similar to reference (ordinary RC specimen) till 70 % GGBS + 30% MK, after such limits, the service load of GC beams was lower than the reference marginally. The load deflection diagrams of that study is illustrated in Figure 12.

Maranan et al, (2017) [59] Conducted an experimental program to inspect the shear behavior of fly ash based GC beams and having secondary reinforcement made by Glass Fiber Reinforced Polymers (GFRP). The included variables were main and secondary reinforcement amounts, shear span to effective depth ratio and the presence of steel stirrups instead of GFRP stirrups. The proposed specimens that designed to represent these variables were compared with reference GC beam without stirrups.

The results of that study showed that the flexural cracks width of the GC beam that reinforced with GFRP stirrups of 150mm spacing was more than the reference by about 8.7%. The shear cracks load was not affected. It was reported that the use of GFRP stirrups enhanced maximum shear carrying capacity by about 200% due to the effect of clamping and the vertical component of stirrups resistance which can play good role for shear strength of GC beams .

Table 3. Specimen designations of Kumar and Poluraju, (2017) [58]

Designation	MK%	GGBS
M1	100	0
M2	90	10
M3	80	20
M4	70	30
M5	60	40
M6	50	50
M7	40	60
M8	30	70
M9	20	80
M10	10	90
M11	0	100
M12	Traditional Concrete	



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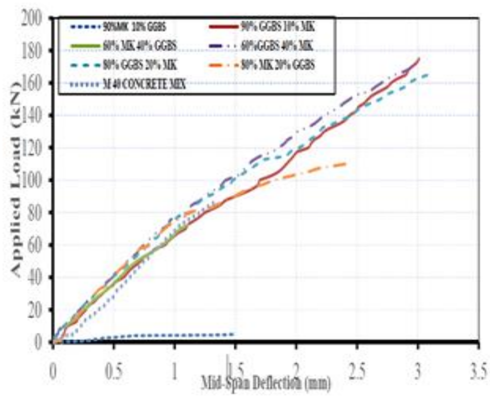

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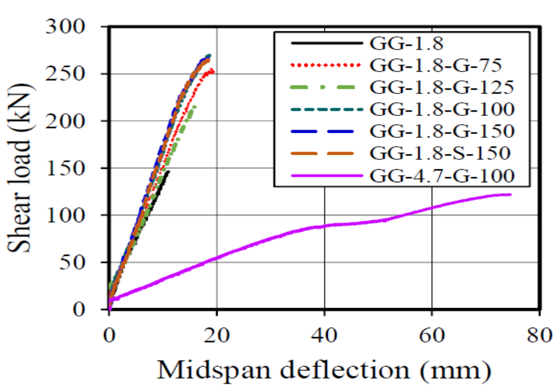
Figure 12. The load deflection response of Kumar and Poluraju, (2017) [58] specimens: (a) M1, M4, M6, M7 and M11. (b) M2, M3, M5, M8 and M9.

It was stated that the shear crack width decreased as the GFRP stirrups spacing increased due to the consequent decrease of minimum concrete mass that can be controlled by stirrups. Figure 13 shows the load deflection and the load strain diagram response of that study.



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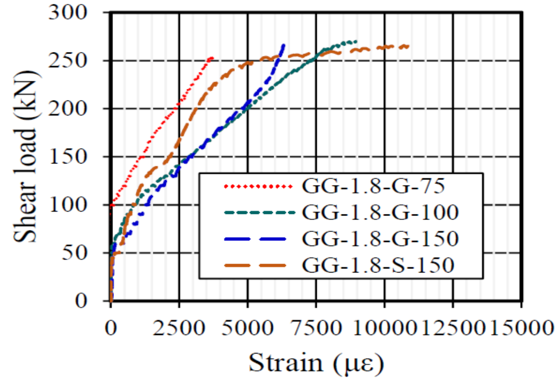

(b)

Figure 13. Results of Maranan etal,m (2017) [59]: (a) Load – deflection. (b) load strain

Srinivas etal., (2019) [60] Studied the flexural behavior of the GGBS based geopolymer RC beams experimentally to include the effect of molar concentration of the alkali liquid. The molar concentrations that obtained were 8M, 10M, 12M, 14M and 16M respectively. The study was divided into two main parts. The first was directed to investigate the effect of molarity on the compressive strength and modulus of rapture in the ages of 7 days and 28 days while the other was devoted to investigate the consequent flexural response of GC beams. The flexural behavior of the study was characterized by the load deflection response and the relevant cracks and ultimate load. Figure 14 shows the test setup of that contribution.

Figure 14. Experimental setup of Srinivas etal., (2019) [60]

The results of the study showed that increasing alkali liquid molarity increased the relevant cracks and ultimate load of GC beams. It was reported that increasing molarity from 8M to 16M increased the cracks load 7.77% and ultimate load by about 26%. Figure 15 illustrates the load deflection response of 8M and 16M within that research. Table 4 lists the first cracks load variation by changing the Molar concentration.

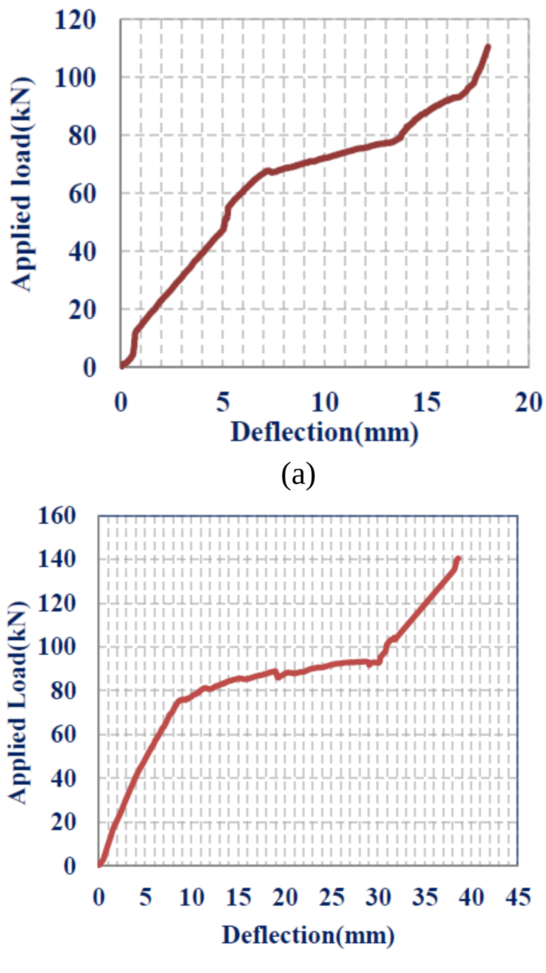

Figure 15. The load deflection response of Srinivas etal., (2019) [16]: (a) 8M. (b) 16M.

Table 4. Results of Srinivas etal., (2019) [16]

Molar Concentarion M	Cracks Load (kN)	Ultimate load (kN)
4	72.1	106
8	74.52	111.5
10	75.1	119.08
12	76.08	131.9
14	78.1	138.84
16	80.31	140.48

Bhavanaa and Srinivas, (2021) [61] Implemented an experimental program to inspect the effect of replacing traditional river sand that used as fine aggregate by the manufactured sand on the flexural behavior of GC beams. The source material that used to produce GC comprised 15% GGBS and 85% fly ash. During the study, the flexural behavior was represented by the load deflection diagrams and the relevant service and ultimate load

The preliminary tests of that study showed that at 28 days, the GC gives between 15 % and 20% more than that of traditional concrete. In addition, the ultimate load carrying capacity of GC beams (river sand as fine aggregate) was more than the traditional by about 10% while GC beams (manufactured sand) was more than the traditional by about 13%. Figure 16 shows the load deflection response of that study while Table 4 shows the effect of molar concentration versus the cracks and ultimate load limits.

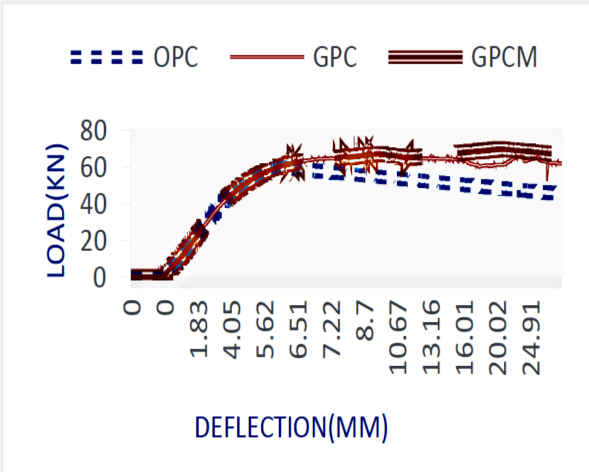

Figure 16. Load deflection response of Bhavanaa and Srinivas, (2021) [61].

5. Summary

The GC represents a good alternative to the conventional concrete with respect to sustainability and cost. Its binder paste can be synthesized by the alkali activation of alimono-silicate source materials such fly ash and GGBS and MK .

During the last decade, the structural behavior of solid geopolymer RC beams was just begun to be understood and there are many justifications for conducting additional reliable experimental program to cover this field more and more.

6. Conclusions

It can be concluded during the presented survey that the vast majority of the source materials that used to manufacture geopolymer concrete are fly ash, metakaoline and slags. In addition, the structural behavior of geopolymer RC beams is varied according to the mechanical strength characteristics. Changing source material dosage, source material origin, NaOH molar concentration and alkali activator properties will govern the resulted mechanical properties and the relevant structural behavior of geopolymer RC beams. furthermore, there is an agreement throughout the literature that there are no major differences between geopolymer and conventional RC with respect to structural behavior and failure modes. In general, the structural behavior of geopolymer RC beams are addressed by load deflection response and the relevant load carrying capacity, first cracks and service loading. On the other hand, no specified standards are now available for manufacturing GC and implementing geopolymer RC members while there is a considerable lack of information about the failure criterions that govern the mechanical behavior of GC. Therefore, there are little research works that included FE formulation of GC. Additionally, little research studies are now available about the presence of transverse web openings within geopolymer RC beams as well as geopolymer RC beams of T – section as well as the mechanical behavior of the inclusion of steel fibers within GC mix and its effect on the related structural performance. However, Further research is needed to account cyclic load behavior and torsional behavior of GC RC beams.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Abbreviations

ASTM	American Standard Testing Measurements
ACI	American Concrete Institute
Ansys	Analysis System
C_3A	Tri-calcium Aluminate
CaO	Calcium Oxide
CSH	Calcium silicate hydrate
FE	Finite Element
GC	Geopolymer Concrete
GFRP	Glass Fiber Reinforced

	Polymers
GGBS	ground granulated blast slag
IR	Insoluble residue
K_2CO_3	potassium carbonate
LOI	Loss on ignition
LRFD	Load Resistance Factor Design
MK	Meta kaoline
Na_2CO_3	Sodium carbonate
Na_2SO_3	Sodium Silicate
NaOH	Sodium Hydroxide
RC	Reinforced Concert
SiO_2	Silicon Oxide

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