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Study of Geopolymer Concrete Beam with Glass Fibre Reinforced Polymer Rebars – A Review

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Abstract Reinforced Concrete (RC) is a widely used composite material in construction. It is composed of concrete with high compressive strength and steel bars and stirrups of high tensile strength placed longitudinally and transversely, complementing each other in overcoming their weaknesses. Corrosion of steel reinforcement and cement sustainability are two main persistent issues creating great difficulty in the entire construction industry across the globe. Sincere efforts were also made to replace ordinary Portland cement with geopolymer cement, and steel reinforcements with fiber reinforcement for more than two decades. Different combinations were tried in using them for beams, slabs, columns, and combinations of the above. Though researchers have shown many leads in the research, no concrete proofs were made about the better combinations and the structural code for common usage. In this paper, available literature were reviewed in detail and summarized. A study was carried out for the intended purpose to identify focus areas for further research, and it is listed.

Keywords Portland Cement, Geopolymer Cement, Steel Reinforcement, Glass Fiber Reinforcements, Structural Beams, Columns

1. Introduction

Reinforced Concrete (RC) is an extensively used composite material in the construction of buildings, roads, bridges, retaining walls, and underground structures. It is composed of concrete with high compressive strength and steel bars and stirrups of high tensile strength placed longitudinally and transversely, supporting each other to overcome their weaknesses. In terms of criticality, Vasti and Ersoy listed that column are most vulnerable, followed by beam-column joints and beams. Structural slabs are relatively less vulnerable, and they can be easily replaced or strengthened [53]. For example, in multi-story buildings, columns and beams provide lateral structural stability by beams carrying the external transverse loads from the floors and roofs and transfer these loads to columns by bending and shear actions. The columns then, transfer these loads to foundations through axial compression or tension along with bending and shear actions. Thus, damage in a beam or column must be avoided through proper design. The structural performance of them is decided based on the bond interaction between the reinforcement and concrete beside the properties of constituents. Adequate bonding is the key to achieve the composite action-transfer of forces from one to the other and vice versa. [20]. The bond strength of deformed steel bars provides mechanical interlock of the surface deformations, with minimum contribution from the chemical adhesion and the mechanical friction between the reinforcement and concrete [38]. Here, the deformations improve the bending, shear, and torsion resisting mechanisms of RC members and control the width of the cracks by reducing the slip of the reinforcement relative to concrete. In addition to the above, providing bends and hooks at the end of the reinforcement provides additional bearing resistance that improves the bar anchorage and prevents slipping, but they may result in steel congestion [15][49]. Thus, headed bars are used nowadays [27]. Despite few issues, across the globe, RC members are used due to the following advantages:

1. Low cost compared to other building materials.
2. Accessibility to its constituents – cement, sand, gravel, water, and steel bars.
3. Mouldability – takes desired structural forms. [38][54].

Steel corrosion and cement sustainability are the principal disadvantages seen while using RC members in severe conditions. Other well-known factors such as lack of tensile strength, process flaws during the production of concrete, and lack of attention during construction, heavier, and non-environment friendly are also conventionally considered as disadvantages of using RC members.

2. Corrosion of Steel Reinforcement

Corrosion of reinforcements causes deterioration of concrete that consequently resulting early strength degradation, loss of serviceability, and sometimes leads to failure of structures in aggressive environments [39]. The expected service life also reduces by almost 50% or even more due to corrosion [35]. Corrosion can be classified into local corrosion and general corrosion [7][48]. Local corrosion or pitting corrosion is predominant when reinforced steel bars are exposed to chloride-contaminated concrete [12]. Here, chloride ions penetrate the concrete and reach a critical threshold value at the reinforcement depth [51]. They may be introduced unknowingly by mixing chloride contaminated waters, gravels, and admixtures. The general corrosion is caused due to carbonation of concrete – carbon dioxide in the atmosphere that penetrates the concrete and reacts with calcium hydroxides to form calcium carbonates [4]. The steel's passive protective oxide layer that shields it from corrosion is destabilized due to the above reaction [42]. The chloride-induced corrosion is more dominant than carbonation-induced corrosion [39]. Internal busting/ tensile stresses may cause cracking, delamination, and spalling of the concrete surrounding the reinforcement due to the weakening of concrete. The volume of the corrosion product (rust) can occupy a large volume than the original volume of steel [24]. The above phenomenon together with the reduction of the load-bearing capacity of the reinforcement, owing to the loss of steel cross-section and the weakening of the steel-concrete bonding directly affect the residual strength and serviceability [6][44]. The process of corrosion can be delayed by providing adequate concrete cover or by the alkalinity of the concrete solution, but it cannot be completely prevented due to the degradation of concrete cover over a period, presence of concrete pores, and poor workmanship. Billions of dollars are spent every year for repair, rehabilitate, and maintain the damaged/deteriorated RC structure due to corrosion [1]. Pitting corrosion in a plain reinforced concrete bar and the effect of carbonation on reinforced concrete is shown in figure 1.

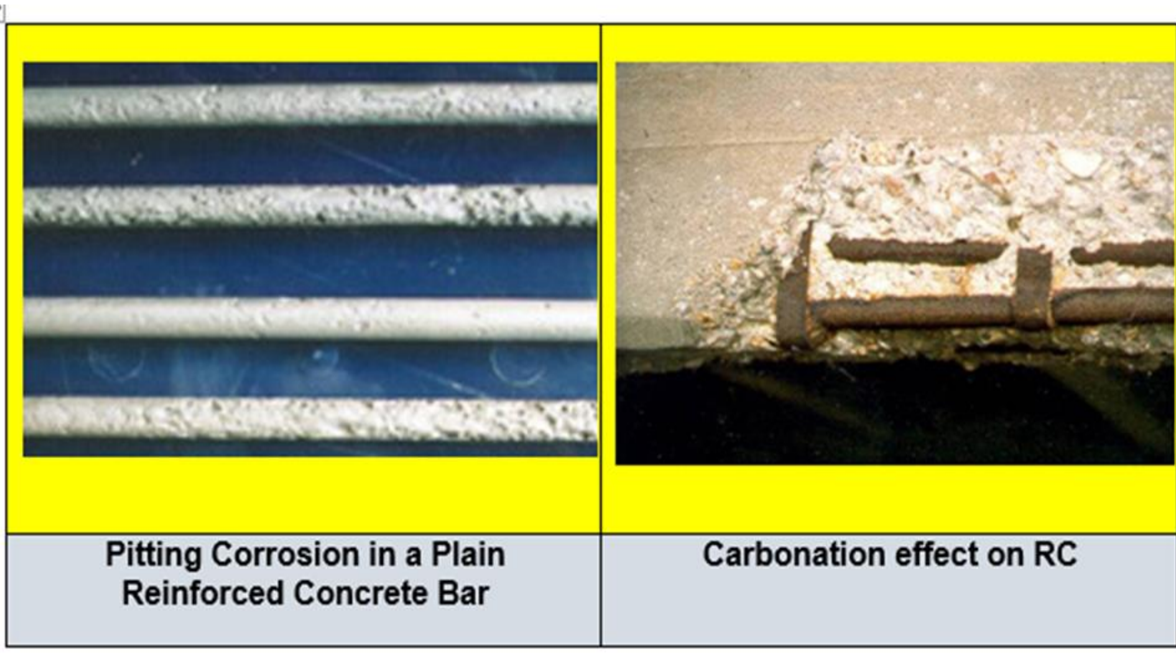

Figure 1. Pitting Corrosion in a plain RC bar and Carbonation Effect in a Reinforced Concrete

3. Cement Sustainability

Cement-based concrete and water are the most commonly and highly consumed materials in the construction world. [45] The rising cement production year on year approximated as 3% as per the data released by Portland Cement Association [42] is an indicator of the above. This is due to the continuing demand for the construction of residential and non-residential buildings to accommodate the growing world population. But cement manufacturing is the major source of anthropogenic carbon dioxide originating from the calcination process, the process that decomposes calcium carbonate to calcium oxide and carbon dioxide [29]. Therefore, huge gigatons of carbon dioxide (8% of total carbon dioxide emission) are released into the atmosphere during cement manufacturing [40]. This is a major concern for the world now, as the extinction of plants and animals, extreme weather events, and rise in sea levels become events due to it [3].

To summarize the above, it is very much needed to identify alternatives/replacements to cement and steel in construction.

4. Comparison of Cementitious Materials used in Construction

Cementitious materials like Fly Ash, GCBS, silica fume etc. are produced as a by-product of industrial processes. They are used as a part of cement. They are mixed in proportions with cement and used in construction to reduce the impact of cement pollution.

a. Fly Ash

Fly Ash is a fine, light, glassy residue generated during ground or powdered coal combustions. The flowability and workability of a fly ash is better, therefore, it flows in pump hoses easily and used for finishing works. It is a combination of silicon dioxide and calcium oxide. Class C type is produced by combusting lignite or sub-bituminous coal with lime. Class F type is produced by burning old anthracite and bituminous coal. Class C type stronger than the class F type and is used in green building projects.

b. Ground Granulated Blast-Furnace Slag (GGBS)

GGBS is produced as a by-product of the iron and steel industry. It is produced from the molten slag obtained from the blast furnace by water quenching it followed by grinding it to a fine powder. It behaves like cement with less reaction compared to cement. It is presently used in variety of proportions to reduce the usage of cement, typically 60 % cement and 40 % GGBS or 30% cement and 70% GGBS, according to the function of the cement. The concrete made with GGBS cement has considerable durability and life since it takes more time to settle than ordinary cement.

c. Silica Fume

Silica fume is generated as a secondary product while manufacturing silicon. In a densified form or in a slurry form, it can be used in producing concrete. Due to its high cost, it is not used nowadays.

d. Slag

Slag is produced as a by-product while manufacturing iron and steel in blast furnaces. It is partially substituted for cement to improve durability and sustainability. The slag produced in furnaces are cooled in water and grounded to become a fine powder. Specific energy consumption for grinding the slag is very less compared to ordinary Portland cement. Therefore, it is used in very high concentrations replacing 50% cement needs.

e. Limestone fines

It is used as one of the constituents while producing Portland limestone cement. Around 6-10% limestone fines are added that results in reduced energy consumption and carbon dioxide emissions. In case of high tricalcium aluminate availability in cement, the calcium carbonate may react during hydration that results in increasing strength and protects from sulfate attacks.

f. Cement Kiln Dust

According to Detwiler, United States of America alone generates close to 14 million tons of cement kiln dust and discarding 5 million tons of it [14]. It is used as a replacement for Portland cement in concrete and flowable slurry due to the similar properties it has like Portland cement [43].

Various cementitious materials used as secondary materials along with cement and detailed above are shown in figure 2.

Figure 2. Various Cementitious Materials used in Construction

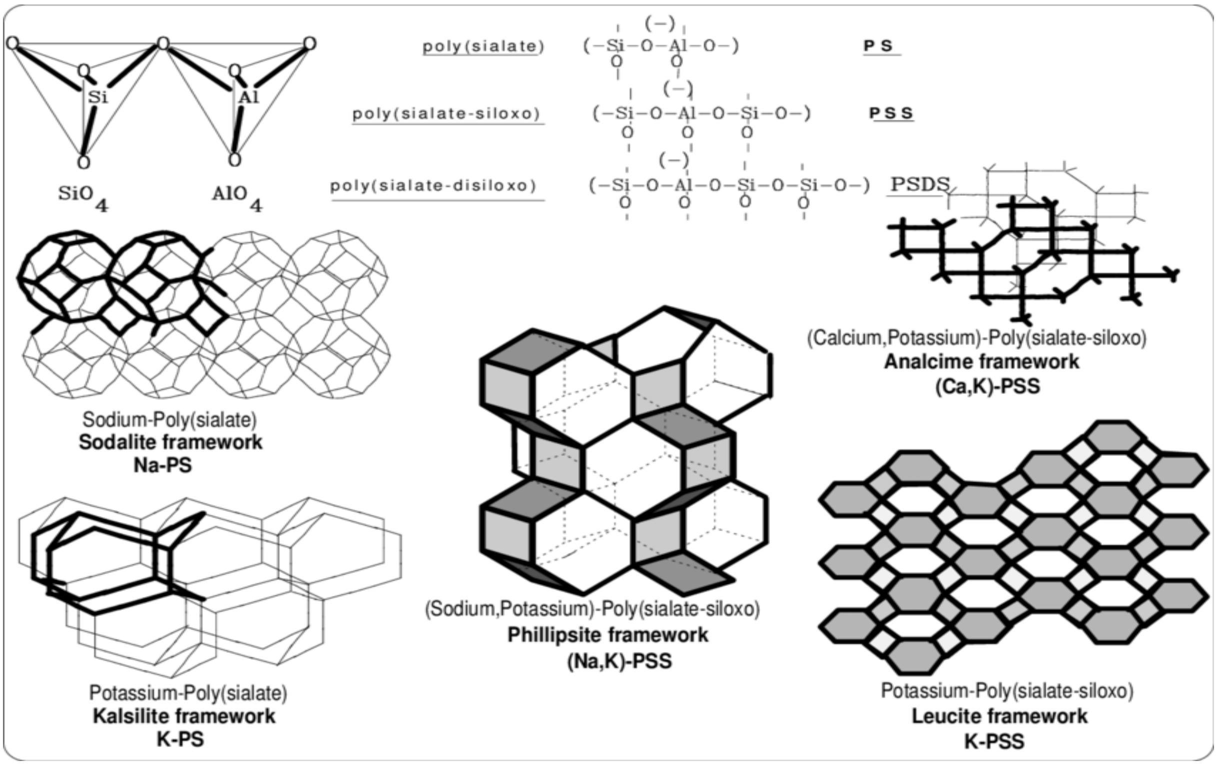

Figure 3. Molecular Arrangements in Geo-Polymerization Process

5. Geopolymer

Davidovits introduced a new science called geopolymer science. He is accredited for the name called Geo-polymer. Through his years' research to find a new heat resistance material in the form of non-inflammable and non-combustible plastic material, he invented the geopolymer. He extended his research and found the combination to produce geopolymer cement. It is a high alkali (potassium, calcium) poly (sialate, silaxo) cement that resulted from an inorganic polycondensation reaction (Geopolymerisation) that yields three-dimensional zeolitic frameworks. The computer molecular graphics of geo-polymerization process captured by him is shown in figure 3. He founded that geopolymer cement hardens rapidly at ambient temperature and provides compressive strength in the range of 20 MPa after 4 hours and after 28 days, the compressive strength increases to 70 to 100 MPa. They have "high early strength, low shrinkage, freeze-thaw resistance, sulfate resistance and, corrosion resistance" [8][9][10][11].

According to Singh, geopolymer cements are produced by treating the waste material containing aluminosilicate minerals such as Fly ash, granulated blast furnace slag, rice husk ash, clay, etc. with alkali solutions and curing of this cement results in high strength [47]. Aluminosilicate and activator are the two key factors having a direct effect on the geo-polymerization process [16]. Geopolymers exhibit superior mechanical properties due to the alkali-activated alumino-silicate constituent of the binding system and the hardening process [8][9][19][5][16][55]. Great attentions are paid by researchers to geopolymers because of their low cost, excellent mechanical and physical properties, low energy consumption, and reduced greenhouse emissions [23][56][57][13].

The compressive and flexural strengths of geopolymer as binding material in concrete by having different proportions as shown in the figure was done [22], with the setting time of seven days and twenty-eight days. It was found that by increasing the percentage of ground granulated blast furnace slag (GGBS) percentage from 0% to 40% and the rest as fly ash, both the strengths are gradually increasing with the increasing % of GGBS. They compared the strengths of fresh concrete, hardened concrete and geopolymer concrete (5 proportions of fly ash and GGBS) and the same is detailed in figure 4.

According to Khale et al., the mechanical strength of the geopolymer concrete is mainly depending on the pH of the activating solution that controls the compressive strength and suggested that the most suitable formation of better mechanical strength can be obtained by an activating solution with a pH range of 13-14 [28]. The source material may also affect the strength. High reactive source materials lead to higher strength [52] and suggested that at elevated temperatures use of high molarity sodium hydroxide with low alkali content would improve the early strength development of GPC.

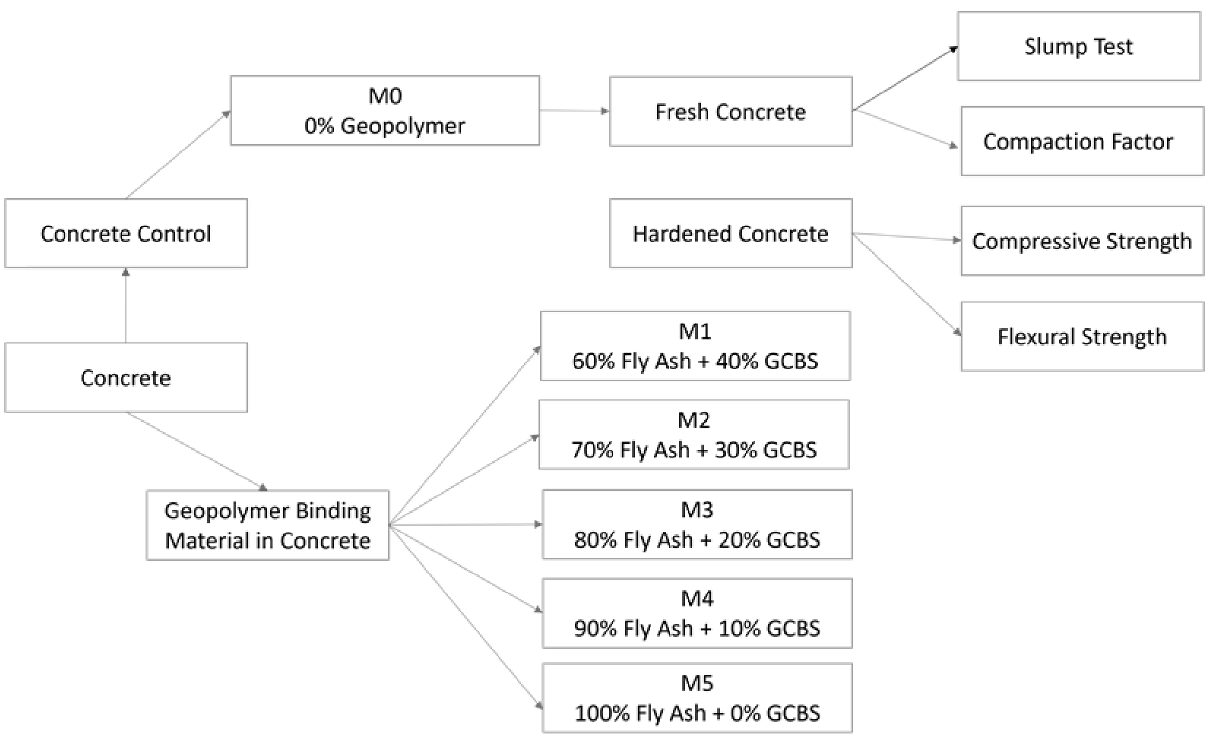

Figure 4. Combination used for study by Hamid Khan et al. 2016

6. Composite Rebar – FRP Bars

The corrosion of steel rebars is becoming an alarming problem for the construction industry. Alternate steel rebars are being warranted due to the high maintenance cost and the safety issues related to outdoor conditions like parking lots, ports, bridges, and their supports. Composite rebars are the alternatives available now with fiber/ glass reinforcements. Their high resistance to corrosion and high pulling strength made it a right choice to replace steel rebars despite their cost. Glass, carbon, aramid, and basalt fibers are used for replacement of steel bars (Figure 5).

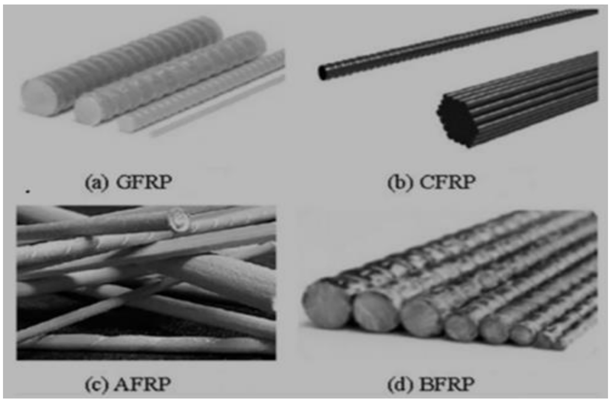

Figure 5. Variety of Fibers of used for replacement of steel

6.1. Advantages and Disadvantages

Table 1. Advantages of FRP over Steel Rebar

Advantages	Reasons
5 times lighter than traditional steel rebars	The density of FRP rebars are lower than the steel rebars
2.5 times stronger than traditional steel rebars	Due to the fiber orientation, tensile strength is higher than the steel rebars
Nontoxic	Composite rebars are graded as 4 which means they are comparatively less dangerous than steel rebars
Low heat conductivity – energy efficient	Steel is highly conducive compared to fiber/glass
High corrosion and chemical resistance	Fiber/glass is not very reactive to salts and sea waters
Electrically non-conductive, non-magnetic	Steel rebars are conductive and magnetic, therefore not suitable for high-intensity electrical applications
Easy to transport	FRP/glass rebars are 5 times lighter, therefore, occupies less volume, and easy handling
Prolonged life	Compared to steel, their industrial life is longer

Comparison of weight, strength, heat and electrical conduction, resistance to corrosion, life, and transportation for fiber reinforced polymers and steel rebars are made in table 1.

Their main disadvantages are [2]:

1. They don't yield before breakage or rupture
2. Their properties degrading at high temperatures
3. They have very low transverse strength compared to their axial strength
4. They have Low modulus of elasticity (Carbon FRP) compared to steel
5. Glass and aramid fibers have shown low durability in an alkaline environment

6.2. Comparison of Mechanical and Physical Properties

Replacement of FRP over steel rebars must thoroughly checked by comparing their mechanical and physical properties and to ensure that, they safely transmit the load subjected on them. These properties are mentioned in table 2.

Table 2. Mechanical and Physical Properties

	Steel Rebar	FRP rebar
Material	Steel	FRP
Tensile Strength, Mpa	360-390	800-1300
Elastic Modulus, Mpa	2,00,000	55,000
Elongation at fracture, %	25	2-3
Density in kg/m^3	>7	1,9 – 2.1
Linear coefficient of thermal expansion in 10-6/K	13-15	9-12

6.3. Comparison of FRP Rebars

Though many FRP rebars are cast for research, three of them were predominantly tested for applications. They are

1. CFRP - Carbon Fiber Reinforced Polymer
2. AFRP - Aramid Fiber Reinforced Polymer, and
3. GFRP -Glass Fiber Reinforced Polymer

The stress-strain curve for various types of FRP rebars and steel rebars is shown in figure 6 below. CFRP and AFRP are having comparatively better tensile strength than the GFRP, the GFRP scores well in terms of ductility.

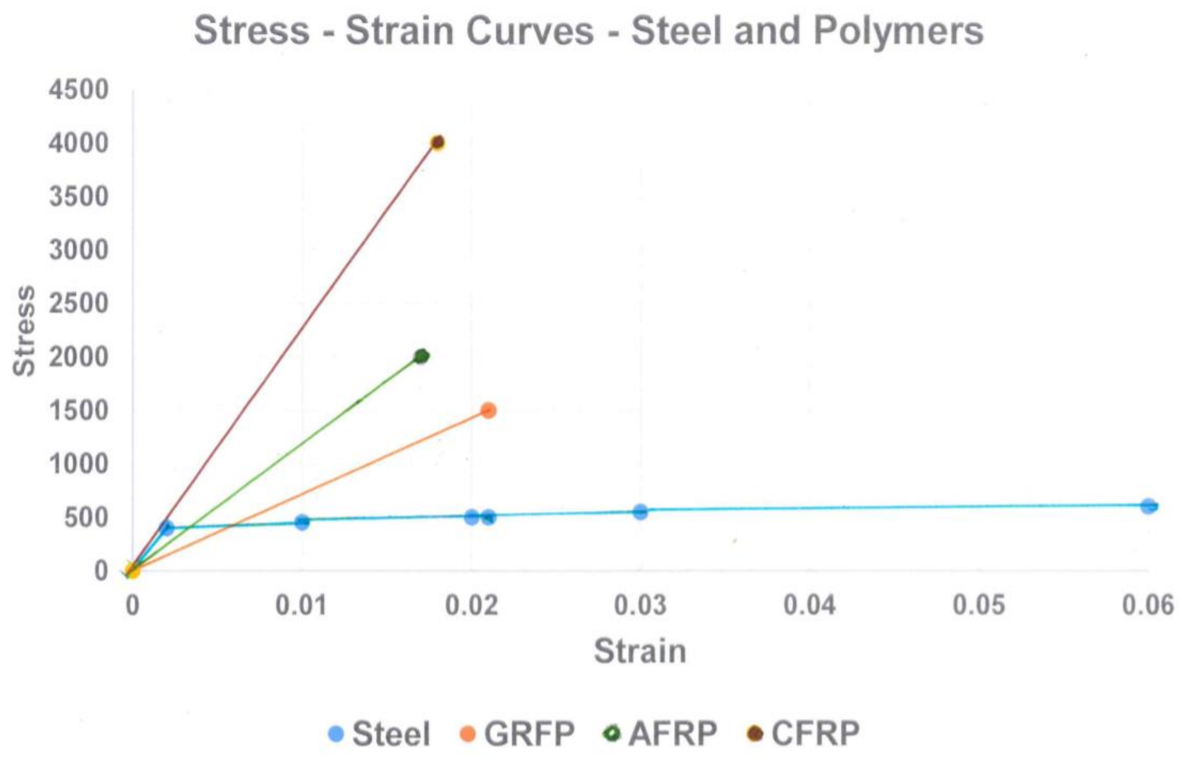

Figure 6. Stress – Strain Curves for Carbon, Aramid, Glass Fibers Reinforced Polymers and Steel

The mechanical behavior of GFRP and CFRP composites at varying strain rates and temperatures were studied and concluded that the tensile strength of CFRP is better than GFRP, but the percentage elongation of CFRP is found to be less than the GFRP, thus, GFRP withstands more strain before failure [18].

6.4. GFRP Rebars

The Glass Fibre Reinforced Polymer (GFRP) rebar is the most used rebar among FRP reinforcement due to its low price comparing to others. The tensile strength of the bare GFRP bar is high due to its anisotropic nature, with high yield strength [18]. GFRP rebars were cast and tested along with the steel rebars with the curing of 7 days and 28 days and it was found that GFRP has higher yield strength than the steel bars due to their unique anisotropic property that made them stronger in tension [48]. These properties are detailed in table 3.

Table 3. Tensile and Bending Measurements by Jabbar et al

Property	Tensile Strength of rebars		Bending Strength of rebars	
	Steel	Glass Fiber RP	Steel	Glass Fiber RP
Yield Strength (MPa)	530	593	1050	760
Yield Strain	17	40	16	20

6.5. GPC Reinforced with GFRP

Maranan et,al, experimentally found that the strength of the geopolymer concrete with glass fiber reinforced polymer is almost equivalent to the steel reinforced geopolymer concrete and suggested it as an alternative to steel reinforced concrete [34]. They also concluded that there is sufficient bonding between the surface of the glass fiber reinforced polymer and sand coating mainly due to the mechanical interlock and frictional force resistance offered between them [31][32][33]. The increasing rebar ratio increases the serviceable behavior of a beam. Modulus of elasticity of glass fiber reinforced polymer bars in beams has shown low past cracking flexural stiffness than the conventional systems. Shear behavior of geopolymer concrete reinforced with glass fibers reinforced polymer bars and stirrups was experimentally studied and found that the shear strength and deflection capacity increased almost by one hundred percent [30]. Similarly, they also observed a better performance from geopolymer concrete reinforced with glass fiber reinforced polymer in terms of flexural capacity and its behavior compared with ordinary Portland cement reinforced with glass fiber reinforced polymer.

Junaid et al. tested glass fiber reinforce polymer tube column prepared with geopolymer concrete reinforced with glass fiber reinforced polymer under various load conditions and studied the experimental load versus axial deformation, lateral deformation and midspan deflection in detail. They also compared them with ordinary Portland cement concrete reinforced with steel reinforcement and found that glass fiber reinforced polymer tube confinement has enhanced ductility for GPC based specimens compared to OPC based specimens. Further they found that, increasing load eccentricity too increases the ductility of the geopolymer concrete reinforced with glass fiber reinforced polymer bars [26].

For commercial usage of fiber reinforced polymer reinforced geopolymer beams, design standards are needed to validate their efficacy. Janeksha et al. considered the following four theories/design standards and compared the performance of GPC reinforced with GFRP.

1. AC1440.1R-15 (Guide for the Design and Construction of Structural Concrete Reinforced with Fibre-Reinforced Polymer (FRP) Bars),
2. CAN/CSA S806-12 (Design and Construction of Building Structures with Fibre-Reinforced Polymers),
3. parabolic stress block theory,
4. equivalent stress block theory for geopolymer concrete.

They concluded that CAN/CSA S806 – 12 yielded most accurate and conservative results compared to others.

Minhao et al. conducted experiments by preparing the geopolymer concrete mix with the composition mentioned in table 4 below:

Table 4. Composition of Geopolymer Concrete experimented by Minhao et al.

Constituent	Percentage
Coarse aggregates	47.3
Fine aggregates	29.4
Binder	15
Alkali activator	6.5
Water	6.1
Superplasticizer	0.1

They used equal parts of fly ash and ground granulated blast-furnace slag binder and cured the specimens under ambient conditions for 28 days and found that the compressive strength of geopolymer concrete is about 26 MPa. They further extended their study by placing stirrups to keep low, medium, and high eccentricities and proposed a model to predict the load-displacement behavior and validated the same with their experimental results [36].

Minhao et al., studied the hardening and bonding behavior of geopolymer concrete prepared with fly ash and ground granulated blast-furnace slag reinforced glass fiber reinforced polymer bars and compared with ordinary Portland cement reinforced with glass fiber reinforced bars. They found that overall behaviors are analogous, and GPC reinforced with GFRP has adequate compressive, tensile and bond strength similar that of ordinary Portland cement reinforced with glass fiber polymer. They also suggested using them in low-rise buildings [37].

6.6. Disadvantages of GFRP Compared to Steel Reinforcement

GFRP is costlier by 2 to 3 times than steel though it has its inherent advantages. Though they are commercially available in the form of bars or sheets, they are not available abundantly due to the special processes involved in manufacturing them. Replacement of GFRP for steel is done very much in an experimental manner and not in a commercial mode [48]. Comparable performances were reported by many researchers, yet to prove that GFRP outperforms steel reinforcement and is a viable alternative.

7. Conclusions

The above review of research related to geopolymer concrete, glass fiber reinforcement polymer usage to cast columns and beams that prevent the impact of stringent environment and enable easy serviceability. These two factors save billions of dollars for the construction industry. The usage of geopolymer concrete with fiber reinforcement polymer would save the earth through the reduction in emission of carbon-di-oxide a major pollutant of the environment. Two decades of research in these areas provided a lot of insights to further engineering research. Lots of combinations have been tried in these areas, but the proven models have not been arrived so far to help the construction engineering industry to take a major shift of using GPC reinforced with GFRP/other fibers. A comprehensive sound structural engineering research is a need of the hour to enlist the combination suitable for industries to adopt, till then, it is difficult to reduce the consumption of cement by the construction industry. The study is at an early stage and requires further experimental and analytical works. There are a lot of areas where one can step in and contribute to increasing the adoptability by industry. Some of the ideas are listed below:

1. Detailed experimental and analytical investigation on how cracks grow and contribute to long-term deflections of GPC beams reinforced with GFRP.
2. Investigation of the use of headed GFRP rebars as a main flexural reinforcement for GPC deep beams
3. Scope of research to detail geopolymer strength, transverse reinforcement ratio, variety of glass fiber reinforcements, strength characteristics against a variety of loads to identify analytical frameworks for using them.
4. Finite element models / finite volume models / fluid-structure interaction models can be built as mathematical simulation techniques to carry forward

the research for easy iterations of combinations and a variety of loads.

5. Establishing internationally recognized design codes for industries to use them.
6. Extending the research beyond beams and columns and evaluate them with slabs, footings, retaining walls, hollow beams, and columns and for precast elements too.

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