Short Polymer Fiber-Reinforced Geopolymer Composites

Subjects: Others
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The article describes the state of the art in reinforced geopolymers, taking into consideration various types of polymer fiber reinforcements, such as polypropylene, polyethylene, or polylactic acid. The description is focused on the usage of polymer short fibers and the mechanical properties of the geopolymer composites. However, to show a wider research background, numerous references are discussed concerning the selected studies on reinforcing geopolymer composites with long fibers and fabrics. The research method applied in the article is the critical analysis of literature sources, including a comparison of new material with other materials used in similar applications. The results of the research are discussed in a comparative context and the properties of the composites are juxtaposed with the properties of the standard materials used in the construction industry. Potential applications in the construction industry are presented. Moreover, the contemporary research challenges for geopolymer materials reinforced with fibers are presented.

Keywords: geopolymer ; geopolymer composite ; mechanical properties ; fiber ; polymer fiber ; synthetic fiber

1. Introduction

Geopolymers are a group of materials that could be defined as inorganic aluminosilicate polymers with specific composition and properties. The geopolymers are obtained in the reaction of polycondensation of ortosilicans (comprising Si and Al atoms in their structure) activated usually by NaOH or KOH [1][2][3][4][5][6][7][8]. The geopolymerization process required binding material, and activator [2][3][9]. The most common applied binding materials are: kaolinite after calcination-metakaolin, calcined clays, industrial waste and by-products (e.g., ashes, slag, waste glass, red mud, mine tailings (different e.g., copper, vanadium), gauges etc.) or other natural and artificial silicoaluminates (e.g., zeolite, pure Al_2O_3–$2SiO_2$ powder as well as magnesium-containing minerals) [9]. As the activators are used usually alkali reactant. It is soluble alkali metal based on sodium or potassium. It includes alkali silicates, hydroxides, carbonates and other addition such as sodium aluminates or cement kiln dust. The most commonly used alkaline reactant solution is a mixture of hydroxides (NaOH or KOH) and silicates solution (Na_2SiO_3 or K_2SiO_3). Recently, some works have been undertaken on activation by acids, such as phosphate acid [9]. That process may be performed at low temperature, but the higher the temperature the better the characteristics of the materials that are obtained [4][5][6].

Currently, geopolymer composites are the most promising environmentally friendly alternative to traditional cementitious materials, including Portland cement. Geopolymers, in contrast to cement and alkali-activated based materials, are also characterized by significant durability. The main advantages of geopolymers are good compressive strength and good thermal properties (high fire and heat resistance), as well as resistance to corrosive environments [4][5][6]. The main weakness of these types of composites is brittle cracking, which limits their use in many areas. Therefore, research connected with the possibility of incorporating fibers as reinforcement into a geopolymer matrix is conducted [10]. Fibers should improve the flexural strength and fracture toughness of these materials [7][8] as well as increase the amount of energy absorbed by geopolymer before damage occurs. In particular, the short fibers, due to their easy fiber dispersion, are an effective way to strengthen geopolymers [11].

The addition of fibers changes the character of the fracture from brittle to more ductile [12]. The number of cracks in the material is reduced (in particular, the propagation of micro-cracks is reduced) as well as their dimensions—the width of the cracks is limited [12]. Thanks to this, damage caused by brittle cracking is minimized, and it is possible to maintain the cohesiveness of materials for a longer period, which can be critical, especially in emergencies to save people inside the structures [13]. Therefore, the introduction of fibers into the geopolymer matrix creates an extremely interesting material for construction solutions, which stands out from other solutions currently available on the construction market.

2. Summarized Mechanical Properties of Composites Reinforced with Polymer Fibers

Different fibers were used for reinforced geopolymer composites (Figure 1).

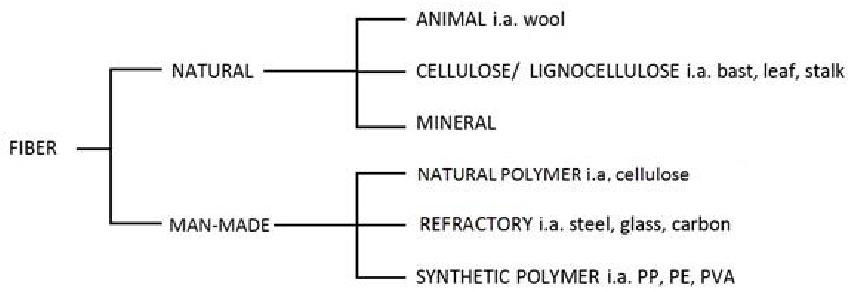

Figure 1. Overall classification of fibers used for reinforcement the geopolymer composites.

These fibers had different inherent properties such as crystallinity, thermal stability, mechanical properties etc. that could significantly influence on the final properties of the material. The basic properties such as density and tensile strength for the most popular polymer fibers are presented in Table 1.

Table 1. Basic properties of selected polymer fibers.

Fiber	Density [g/cm^3]	Tensile Strength [MPa]	Tensile Modulus [GPa]	Reference
Aramid	1.39–1.44	3 280–4 120	79–83	[14]
PAN	1.1–1.2	1 000–2 200	35–55	[15]
PA	1.09–1.37	50–90	0.35–20	[16]
PE	0.96–0.98	3 500–4 200	135–235	[17]
PP	0.89–0.92	50–600	0.5–3.0	[18][19][20]
PVA	1.19–1.31	1 600	250	[17]

The properties of polymer fibers can have significant influence on the composites, including the fibers pre-treatment. Moreover, the fibers from different suppliers could have slightly different properties. It could cause differences in the composites properties. Nevertheless, the polymer fibers have some advantages that make their use popular, such as: more predictable properties than natural fibers, repeatable dimensions, lack of problems with cohesion into the matrix, and the possible design of the properties.

The research work carried out so far for polymer fiber-reinforced geopolymer composites shows that their addition is an effective method of improving mechanical properties. The most common applied as a reinforcement are PP and PVA fibers (Table 2.).

Table 2. Characteristics of the short fiber-reinforced geopolymers.

Fiber	Length	Diameter	%wt.	Reference
Aramid	30 mm	0.5 mm	1.0%vol.	[14]
PAN	6 mm	12 µm	0.4%, 0.8%, 1.2%	[15]

PA	10 mm	55 µm	0.4%, 0.8%, 1.2%vol.	[16]
PA	8 mm	40 µm	2.0%vol.	[21]
PE	12 mm	12 µm	2.0%vol.	[21]
PE	12 mm	12 µm	0.5%, 1.0%, 1.5%, 2.0%	[22]
PP	3 mm	10 µm	0.25%, 0.5%, 0.75%	[20]
PP	12 mm	7.5 µm	0.4%, 0.8%, 1.2%vol.	[17]
PP	12 mm	18–30 µm	0.1%, 0.2%, 0.3%, 0.4%vol.	[23]
PP	20 mm	38 µm	2.0%vol.	[24]
PP	30 mm	1 mm	1.5%vol.	[25]
PP	3–19 mm	17 µm	0.5%, 1.0%, 1.5%, 2.0%	[26]
PP	6 mm	11.2 µm	0.25%, 0.5%, 0.75%, 1.0%vol	[27]
PP	19 mm	40 µm	0.5%, 1.0%	[28]
PP	8 mm	40 µm	0.1%, 0.2%, 0.3%, 0.4%vol.	[29]
PP	18, 19 and 51 mm	22 µm	0.5%vol.	[30]
PP	10 and 15 mm	50 µm	0.5%, 1%, 1.5%vol.	[31]
PP	6 mm	20 µm	0.3%, 0.5%, 1.0%	[32]
PP	12 mm	40 µm	0.15%, 0.30%, 0.45%	[33]
PVA	8 mm	39 µm	0.4%, 0.8%, 1.2%vol.	[16]
PVA	8 mm	40 µm	0.4%, 0.8%, 1.2%	[17]
PVA	15/18 mm	20/30 µm	2.0%vol.	[25]
PVA	7 mm	18 µm	1.0%	[34]
PVA	10 mm	12 µm	2.0%vol.	[35][36]
PVA	8/12 mm	40/100 µm	2.0%vol.	[37]
PVA	8 mm	39 µm	2.0%, 5.0%, 7.0%	[38]

PVA	8 mm	40 μm	2.0%	[21]
PVA	12 mm	20 μm	0.15%, 0.30%, 0.45%	[33]
PVA	12 mm	40 μm	0.2%, 0.4%, 0.6%, 0.8%, 1.0%, 1.2%vol.	[39]
PVC	7 mm	0.4 μm	1.0%	[34]
PO	48 and 55 mm	N/A	0.5%vol.	[30]

Most of the research work showed an improvement in both the compressive strength and the flexural strength of composites (Table 3).

Table 3. Mechanical properties for the composites—short fiber-reinforced geopolymers.

Fiber	**Geopolymer Matrix**	**Compressive Strength (Matrix) [MPa]**	**Flexural Strength (Matrix) [MPa]**	**Compressive Strength (Composite) [MPa]**	**Flexural Strength (Composite) [MPa]**	**Reference**
Aramid	Fly ash	70.0	7.1	88.0 (+25.7%)	10.4 (+46.5%)	[14]
PAN (0.8%)	Metakaolin + slag	80.0	4.0	99.8 (+24.8%)	13.8 (+244%)	[15]
PA [1]	Metakaolin + slag + sand + collemanite	61.6	8.8	62.0 (+0.6%)	11.4 (+22.8%)	[16]
PA (2.0%vol.)	Fly ash + slag	48.6	N/A	48.7 (+0.2%)	N/A	[21]
PE (2.0%vol.)	Fly ash + slag	48.6	N/A	44.3 (−8.8%)	N/A	[21]
PE (0.5%)	Fly ash + slag	80.0	N/A	70.7 (−11.6%)	N/A	[22]
PP (0.75%)	Metakaolin	32.6	5.0	54.7 (+59.6%)	10.0 (+50%)	[20]
PP [2]	Fly ash + slag + sand	60.5	8.4	61.0 (+0.8%)	9.7 (+14.7%)	[17]

PP (0.2%vol.)	Fly ash + slag + sand	35.0	6.5	39.0 (+10.3%)	7.0 (+7.4%)	[23]
PP (2.0%vol.)	Slag + sand	80.0	8.0	100.0 (+20%)	32.0 (+400%)	[24]
PP (1.5%vol.)	Fly ash	70.0	7.1	91.7 (+31%)	8.4 (+18.6%)	[25]
PP (0.5%)	Fly ash (foamed GP)	0.88	N/A	1.5 (+70.5%)	N/A	[26]
PP (0.25%vol.)	Fly ash + micron-scale silica	22.3	7.6	35.8 (+60.5%)	7.8 (+2.6%)	[27]
PP (1.0%)	Fly ash/slag	N/A	8.8	N/A	6.0 (−46.7%)	[28]
PP (0.2%)	Metakaolin	48.0	5.6	49 (+2.1%)	6.9 (+23.2%)	[29]
PP (0.5%vol)	Fly ash + slag	50.4	N/A	47.3 (−6.1%)	N/A	[30]
PP [3]	Fly ash + aggregates	32.0	5.9	43.3 (+35.3%)	8.0 (+35.5%)	[31]
PP (1.0%)	Metakaolin + aggregates	52.6	3.6	52.7 (+1.0%)	4.9 (+36.1%)	[32]
PP (0.15%vol.)	Fly ash + slag	80.0	N/A	74.8 (−6.5%)	N/A	[33]
PVA [4]	Metakaolin + slag + sand + collemanite	61.6	8.8	66.2 (+7.5%)	12.2 (+38.6%)	[16]
PVA (1.2%vol)	Fly ash + slag + sand	60.5	8.4	63.0 (+4.3%)	11.8 (+39.8%)	[17]
PVA (2.0%vol.)	Fly ash	70.0	7.1	101.9 (+45.6%)	10.5 (+47.9%)	[25]

PVA (1.0%)	Metakaolin + slag	N/A	6.9	N/A	11.2 (+62.3%)	[34]
PVA (2.0%vol.)	Fly ash	54.6	N/A	63.7 (+16.7)	N/A	[35][36]
PVA (2.0%vol.)	Fly ash	49.2	4.8	84.9 (+72.7)	18.2 (+278.2%)	[37]
PVA (5.0%)	Fly ash + sand	40.2	3.6	43.6 (+8.5%)	6.9 (+94.1%)	[38]
PVA (2.0%)	Fly ash + slag	48.6	N/A	48.7 (+0.2%)	N/A	[21]
PVA (0.30%vol)	Fly ash + slag	82.0	N/A	94.1 (+12.8%)	N/A	[33]
PVA [5]	Metakaolin + fly ash	50.0	6.5	65.0 (+30.0%)	10.0 (+53.8%)	[39]
PVC (1.0%)	Metakaolin + slag	N/A	6.9	N/A	10.0 (+44.9%)	[34]
PO (0.5%vol)	Fly ash + slag	50.4	N/A	43.8 (−13.1%)	N/A	[30]

[1] Results for: compressive strength (cs)—0.8%vol. of fiber and flexural strength (fs)—1.2%vol. of fiber. [2] Results for: cs—0.4%vol. of fiber and fs—1.2%vol. of fiber. [3] Results for: cs—0.5%vol. of fiber and fs—1.5%vol. of fiber (10 mm length). [4] Results for: cs—1.5%vol. of fiber and fs—1.2%vol. of fiber. [5] Results for: cs—0.8%vol. of fiber and fs—1.2%vol. of fiber.

It is worth noting that in some cases the authors report a very high flexural strength value after adding fibers, compared to the compressive strength [37]. These works require verification of the research methodology before the wider application of the results, as this behavior is not typical for this type of material.

The compressive strength for polymeric fibers usually increased, and only for some cases does it decrease. However, the main reason of polymer fiber addition is not a compressive strength, but the flexural strength and fracture tongues behavior. The flexural strength for presented research increased generally (about 50%). In the case of research where it decreased or does not significantly change, the authors explained it by voids in material, fibers agglomerations or improper interfacial mechanism between fibers and matrix [40][41].

The most of mentioned research was focused on compressive and flexural strength of fiber-reinforced geopolymer, because of planned applications in the construction industry. Some investigations also discussed other mechanical properties such as tensile strength [40]. The research shows the increasing tensile strength is correlated with increasing of flexural strength. The improving the tensile performance of the composites is also important factor for fibers addition [41].

Another important reason for fiber reinforcement is fracture toughness, including changing the fracture form brittle to more ductile. These mechanism were observed by some authors [42][43]. It was mainly described together with results of flexural strength as a changes in material behavior. The polymer fibers have significant influence on that mechanism by the energy absorption and limitation of micro-cracks propagation. Fracture toughness is important for polymer fiber composites, because it expand the area of application for this materials. The more ductile mechanism increased safety of buildings in such situations as fire or earthquakes, because it gives time for evacuation.

3. Comparison of the Properties of Composites with Traditional Building Materials

The values of the obtained mechanical properties can be compared to traditional building materials. The value obtained for the geopolymer matrix can be compared to the properties of the most popular concretes, which are used practically at every stage of building a house, both from pouring foundation alloys, foundation slabs or the foundations themselves, as well as for various types of foundation, walls, columns, lintels, terraces, stairs, ceilings, etc. It is used both in internal and external applications, including for pouring and embedding fence posts and for making small concrete elements and small architecture. The values given for this type of concretes are usually: the compressive strength of 20 MPa and the flexural strength above 4 MPa. In all these applications, the said concrete can be replaced by a geopolymer material.

Moreover, the addition of fibers increased the mechanical properties of composites and made it possible to meet the requirements for the so-called architectural concretes, i.e., the compressive strength of 35 MPa and the flexural strength of 8 MPa, which allows their use for complex spatial elements. Selected composites allow for specialized applications—Table 4. The addition of fibers not only increased the mechanical properties but also improved other properties of composites, such as resistance to high temperatures and durability [40].

Table 4. Area of investigated applications for the composites—short fibers reinforced geopolymers.

Area of application	Fiber	Reference
High-temperature resistant	PA, PP, PVA	[44]]
Structures	PAN, PP, PVA	[45][46]
Lightweight application	PP	[47][48]
Repair works	PVA	[49]
Isolation material	PP	[50][47][48]
3D printing technology	PP, PVA, PBO	[27][51]

4. Contemporary Research Challenges for Geopolymer Materials Reinforced with Fibers

The area of research on geopolymers reinforced with fibers, in particular short fibers, faces many challenges[40][41]. Some of them are related to the geopolymer material itself, others to the proper functioning of the fiber-matrix system. Eventually, the specific research issues connected with fiber-reinforcement for geopolymer composites are required. The many types of fibers have not been tested in terms of their applicability in such composites yet [52]. It is also necessary to conduct more comprehensive and advanced research in this area since in the case of many fibers only preliminary tests were performed on a small number of samples, which were not followed up further [53].

One of the most important research challenges related to the properties of the geopolymer matrix is the variable quality and composition of fly ash. This causes not only the problem of comparing research results between particular works but above all problems with the implementation of geopolymers based on recyclable materials in practice [54]. One of the possible solutions to this problem is geopolymers based on metakaolin. However, important environmental benefits are then lost, in the form of the possibility of managing anthropogenic waste [55][56]. When treating the problem a bit more broadly, it is worth noting that there is also the possibility of developing geopolymer materials based on other types of waste. Research in this area was carried out, among others with the use of waste from coal mining, in particular, the so-called gangues and also wastes from the extraction of metal ores [56].

Another research challenge related to the geopolymer material itself is the small amount of data on the durability of the material and the lack of appropriate standards defining the possibilities of its applications [57]. It should be noted that the durability of traditional building materials is also questioned by many scientific works [57]. Theoretical predictions show the long-term usefulness of geopolymer materials [57], however, no studies confirm these calculations in practice. Preparation and carrying out of such tests for individual materials is necessary for their implementation in practice.

The next research challenge is also the optimization of the production process of these materials. In this aspect, it is worth mentioning the elimination of the curing at high temperatures and the possibility of developing geopolymer materials hardened at ambient temperature . Such research works are undertaken in some research centers, but they do not always allow obtaining materials with satisfactory mechanical properties . Such work is currently carried out for composites with polymer fibers and brings much better results than for a plain matrix . The second solution that allows the price of materials to be reduced, and at the same time the safety of their production to be improved, is to replace the alkaline compounds used in the geopolymerization process with acids. Currently, work in this field is carried out in several centers around the world, with the best results being obtained in China [58].

Currently, an important direction of development is the creation of new materials friendly for the environment. There is a significant market demand for ecological materials, and in particular for materials based on renewable raw materials or waste products. The rational management of natural resources and the use of waste materials are becoming increasingly important. It also gives the chance to use polymer waste fibers [59]. The growing ecological awareness of society, including the awareness of sustainable development, means that the issue of environmental impact is increasingly being discussed. Modern composites, based on geopolymers, allow to reduce the emission of substances harmful for the environment and at the same time save natural resources by waste using [59]. Geopolymer composites, in particular with fiber reinforcements, intended for advanced applications, are part of the sustainable development policy that is currently a guideline for the creation of legal standards in many countries in Europe and the world .

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