

Review

An Application Review of Fiber-Reinforced Geopolymer Composite

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Abstract: Fiber-reinforced geopolymer composites (FRGCs) were considered in terms of application in various areas, and a review is presented in this article. FRGCs are emerging as environmentally friendly materials, replacing cement in the construction industry. An alternative inorganic binder such as a geopolymer matrix promotes environmental awareness on releasing less CO₂. The inorganic matrix geopolymer is considered a greener cement for FRGCs. Various types of fiber reinforcements and their role toward the improvement of tensile, flexural, impact strength, fracture toughness, and energy absorption in overall mechanical performance in FRGCs were discussed. FRGCs and their properties in mechanical response, with correlation toward microstructure evolution at room and elevated temperatures, were also discussed. Simultaneously, the durability and impact strength of FRGCs and damage area as a function of the energy absorption were presented with 3D reconstruction images. Moreover, 3D images will cover the internal volume of the FRGCs with internal porosity and fiber orientation. Hybrid fiber reinforcement adds an extra step for the application of geopolymer composites for structural applications.



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Keywords: fiber; geopolymer; fiber-reinforced geopolymer composite (FRGC); mechanical strength; impact; damage

1. Introduction

Fiber-reinforced geopolymer composite (FRGC) is emerging as one of the alternative materials for cement in the construction industry. FRGC is considered an eco-friendly material due to its role in the global reduction in emission of CO₂ to the environment. Simultaneously, the composite provides good mechanical strength of flexural modulus, loss modulus, post-impact strength, and durability for a definite period at room and elevated temperatures. A positive aspect of the geopolymer matrix used for this composite is that could provide a finite period of durability at elevated temperatures without releasing toxic gases to the surroundings [1–3]. Fibers enhanced the brittle behavior of the geopolymer matrix into ductile one with improved mechanical strength and residual impact strength [4,5].

Unfortunately, there are no standard procedures or guidelines for the design of geopolymer mixtures that limit the wide acceptance of geopolymer in the industry [6]. Metakaolin binders, based on aluminosilicate and sodium -hydroxide and obtained via polycondensation reaction process, are the main constituents of geopolymers, but in recent years, waste materials such as fly ash and mining waste are largely employed for binder purposes, thus giving rise to eco-friendly geopolymers [7,8]. The mineral geopolymers are the inorganic matrices of various types such as poly(sialate (Si:Al = 1), poly(sialate-siloxo (Si:Al = 2), poly(sialate-disiloxo) (Si:Al = 3), and poly(sialate-multisiloxo) (Si:Al > > 3) [6]. This new class of hybrid materials emerges among the classic organic ones, exhibiting fire-resistant properties and zero toxicity. The demand is growing in the area of harsh temperatures operating conditions for composite materials sustainability. The survival and performance of FRGCs at elevated operating temperatures is needed. The geopolymer

matrix is considered to sustain and survive at high temperatures during the manufacture of composite materials, in comparison to the plastic ones [9,10]. The operational temperature of more than 200 °C allows the temperature exposure of geopolymer composites and leads to their important property of heat resistance [11–13]. FRGC is proposed as one of the alternative construction materials in the cement industry and as a repair material in the construction industry [14], emerging as a hybrid material for repairing damaged cementitious material [15,16]. The geopolymer composite could be used as an integrated material with thermoplastic and polyamides parts in various applications [17,18]. The geopolymer matrix satisfies one of the main requirements for structure safety, namely, the fire-resistant properties, i.e., the ability to resist at elevated temperatures resulting from fires [19–21].

The fiber-reinforced composite could sustain from room temperature (RT) to 1000 °C with excellent durability [22–24]. The behavior of organics, such as epoxy and geopolymer matrices, concerning resistance to fire, together with their most specific behaviors and properties, are reported in Figure 1, representing a transition from 2D to 3D technologies with varying Si:Al ratio.

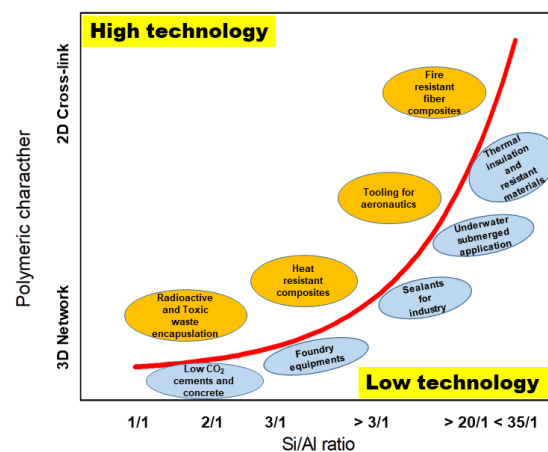


Figure 1. Polymeric character in geopolymers as a function of Si/Al ratio. From low to high technological applications.

Fire-resistant panels for aircraft cabin interiors are demanding materials that could allow people to escape from the plane after a crash. The composite with carbon and E-glass FRGCs allows survivors more time to escape. The flashover phenomenon describes the total time it allows for total burnout of the material, in other words, the total time it allows for escaping from the fire hazard. In the case of geopolymer, the matrix does not burn or generate smoke in case of fire hazards until the temperature of 1000 °C. By far, carbon and E-glass fibers are the most suitable reinforcements in the geopolymer matrix for composite to maintain the strength of the material. Thermoplastic-based composite ignites at irradiance levels of 50 kW/m² heat flux, whereas E-glass, and carbon FRGCs did not burn or release any smoke even after extended heat exposure at 800 °C. In the case of carbon FRGCs, they maintain the strength of 63% of initial flexural strength after heat exposure [25]. Retaining strength in FRGCs after exposure to elevated temperature is a very interesting topic for these materials in terms of maintaining mechanical strength. In various typologies of fiber reinforcements, longitudinal and transverse directions of fibers in both planes act as a frame for the FRGC material, which contributes significantly to its improved performance, in comparison to unidirectional reinforcement. In the case of E-glass, the strength of the FRGCs materials is lower. The introduction of polymeric fibers into the geopolymer matrix creates an extremely interesting material for construction solutions, which stands out from other solutions currently available in the construction market [26]. Some researchers also focused on hybrid fiber reinforcement with layered composites to use the combined effect of both fibers in the FRGCs materials [27–29]. The addition of

E-glass fibers increases the deflection of the composite that leads to failure. The optimized hybrid FRGC configuration demands high specific strength and stiffness [30–32]. The better adhesion of the geopolymer with fibers and concrete offers a good platform for use as repair and composite material. In contrast to geopolymer, which, as reported above, is considered a fire-resistant material that can survive after exposure to the flame temperature of 1000 °C, basalt FRGCs survive until 600 °C. Thus, the inorganic aluminosilicate matrix of geopolymers ensures excellent thermal stability after exposure to elevated temperature, but its mechanical properties are weak due to the brittle nature of the material. This limitation, which is related to the mechanical properties, may be overcome by reinforcing with fibers, which could improve the strength and toughness of the resultant composite. The fibers considered for reinforcing a geopolymer matrix can be divided into synthetic fibers, such as carbon, E-glass, and basalt (derived from mineral), and bio-fibers, such as flax, cotton, wool, and jute. In this application review, FRGCs are described and discussed. We focused on the effect of temperature on the strength and durability of the composite and addressed the durability, impact, and adhesion of the fiber–matrix interface and the inner volume of the composite.

2. Materials and Methods

2.1. Relevant Sources for Literature Review

A broad range of sources in the literature was reviewed from 1991 to 2021 in the areas of geopolymer and geopolymer composites for this article. The databases of this literature survey include various sources such as MDPI, Scopus, Science Direct, Google Scholar, and Springer. Articles, conference proceedings, data, reviews, chapters, and books of similar topics were filtered using keywords such as geopolymer, composite, fiber–matrix interface, microstructure evolution, thermal conductivity, impact, and damage characteristics of the materials. Section 1 in the introduction includes all the potential previous studies in this area. Section 2 includes various types of matrix and fibers with potential application follows. The basic and advanced application of matrix and composite is followed in Section 3 with emphasis on some recent literature surveys. Section 4 compares the data with the present scenario through an exhaustive literature survey.

2.2. Geopolymer Matrix and Its Various Types

Geopolymers have only recently emerged as solid materials from the powder-and-binder combination, and there are significant improvements in the matrix to meet various needs in application areas. One of the most progressive steps could be the use, in geopolymer foams, of highly porous materials, contributing in areas of thermal and acoustic insulators [33]. With one-step addition, the geopolymer matrix could be modified as a bilayer composite with the incorporation of the filler that may enhance properties such as thermal insulation and adsorbents in various developed functional properties [34]. Additives such as red mud could be combined with a geopolymer matrix as a pH regulator for the anaerobic digestion process. Environmental suitability enhances the application of geopolymer in areas of underwater applications [35].

2.3. Inorganic Synthetic Fiber Reinforcements in Geopolymer Matrix Composites

Basalt fiber is derived from a mineral that shows better chemical resistance against alkali, and it is considered as one of the reinforcements in the geopolymer matrix. For basalt, FRGCs have been shown to result in an increase in flexural strength after exposure to high temperature that may be due to the sintering behavior of both minerals' exchange between basalt fiber and geopolymer matrix [36]. As a result, the fiber–matrix interaction leads to good adhesion. Karvanis et al. studied the thermomechanical behavior of a 53 Vol.% basalt fiber-reinforced polymer (BFRP) composite with epoxy matrix, prepared by a hand layup compression molding combined method, using dynamic mechanical analysis (DMA) and thermomechanical analysis (TMA) [37]. The BFRP composites showed very good tensile and flexural strength, indicating that the epoxy matrix formed a very good interfacial bond

with the basalt fibers and demonstrating low mechanical behavior in case of a poor bond between matrix and fibers [38]. Additionally, short-fiber reinforcement in the geopolymer matrix enhances the mechanical strength of the composite. For example, short carbon fiber (7 mm length) reinforcement in geopolymer matrices increases the flexural strength from 16.8 to 91.3 MPa at room temperature. In the case of short Si-C fiber reinforcement (5 mm), the content of 2 Vol.% of the composite showed the highest flexural strength of 94 MPa. The composite prepared from carbon fiber with geopolymer matrix showed lightweight, strong, and durability with a low coefficient of thermal expansion [39]. Khan et al. observed that micro steel fiber-reinforced composite showed strong adhesion in the geopolymer matrix, and a 3 Vol.% provided 35 MPa flexural strength in the obtained composite material [40].

2.4. Organic Synthetic Fibers Reinforcements in the Geopolymer Matrix Composites

Polyvinyl alcohol (PVA) fibers were used in the geopolymer matrix, enhancing the flexural strength of the obtained composite; the addition of 1 Vol.% of PVA fibers to the geopolymer matrix increases the ductility and impact resistance of the composite. Zanotti et al. prepared metakaolin-based geopolymer and compared its behavior with ordinary portland cement (OPC) concrete. They provide reinforcement by adding 0.5% and 1 Vol.% of short PVA fibers at two different curing regimes (ambient curing and 24 h mild heat curing at 45 °C), observing a significant improvement in cohesion with the addition of PVA fibers. The incorporation of 0.5% Vol. of PVA fibers to the plain matrix resulted in a 65% increase of cohesion (1.32 MPa) in heat-cured specimens and a 204% increase (1.00 MPa) in ambient-cured specimens [41]. The polyoxometalate (POM) fibers provide significant mechanical reinforcement with a flexural strength of 11 MPa and compressive strength up to 62 MPa [42]. The porous geopolymer has emerged as one of the cooling mechanisms in buildings, which could act as wetting porous materials for the capillary rise of water. A porous composite of a geopolymer could be achieved by incorporating poly lactic acid (PLA) fiber reinforcement in the matrix with optimized parameters of 29 µm length of short fibers at 30 Vol.% of content [43].

2.5. Bio-Fibers Reinforced Geopolymer Composite

Bio-fibers such as cotton, jute, flax, and wool are hydrophilic in characteristics. This is one of the reasons why bio-fibers are considered good candidates for reinforcement in the geopolymer matrix. Riberio et al. proposed Amazonian metakaolin geopolymer reinforced with bamboo as potential green sustainable construction material. They measured a compressive strength in the ranges of 23–38 MPa for micro bamboo fibers (BF) alkali-treated (BF1A), 23–25 MPa for short BF alkali-treated (BF4A), and 25–29 MPa for short BF water treated (BF4W), and flexural strength values ranged from 4 to 8 MPa for geopolymer reinforced with bamboo fibers [44]. Modulus of elasticity of sisal fiber reinforced geopolymer composite improves up to 3.19 GPa with 5.15 Vol% addition [24]. Cotton fibers enhance the compressive and impact strength of the geopolymers to 46 MPa and 4.5 kJ/m² with the addition of 0.5 wt.%. However, adding more cotton fibers until 1 wt.% reduces the compressive strength of the composite [41–43]. Natural fiber reinforced geopolymer matrices such as wool and bio-fibers produce environmentally friendly, low-cost, and light composites with improved flexural strength. The strength of the composite is based on the interfacial adhesion between the fiber–matrix interfaces. Interaction between fiber and matrix interface arises from the surface chemistry of fiber surface. With an average of 5 wt.% of wool fiber content, the flexural strength improved until 9.1 MPa with failure at the end [45]. The interaction of the wool fiber with a geopolymer matrix creates a sulpho-aluminosilicate compound named sodalite. Flax fiber reinforced geopolymer composite shows the ultimate flexural strength of 70 MPa at 10 Vol.% of the fiber content [46].

2.6. Steel Fiber Reinforced Geopolymer Composites

In competition with other fibers, steel fiber is also considered as one of the potential additives in geopolymer composites to enhance the properties of flexural strength, ten-

sile strength, ductility, toughness, chemical resistance [47,48]. The load-carrying capacity increased with the addition of the reinforcement materials of high strength, which significantly increased the compressive strength of the materials. One of the various shapes of the steel fiber reinforced additive in the geopolymer composite with approximately 67.1% belongs to the hook category and <10% to others. However, steel fibers have a negative effect on the porosity and workability of the geopolymer composite materials.

2.7. Short and Hybrid Fiber-Reinforced Geopolymer Composites

Fibers of various lengths are considered as reinforcement in geopolymer matrices [49]. Based on the requested application, polymeric short fibers such as polypropylene (PP), polyethylene (PE), or PLA are considered as reinforcements [50]. The effect of various combinations of hybrid reinforcement has significantly improved the mechanical properties of FRGCs, thus not limiting the structural applications of these materials.

2.8. Methods for Composite's Fabrication

There are several procedures for the incorporation of fibers, fabrics, and fillers into the geopolymer matrix. Various stacking sequences have been implemented, such as single, multiple layers, random, oriented direction, which could lead to an isotropic or anisotropic distribution of fibers within the geopolymer's matrix. One of the standard techniques of the hand layup process is explained as follows. Geopolymer composite is fabricated by the incorporation of various fibers either by hand layup technique or mold reinforcement. The fiber content with 30 Vol.% was incorporated into the geopolymer matrix by the hand layup technique. The composites were vacuum bagged for removal of voids and porosity and undergoes curing at a furnace temperature of 60 °C for 24 h. After drying, the composite was maintained at RT for characterization and mechanical testing. To maintain a certain thickness, various layers of fiber were reinforced inside the geopolymer matrix. The samples were then tested for the mechanical properties at RT.

Several methods have been used in the literature to evaluate the quality of the composite, such as scanning electron microscopy (SEM) or micro-computed tomography (μ -CT), for which 3D images can be built by using appropriate graphics software. Generally, to test the flexural behavior, impact tests (drop in height) were carried out to determine the mechanical performance of the geopolymer reinforced fiber composite (GRFC) materials.

3. The Physical, Chemical, and Mechanical Domains of Geopolymer-Based Composite

3.1. Chemical Structure of Geopolymer Matrix

A silioxo group has been emerged from low to high technology in the ratio of Si:Al group with various properties. Emerging technology from 2D to 3D network could offer fire- and heat-resistant fiber composites materials. Inorganic matrix of chemical composition poly(sialate) to poly(sialate-disiloxo) with Na, K, and Ca network structure were largely used. Network structures of this geopolymer inorganic matrix are shown in Figure 2.

3.2. The Domain of Composites in Various Fields

Composites are fall in the category of economic benefit material in terms of density and cost. Composites show Young's modulus more than 100 GPa, which represents the market demand. Nowadays, composites dominate the material market due to being lighter weight, strong materials with higher toughness. Composites, including those based on geopolymers, stand as the most efficient material in the market in comparison to ceramic and metallic materials.

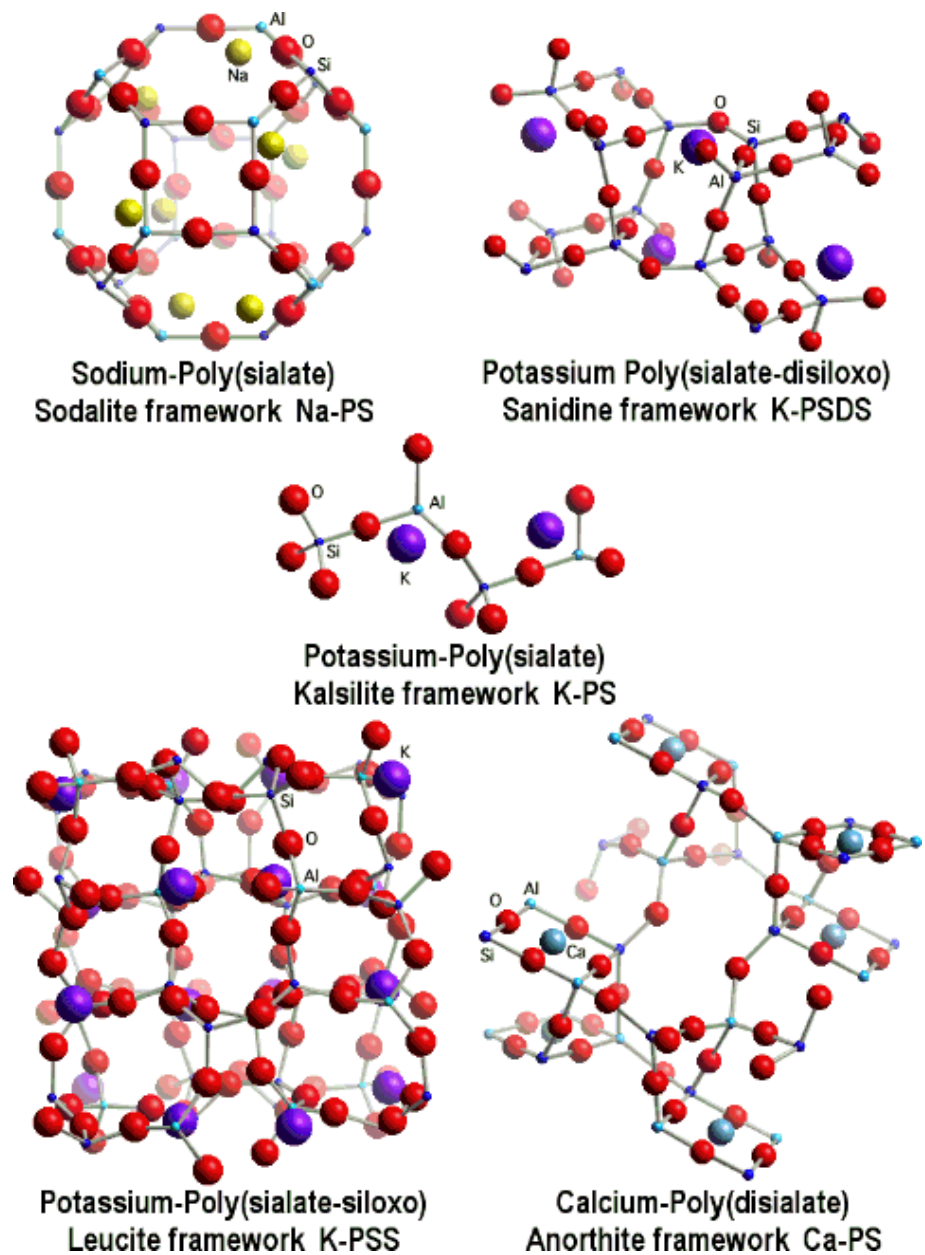


Figure 2. A framework of geopolymer structure with Na, K, and Ca–poly (sialate-siloxo). Reprinted from <https://www.geopolymer.org/science/examples-geopolymer-frameworks/>; with permission of Geopolymer Institute. Last accessed on 16 February 2021.

Regarding the operational environment and the service temperature, composite strength and Young’s modulus as a function of elongation, toughness, density, and cost are plotted as examples in Figures 3 and 4. Although composite is expensive in the market, the material can be fully recycled.

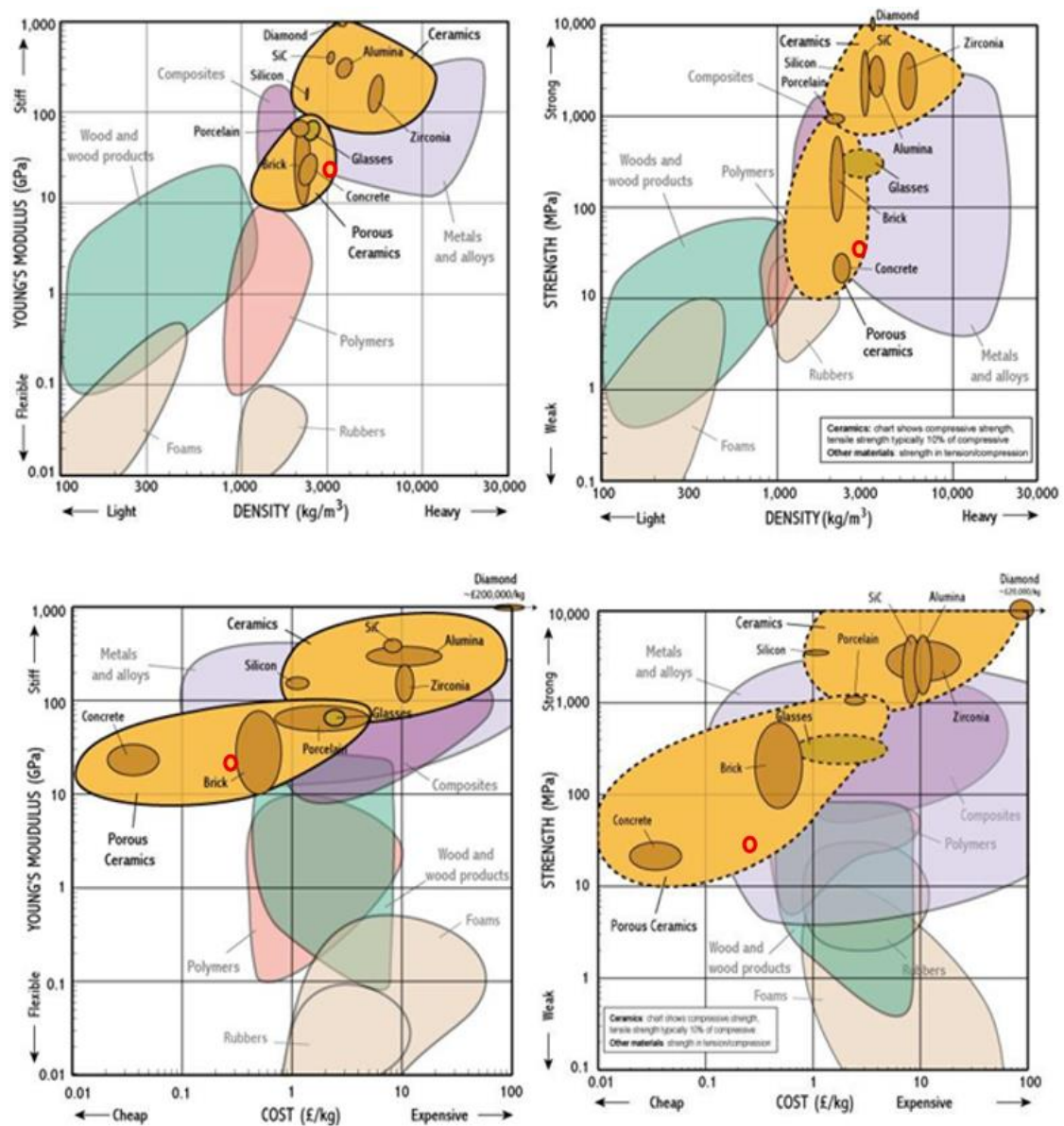


Figure 3. Schematic representation of Young’s modulus and strength as a function of density and cost for various materials (geopolymer is marked in red for comparison). Reprinted from http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts/default.html. Last accessed 16 February 2021.

The composite performance based on polymer matrices at service temperature is of major concern in various application fields. As it releases CO₂ into the surrounding, it becomes economically endangered. The matrix has been categorized into several kinds such as thermosets, thermoplastics, metals, and ceramics in the category of organic, synthetic types. Composites are prepared by various routes or procedures such as chemical vapor deposition scheme, sol–gel processing, and vapor phase grow/reaction process. Fibers such as long and short fibers, woven fabric, whiskers, and particulates are used in various matrices for the composite preparation. These materials are categorized into various typologies such as fiber-reinforced or particle-reinforced composites and in various combinations. Furthermore, fiber-reinforced composites can be categorized into single- and multi-layered composites with preferred orientations in various directions. Based on the various categorizations, composites are represented in Figure 5.

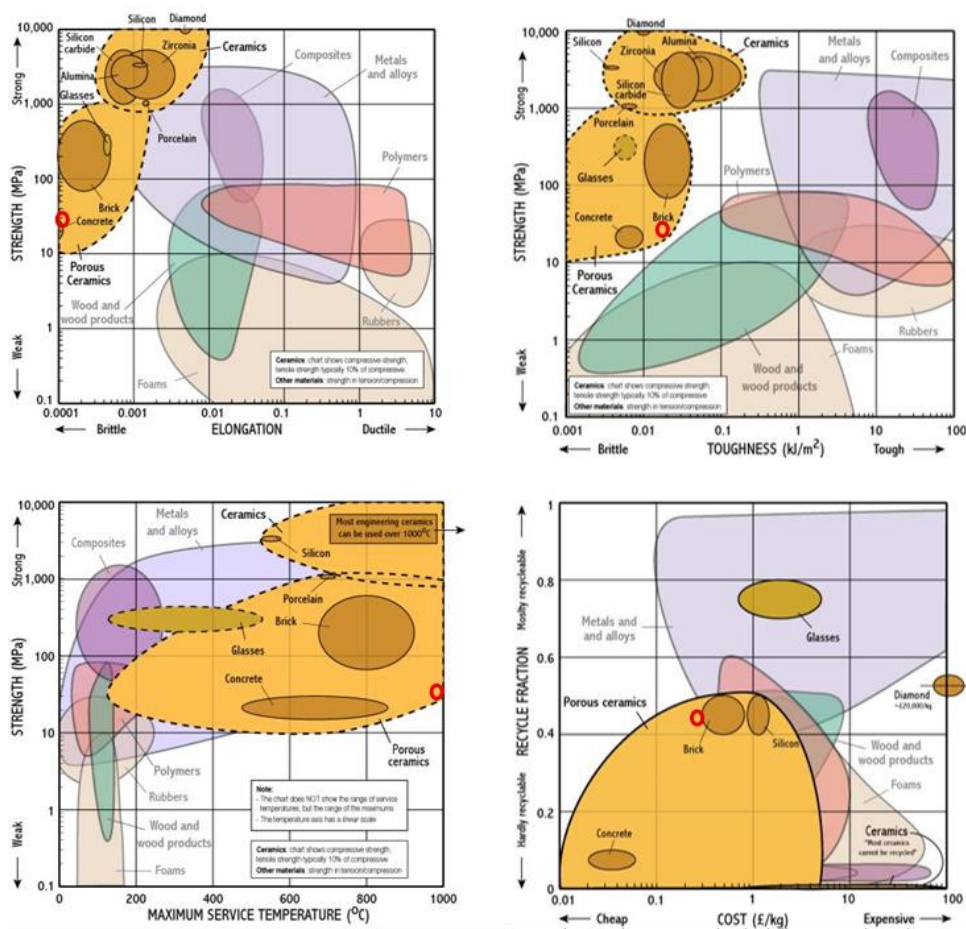


Figure 4. Schematic representation of strength as a function of elongation, toughness, and maximum service temperature, and the cost of recycled fraction for the various materials (geopolymer is marked in red for comparison). Reprinted from http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts/default.html. Last accessed 16 February 2021.

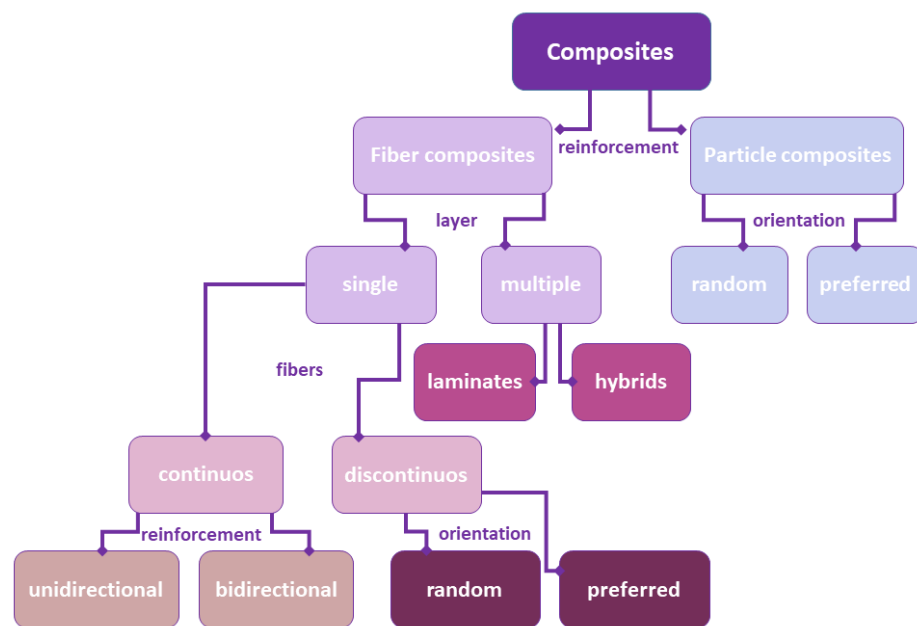


Figure 5. Schematization of different composite materials based on their constitution.

4. Characterization of Pure Geopolymer and Fiber-Reinforced Composite

4.1. Characterization of Pure Geopolymer

Physical, chemical, structural, thermal, and mechanical characterizations of geopolymer are largely analyzed and investigated [51]. The matrix geopolymer is based on fly ash or metakaolin binder; the minerals that characterized silicate-oxo compounds show very different physical, chemical, and mechanical properties. The reaction process of polymerization has a strong influence on the chemistry of the material. The metakaolin binders show distinct sharp edges, while the fly ash particle is spherical in surface features. The thermal characterization of the geopolymer matrix shows the evolution of exothermic and endothermic peaks as a function of the temperature. The particle size distribution of geopolymer powder falls within the range of 0.1 to 100 μm . Although at RT, the geopolymer matrix shows compactness, at elevated temperature, it shows expansion in the volume of the matrix with cracks on the surface (Figure 6). The shrinkage of the geopolymer matrix as a function of the curing temperature and time of exposure is 13.2 with a density of 1.8 g/cm^3 [52,53].

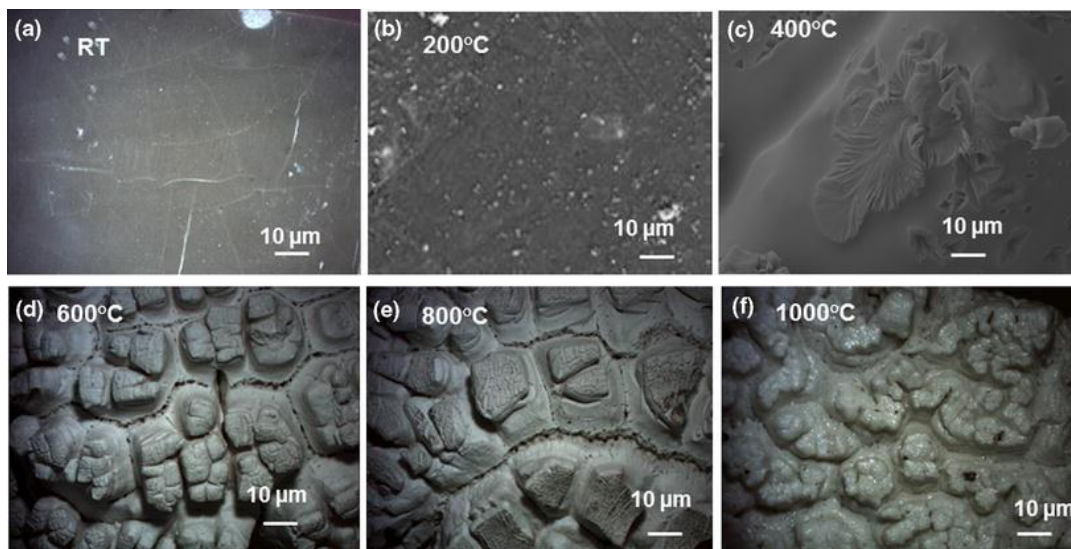


Figure 6. Microstructural evolution of (a) pure geopolymer matrix and (b–f) sintered geopolymer at various temperatures from 200–1000 °C. Reprinted from [4] with permission from MDPI.

The mechanical properties of the geopolymer matrix fall within the range of 55–65 MPa. Its mixing vibration shows improved compressive strength for 15 min [54,55]. The compressive strength and flexural strength of the geopolymer matrix as a function of vibration time for the mixture is displayed in Figure 7, in which it is possible to observe an initial increase of both typologies of strength with reaching of a plateau between 15 and 25 min of vibration.

4.2. Fiber-Reinforced Geopolymer Characterization

4.2.1. Synthetic Fibers Such as Carbon, E-glass, and Basalt Fiber-Reinforced Geopolymer Composites

Synthetic fibers are considered as potential fillers such as short fiber, long fiber, and fiber in plain reinforcement in the geopolymer matrix. An example of short fibers is represented by the E-glass, which are used at various lengths in reinforcing the geopolymer matrix. Figure 8a,b shows the compressive and bending strength of geopolymer as a function of fiber length of E-glass fiber at various volume fractions.

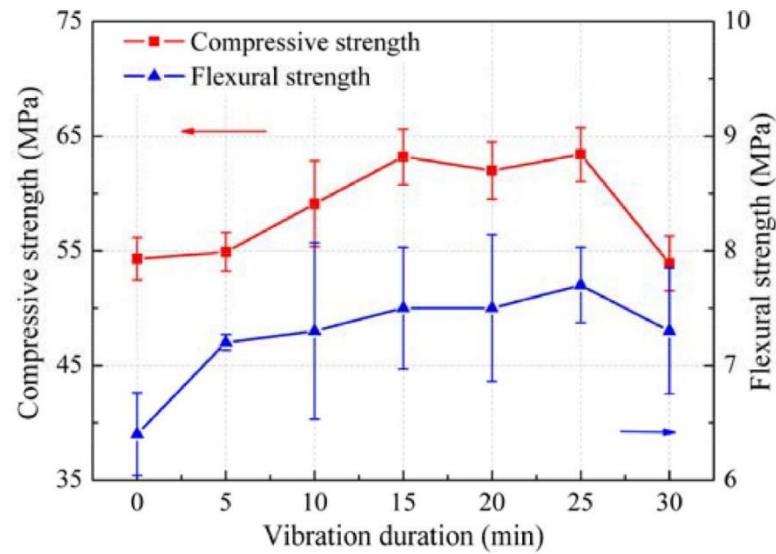


Figure 7. Compressive strength and flexural strength of the geopolymer matrix as the function of the vibration time of mixing. Reprinted from [16] with permission from Elsevier.

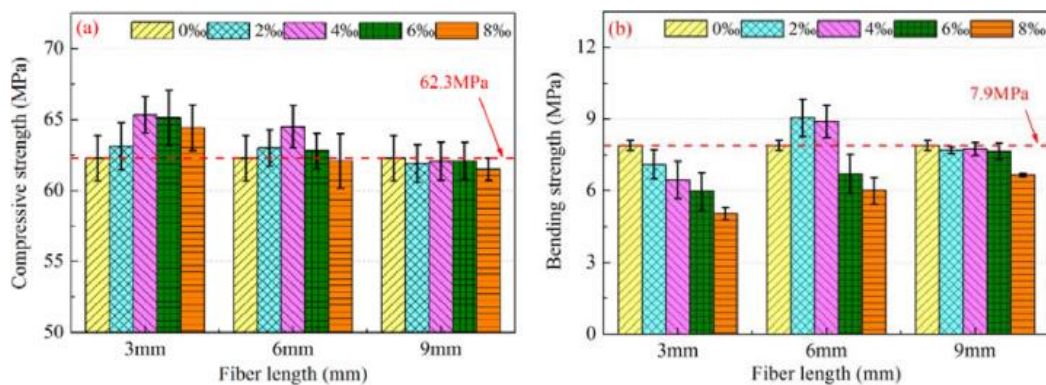


Figure 8. Compressive (a) and bending (b) strength of geopolymer as the function of fiber length of E-glass fiber at various volume fractions. Reprinted from [16] with permission from Elsevier.

Based on the fiber-reinforced characterization, microstructural evolution results in a fiber–matrix interface with contributing mechanical properties [56,57].

The microstructure evolution of fiber in plain reinforced geopolymer composite showed adhesion of the fiber at RT and evolution of the matrix and interface as a function of the exposure temperature.

Figure 9a,f shows the carbon fiber reinforcement in the geopolymer matrix at RT and their microstructural reinforcement at various temperatures until 1000 °C for a definite period. Similarly, the microstructural evolution of E-glass and basalt fiber-reinforced geopolymer matrices are reported in Figures 10 and 11.

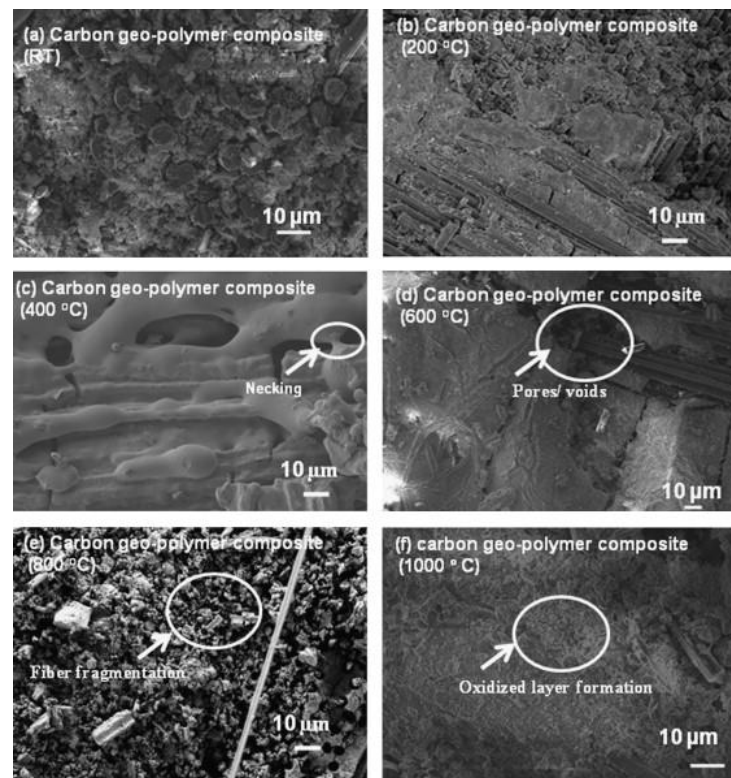


Figure 9. Microstructure evolution of (a) carbon fiber reinforced geopolymer composite at room temperature and (b–f) sintered at various temperatures from 200–1000 °C. Reprinted from [2] with permission from Elsevier.

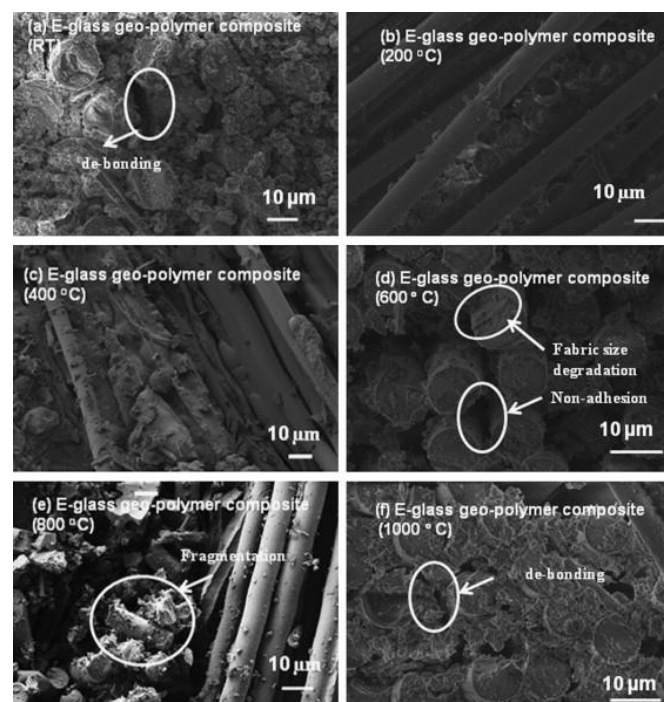


Figure 10. Microstructure evolution of (a) E-glass fiber-reinforced geopolymer composite (FRGC) at room temperature (RT) and (b–f) sintered at various temperatures from 200–1000 °C. Reprinted from [2] with permission from Elsevier.

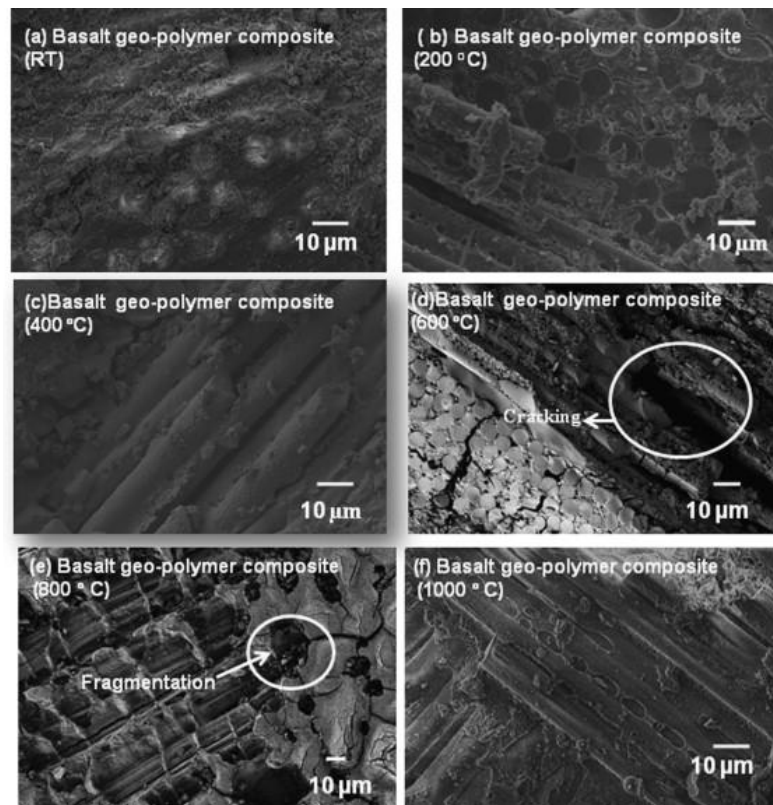


Figure 11. (a) Basalt fiber reinforced geopolymer composite at RT and (b–f) sintered at various temperatures from 200–1000 °C. Reprinted from [2] with permission from Elsevier.

Carbon fiber reinforced composite shows better adhesion and homogeneity on the surface layers, while E-glass shows sliding behavior and detachment of fiber from the matrix at elevated temperature, leading to the fragmentation phenomenon [58,59]. In the case of basalt reinforced geopolymer composite, sintered porosity was observed, which may be developed due to the chemical interaction of basalt fibers with the geopolymer matrix. Basalt fiber has a composition derived from rocks and minerals; thus, an exchange of minerals from fiber to the matrix causes the composite materials to be more brittle in nature. Flexural strength and modulus of the geopolymer composite as a function of the temperature for carbon, E-glass, and basalt fiber reinforcement are shown in Figure 12.

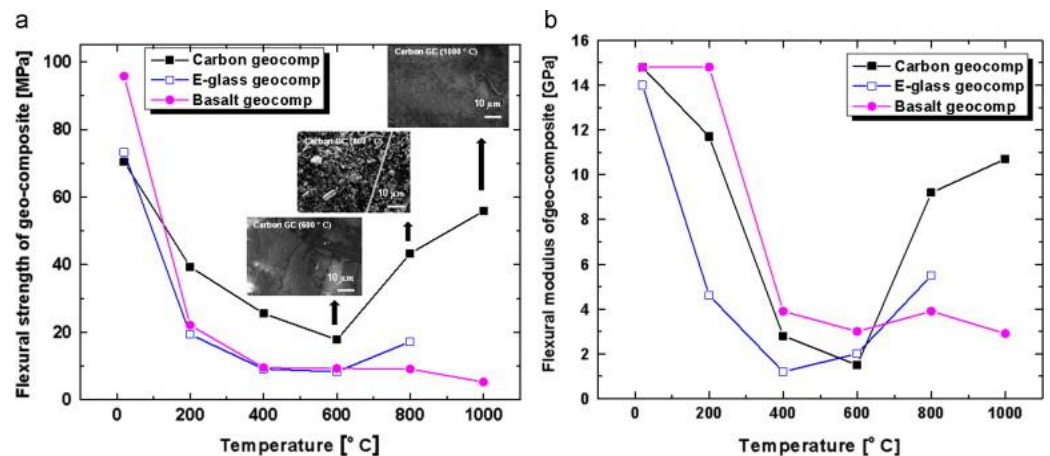


Figure 12. Flexural strength (a) and modulus (b) of carbon, E-glass, and basalt fiber-reinforced geopolymer composite (FRGC) versus at various sintered temperatures. Reprinted from [2] with permission from Elsevier.

After sintered at various temperatures, carbon FRGCs could survive and retain two-thirds of their initial strength. However, E-glass FRGCs experience volumetric expansion at sintered temperatures. Basalt FRGCs undergo sintering and transform into a ceramic-like structure; as a result, the strength of the material is brittle.

4.2.2. Durability on Impact of Fiber-Reinforced Composite

The durability of the fiber-reinforced composite is determined by performing an impact test and calculating the residual strength and damaged area of the composites (Figure 13). The damaged area and the depth of the damage were determined by μ -CT analysis.

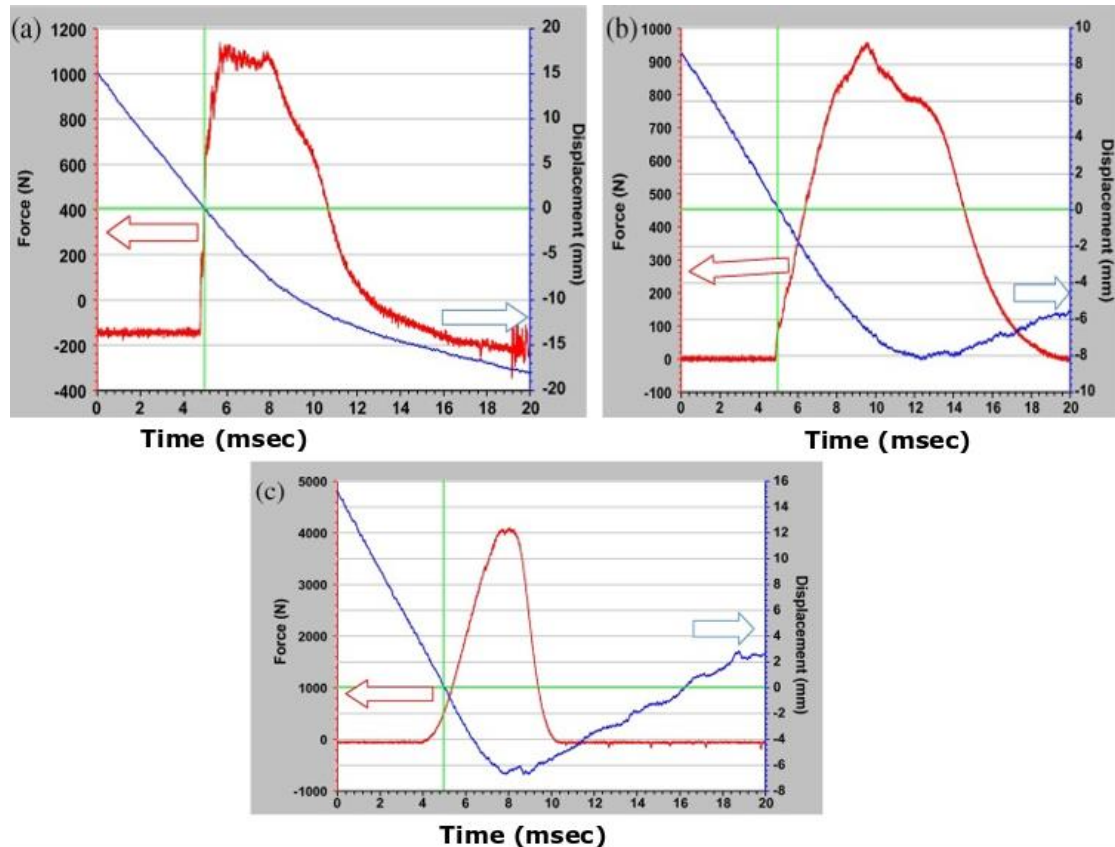


Figure 13. Force and displacement versus time for the (a) carbon, (b) E-glass, and (c) basalt fiber reinforced geopolymer composite. Reprinted from [5] with permission from Elsevier.

The inner volume of the composite could reveal the fiber orientation and the alignment within the volume of the matrix. The μ -CT scan reveals the inner volume and structure of the composite. Delamination, i.e., rupture of the fiber and matrix during impact from the damaged area to the surrounding area, is revealed from the image below (Figure 14). Based on the durability investigation, carbon fiber reinforced geopolymer composite shows less damage area with intact residual strength in the case of E-glass fibers, which remains with minimum loss in strength. In the case of basalt fiber reinforced geopolymer composites, the loss in strength is 65%. The minimum loss in strength of 27% in the case of E-glass fiber may have resulted due to the slipping mechanism of E-glass in the geopolymer matrix during impact. This leads to the weak interface bonding between E-glass fiber and the matrix within the composite [60,61]. The bonding is strong between carbon fiber and geopolymer matrix, which leads to the intact behavior of the fiber within the composite resulting in less damage.

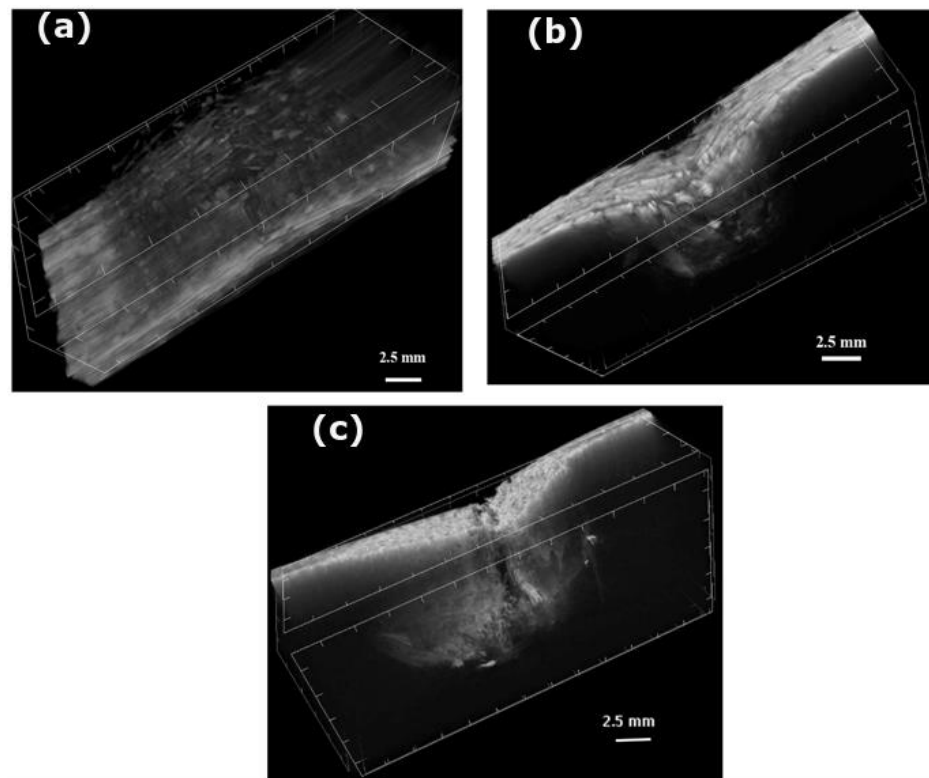


Figure 14. Inner volume around the notch and damaged area of the composite with (a) carbon (b) E-glass, and (c) basalt fiber. Reprinted from [10] with permission from MDPI.

4.2.3. Natural Fibers Such as Cotton, Flax, Jute Fiber Reinforced Geopolymer Composites

There is a limitation on adding cotton fiber into the geopolymer matrix for the formation of the composite. The increase in the volume of the hydrophilic natural fibers, within the geopolymer matrix leads to a reverse effect on the strength of the composite. Figure 15a,b represents stress–strain curves of geopolymer composites with cotton fabric alignment.

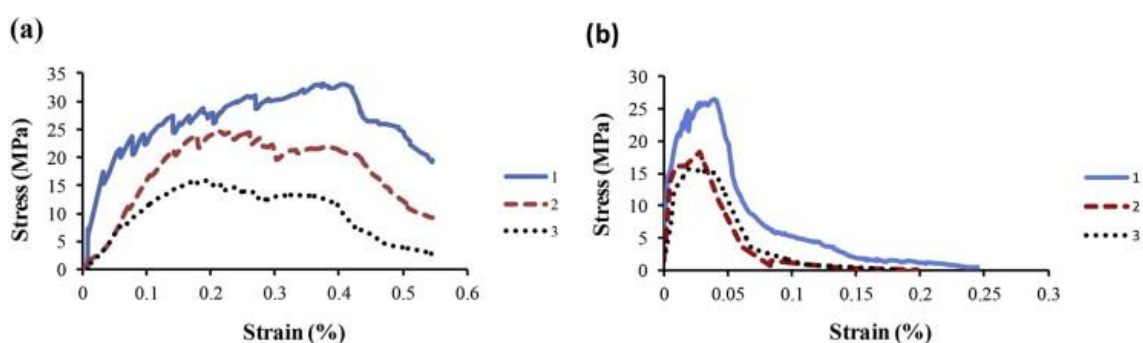


Figure 15. Stress–strain curves of geopolymer composites with the cotton fabric (a) horizontally aligned and (b) vertically aligned to the applied load. [Legend: (1) = 8.3 wt.%, (2) = 6.2 wt.%, (3) = 4.5 wt.%]. Reprinted from [18] with permission from Elsevier.

Cotton, flax, and jute types of natural fabrics have some limitations as geopolymer composites since they are unable to operate at high temperatures. Figure 16 displays Young's modulus and tensile strength of various fibers and materials as a function of density. It has been observed that carbon fiber reinforced geopolymer composite stands ahead and more reliable in terms of Young's modulus and tensile strength [62–64].

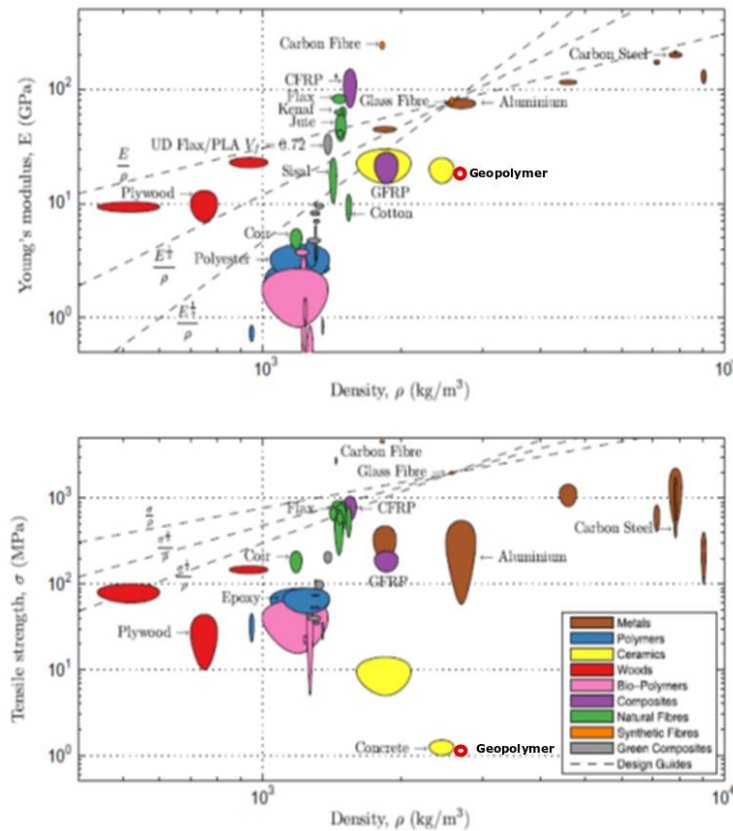


Figure 16. Young’s modulus and tensile strength as the function of density for various materials (geopolymer is marked in red for comparison). Reprinted from [19] with permission from Elsevier.

Table 1 displays the summary of the geopolymer matrix and the possible fiber properties for the composites.

Table 1. Bulk density, flexural strength, modulus, compression, elongation of geopolymer, and fibers [1–5,18,25,27,28,30].

| Geopolymer | Bulk Density (g/cm ³) | Flexural Strength (MPa) | Flexural Modulus (GPa) | Compression |
|-------------------------------|-----------------------------------|-------------------------|------------------------|-------------------------|
| Matrix | 2.0 ± 0.1 | 27.8 ± 0.1 | 18.5 ± 0.1 | 11.7 ± 0.1 |
| Fibers | Bulk density (g/cm ³) | Tensile strength (MPa) | Elastic Modulus (GPa) | Ultimate Elongation (%) |
| Steel | 7.65–7.85 | 345–2850 | 200–210 | 0.5–3.5 |
| Carbon fiber, carbon nanotube | 1.4–2.2 | 500–3500 | 35–1800 | 0.3–2.5 |
| Synthetic Polymers | | | | |
| PVA | 1.2–1.3 | 800–2500 | 29–42 | 5.7–7 |
| PP | 0.9–0.95 | 240–760 | 1.5–10 | 15–80 |
| PE | 0.92–0.97 | 80–3500 | 5–113 | 3–100 |
| Aramid | 1.38–1.47 | 2300–3500 | 63–120 | 2–4.5 |
| Acrylic | 1.16–1.18 | 270–1000 | 13.8–19.3 | - |
| Polyester | 1.22–1.38 | 580–1100 | 15 | 35 |
| Nylon | 1.13–1.41 | 440–1000 | 4.1–5.2 | 16–20 |
| PET | 1.3–1.4 | 420–450 | 3.1–10 | 11.2 |

Table 1. Cont.

| Geopolymer | Bulk Density (g/cm ³) | Flexural Strength (MPa) | Flexural Modulus (GPa) | Compression |
|------------------|-----------------------------------|-------------------------|------------------------|-------------|
| Natural Fiber | | | | |
| Jute | 1.3–1.5 | 250–350 | 26–32 | 1.5–1.9 |
| Sisal | 1.34–1.45 | 280–750 | 13–26 | 3.0–5.0 |
| Coconut | 0.87–1.4 | 120–200 | 19–26 | 10.0–25.0 |
| Bamboo | 0.6–1.1 | 140–800 | 11–32 | 2.5–3.7 |
| Cotton | 1.5–1.6 | 390–600 | 5.8–11 | 6.0–10.0 |
| Palm | 1.3–1.46 | 21–60 | 0.6 | - |
| Wool | 1.3 | 160 | 3.5 | - |
| Hemp | 1.4–1.5 | 270–900 | 23.5–90 | 1–3.5 |
| Kenaf | 1.4 | 223–930 | 14.5–53 | 1.5–2.7 |
| Coir | 1.15–1.46 | 95–230 | 2.8–6 | 15–51.4 |
| Banana | 1.4 | 500 | 12.0 | 1.5–9 |
| Flax fabric | 1.5 | 500–1500 | 50–70 | 1.1 |
| Bagasse | 1.3 | 222–290 | 17–27 | - |
| Inorganic fibers | | | | |
| E-Glass | 2.5–2.62 | 3100–3800 | 72.4 | 4.8 |
| S-Glass | 2.46–2.49 | 4020–4650 | 86.9 | 5.4 |
| C-glass | 2.6 | 3310 | 69 | 4.8 |
| AR-glass | 2.7 | 3240 | 73 | 4.4 |
| Basalt | 2.65–2.80 | 3000–4840 | 89–110 | 3.00–3.15 |
| Asbestos | 2.55 | 620 | 160 | - |
| Alumina | 3.3–3.95 | 1700–2000 | 300–380 | 0.4 |
| Alumina-silica | 3.4 | 1590–2550 | 200–248 | 0.8–1 |
| SiN | - | 2500–4800 | 195–300 | - |
| SiC | 2.5–2.7 | 2200–3450 | 221–250 | - |
| BN | 7.65–7.85 | 2100 | 345 | - |

The summary of various types of fibers such as metallic, inorganic, polymeric, carbon-based, and natural fibers as a function of fiber content (%) for the determination of the relative compressive strength of composite materials is represented in Figure 17. Natural fibers reinforced geopolymer composite shows a compressive strength below 100%. The carbon-based geopolymer shows strength above 100%, with similar behavior from E-glass and Si-C ones. However, carbon fiber reinforced geopolymer composite stands ahead in terms of operational temperature at a value of 1000 °C. Regarding the strength and durability of the fiber-reinforced composites, carbon fibers composite displays better performance in mechanical strength with durability after damage [65–67]. In comparison with E-glass fibers, reinforced geopolymer composite shows optimum durability with residual strength. However, the remaining strength of carbon fiber reinforced geopolymer composite remains unchanged.

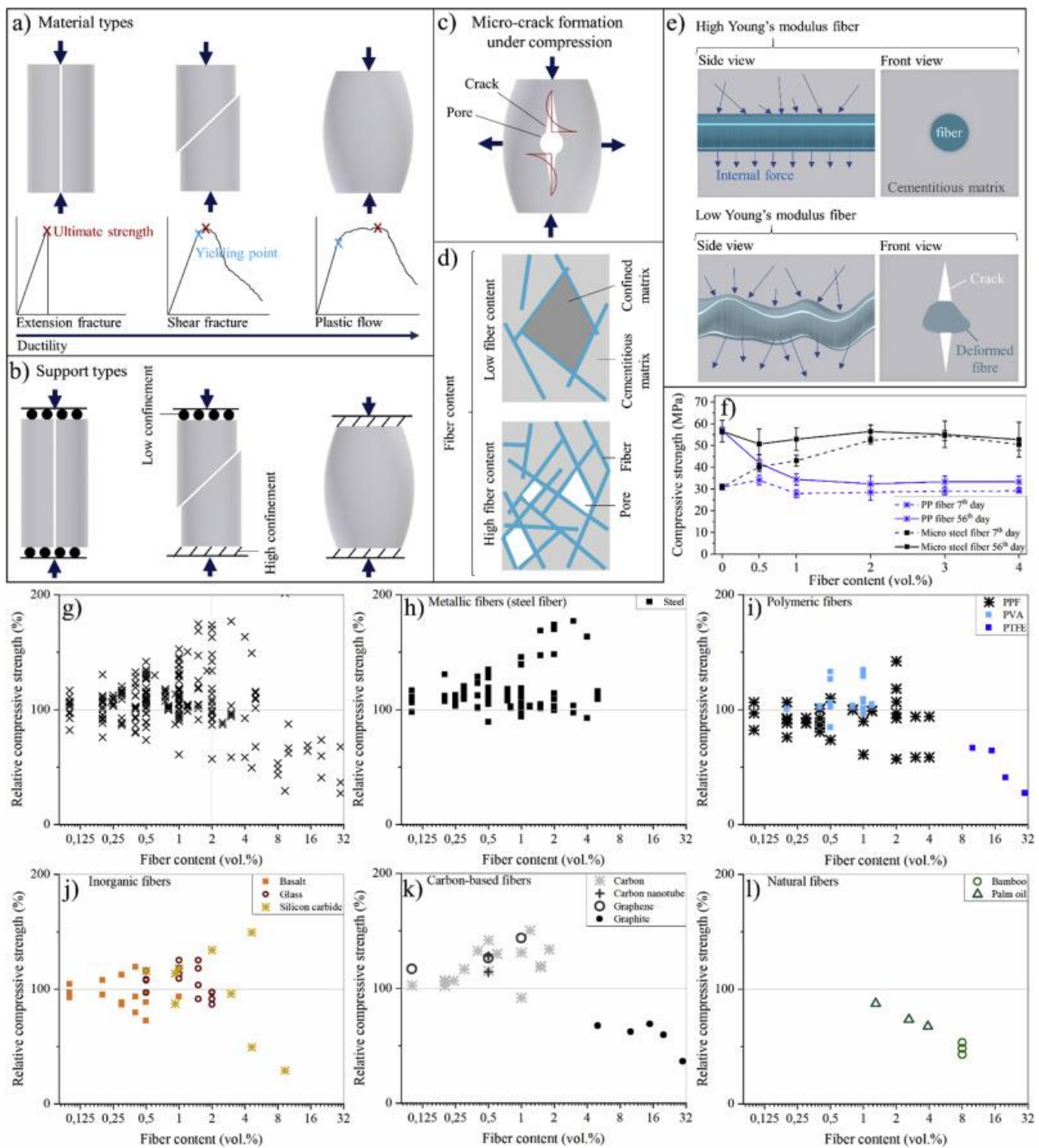


Figure 17. (a) Material strength in the various condition of fracture (b) Compression as the function of deformation (c) Crack formation mechanism (d) influence of fiber content on structure of the composites; (e) fiber performance under compression; (f) development of compressive strength of FRGC over time; the influence of fiber content (g) relative compressive strength as the function of fiber content for all fiber types, (h) steel fibers, (i) synthetic polymeric fibers, (j) inorganic fibers, (k) carbon-based fibers, and (l) natural polymeric fibers. Reprinted from [27] with permission of Elsevier.

5. Discussion

Based on various applications, geopolymer composites show better strength in a certain specific application at room temperature [68,69]. Synthetic carbon and E-glass fibers contribute toward better mechanical properties at RT and higher temperatures. Basalt fiber has strong adhesion with the geopolymer matrix at RT [70,71]. The durability of the

FRGCs sustains after damage to a certain extent. The current literature suggests that in the near future, investigations will be carried out on the idea of hybrid laminates produced using carbon and flax fiber with different sequences inside the geopolymer matrix. Hybrid laminates emerge as the improved technique due to their combined effect of both synthetic and natural fibers [72]. The hybrid fiber reinforced makes use of the synergetic effect of both organic and inorganic components and leads to a better mechanical strength of the composites. In addition to hybrid fibers, researchers also focus on weave plain fabric in comparison to uni-reinforcement; the focus has been shifted toward bi-direction knitted fabric [73]. The aim is to compact the reinforcement of the matrix inside a frame of fabric in both directions for the formation of the stable composite. Increasing demand for the geopolymer matrix reveals its potential as an alternative material for the building and construction industry. As a composite, it could act as insulators and repair structural materials. Additionally, it opens up new areas of application such as when used as foam ceramics for construction walls or for keeping a water cooling system. Both structural and constructional areas can be addressed by geopolymer composites [74–80].

6. Conclusions

This review reveals various challenges, current findings, and possible applications of FRGCs. Fibers are categorized into various typologies such as synthetic fibers, organic fibers, inorganic fibers, and natural fibers considered for reinforcement in the geopolymer matrix. The review explores the effect of various types of fiber reinforcement and a combination of hybrid fibers on the overall performance of the composite. The investigations about the overall strength of geopolymer composites are reported by considering various techniques, such as flexural strength, flexural modulus, and impact strength toward the durability of the composite. Moreover, hybrid fiber reinforcement has emerged as one of the new technologies for improving fibers' mechanical strength in geopolymer composites. The wide range of geopolymers' applications, from the basic construction industry to advanced foams and thermal insulators, has been covered. More detailed insight into the application of fiber or filler reinforced geopolymer composite materials has been revealed in this review.

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