Composites Reinforced with Polymer Fibers

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Synthetic fibers are currently the most commonly used addition to various types of composites. The main aim of the addition of polymer fibers is improving mechanical properties, in particular bending strength and reducing the propagation of micro-cracks in the material. Depending on the type of fiber used, other benefits could be achieved, for example, increasing fire resistance, a decreasing thermal conductivity coefficient, or other features desirable for a particular application such as decreasing weight of the composites. The disadvantage of the polymer fiber could be used as raw material mainly not renewable resources. These kinds of fiber are usually obtained from limited resources such as crude oil, however, modern technologies allow also extract plastics from renewable raw materials—bio-based polymers. As the raw material, starch or bio-succinic acid are commonly used.

geopolymer geopolymer composite mechanical properties fiber polymer fiber synthetic fiber

1. Aramid

The research of geopolymer composites with aramid fiber was carried out using a geopolymer matrix based on fly ash and aramid fibers with a length of 30 mm and a diameter of 0.5 mm in an amount of 1.0% by volume [1]. The samples were cured at a high temperature: 85 °C for 10 h [1]. The results show increasing the mechanical properties—matrix material reached 70 MPa compressive strength, while composites with fiber addition reached 88.0 MPa [1]. A significant increase in value occurred also for flexural strength, respectively: 10.4 MPa for a composite with 1.0% fiber content, compared to the value of 7.1 MPa obtained for a matrix material and tensile strength—an increase from 3.1 MPa for matrix material up to 7.7 MPa for composite [1]. The short aramid fibers seem to be a promising reinforcement for the geopolymer matrix, however, this kind of fiber is usually applied as long fibers or textiles [2]. There is a problem with the availability of aramid short fibers in the market.

2. Polyacrylonitrile (PAN)

Polyacrylonitrile (PAN) fibers were investigated in a geopolymer matrix made of metakaolin and slag. The PAN fibers had a length of 6 mm and a diameter of 12 µm. Fiber additives were used in the following weight proportions: 0.0%, 0.4%, 0.8%, and 1.2% [3]. The best results were achieved for the composite with 0.8% PAN fiber addition. It was, respectively, 99.84 MPa for compressive strength, compared to the result of about 80 MPa obtained for the matrix material and 13.76 MPa for flexural strength, compared to the result of about 4 MPa obtained for the matrix material [3]. However, increasing the flexural strength is significant and gives a perspective for the application of this composite in civil engineering, there is a lack of information about further research for the composites with PAN fibers.

3. Polyamide (PA)

Research with polyamide (PA) fibers was conducted based on a geopolymer matrix composed of metakaolin, slag from the Bolu Cement Company in Turkey, sand, and colemanite waste (borate mineral) from the Eti Mining Company in Turkey [4]. The PA fibers were added in the following proportion: 0.4%, 0.8%, and 1.2% by volume. The fiber dimensions were: diameter 55 μm and length 10 mm. The studies were conducted after 3, 7, and 28 days after samples production [4]. Research results show the increase of the mechanical properties of composites over time. In the case of compressive strength, after 28 days, the best results were obtained for a sample containing 0.8% volume PA fibers: 62 MPa, compared to the value of the sample without reinforcement of 61.6 MPa. The best result of flexural strength was found for composites with a 1.2% PA fiber content: 11.4 MPa, compared to the matrix material of 8.8 MPa [4]. The results obtained were referred to other types of fillings—basalt, polyolefin, and PVA fibers. Composites with the addition of PA fibers had worse mechanical properties than those with the addition of basalt fibers or PVA, but they had better properties than composites with polyolefin fibers [4].

4. Polyethylene (PE)

Polyethylene (PE) fibers are in third place of the most investigated polymer fibers in the geopolymer matrix (after PP and PVA). Nematollahi et al. [5] made comparative studies on the addition of PE and PVA fibers to geopolymer matrix composed of fly ash and slag [5]. PVA fibers had the following dimensions: length 8 mm and diameter 40 μm, and PE fibers: length 12 mm and diameter 12 μm. Composites were formed with 2% by volume fiber addition [5]. The mechanical properties were investigated after 28 days. The results of the tests showed a reduction in compressive strength as a result of the addition of PE fibers and a slight increase in this property for PVA fibers. The compressive strength was 48.6 MPa for the geopolymer matrix, 44.3 MPa for the composite with PE fibers, and 48.7 MPa for the composite with PVA fibers [5]. In the case of tensile strength, the composites with PVA fibers reached 4.6 MPa, while with the addition of PE it was 4.2 MPa. There is lack of information about tensile strength for the matrix material [5].

The PE fibers (length 12 mm and diameter 12 μm) were also tested as an addition for the geopolymer in amount: 0.0, 0.5, 1, 1.5 and 2.0% by weight [6] and with a content of 0.0%, 0.5%, 0.75%, 1.0%, 1.5% by weight [7]. The matrix components were mainly products from the Gladstone power plant in Queensland, Australia [6][7]—fly ash and slag. Samples were tested after 28 days. In both articles, results are very similar. The decrease of compressive strength of the composites was noted. However, in both experiments, fiber composites behaved slightly differently. In the first experiment, the highest value was obtained for the matrix material—about 80 MPa, for subsequent samples this value decreased with the increasing amount of the fibers. The value was above 70 MPa for the 0.5% PE fibers addition and only about 30 MPa for 2.0% fibers addition [6]. In the second experiment, the highest value was obtained also for the control sample, matrix material, of 56.7 MPa. For composites with PE fibers, these values were lower and increasing with the fiber content: 0.5%—28.4 MPa, 0.75%—35.0 MPa, 1.0%—44 MPa and 1.5%—45 MPa [6]. The best results for the bending strength were achieved for about 0.75–1.0% of the addition of PE fibers [6][7].

Other research was provided for composites reinforced by PE fibers—1.75% by weight. The fibers have dimensions: length 18 mm and diameter 12 μm [8]. The matrix was based on slag with different proportions of water and activator. The authors obtained the results of compressive strength between 36.3 and 54.8 MPa and flexural strength between 5.1 and 13.1 MPa, however, in this research, there is a lack of information about mechanical properties of plain samples [8].

5. Polyethylene Terephthalate (PET)

Polyethylene terephthalate (PET) fibers were investigated in a geopolymer matrix made of fly ash and slag and compared with composites reinforced by polypropylene (PP) fibers. The PET fibers had a length of 12 mm and a diameter of 38 μm and the PP fibers had a length between 12 and 19 mm and a diameter of 22 μm. Fiber additives were used in the following volume proportions: 1.0 and 1.5% [9]. The results show that irrespective of fiber types the compressive strength of all composites decreased due to an increase in fiber volume from 1% to 1.5%. The flexural strength of PET fiber reinforced geopolymer was increased due to an increase in PET fiber volume fractions from 1% to 1.5%. Additionally, PET fiber exhibit higher tensile strength than their counterpart PP fiber reinforced composites. There is a lack of comparison with a plain matrix in [9].

6. Polypropylene (PP)

Polypropylene (PP) was originally used as reinforcement for concretes, improving their flexural strength. Therefore, attempts were also made to use it to reinforce composites based on geopolymers. PP fibers were one of the first fibers added to geopolymers [10][11]. PP fibers have been added to both fly ash and metakaolin geopolymers. The first studies in this field were carried out based on a matrix made of slag and fly ash with 0.5% and 1% by volume of the fibers [10]. The research results showed that too low fiber content does not have a positive effect on the properties of geopolymer concrete.

Further studies with the use of PP fibers showed a positive influence on the mechanical properties of geopolymer composites [12]. Zhang et al. tested geopolymer composites made with the metakaolin (kaolin calcined at 900 °C for 6 h) and the short PP fibers (diameter: 10 μm and length: 3 mm) [12]. The fibers were added in the amount of 0.0%, 0.25%, 0.5%, and 0.75% by weight. The samples were tested after 1 day and 3 days. The results showed an increase in compressive strength and flexural strength depending on the addition of fiber. The best results for compressive strength were obtained for 0.5% fiber content, which was, respectively: 54.7 MPa after 1 day and 52.3 MPa after 3 days. For reference samples without fiber content, these results were respectively: 32.6 MPa and 41.5 MPa. The best results for flexural strength were obtained for the sample with the addition of 0.75% PP fiber, it was

10 MPa after 1 day and 9.4 MPa after 3 days. For reference samples, these values were 5.0 MPa and 5.5 MPa. The authors do not explain the decreasing of mechanical properties over time for samples with PP fiber [12].

Also, studies with fly ash-based geopolymers have shown the positive effect of PP fibers on the mechanical properties of the composites. PP fibers were added to the composites based on class F fly ash in an amount of 0.05% and 0.15% by weight [13]. The research showed an increase in the mechanical properties over time and the achievement of higher compressive strength values (over 30 MPa) for composites with 0.15% PP fiber addition compared to the base material [13]. The beneficial effect of PP fibers on the properties of geopolymer composites based on fly ash class F was also confirmed [14]. Short PP fibers for dedicated concrete in the amount of 5%, 10%, 15%, and 20% by volume were used as reinforcement for geopolymers. The flexural strength was investigated. The best results were obtained for 15% and 20% by volume of fibers, it was respectively 7.6 MPa and 7.9 MPa compared to the samples with 5% PP content, for which only 2.1 MPa was obtained [14]. The tests also confirmed the good cohesion of the fibers with the matrix [14].

Fly ash class F ashes from Malayan Cement Bhd of Malaysia were used for manufacturing the composites with 0.5%, 1%, 2%, 3%, 4%, and 5% by volume of PP short fibers. The studies were conducted after 2, 7, 14, 28, 56 days [15][16]. The results obtained were presented in a graphic form, which does not allow giving precise values for mechanical properties. However, the results show that the addition of the fibers increases the flexural strength and cause a decrease in the compressive strength [15][16]. In the case of flexural strength, a positive effect was noticed for composites with the addition of more than 1% of PP fibers (for 0.5% there was a decrease in the value compared to the matrix material) on the results obtained in the early period of material curing—up to about 2 weeks. After this period, the bending strength of the matrix material increased, and it stabilized for composites with 1%, 2%, and 3% fiber addition, but its values were lower than for the plain material. The best results were obtained for 4% and 5% fiber addition. Even after 56 days, they were higher than for the matrix material itself and exceeded 10 MPa [15][16]. The compressive strength was tested after 7 days, the properties of the composites with various fiber additions were similar to the value obtained for the matrix material itself and had about 30 MPa. After this time (the tests were carried out for 56 days), the strength of the matrix material itself increased to about 60 MPa, and for composites with fibers, it changed only slightly—up to about 35 MPa [15][16].

Tests of composites with short PP fibers were also conducted based on a matrix composed of class F fly ash from the Catalagzi/Zonguldak power plant in Turkey and slag from the Bolu cement plant [17]. PP fibers were added to the matrix in a volumetric ratio: 0.4%, 0.8% and 1.2%; fibers had dimensions: 0.0075 mm in diameter and 12 mm in length [17]. The composite was heated at 80 °C for 24 h. The samples were tested after 7 and 28 days [17]. The test results showed slight changes in strength compared to the control samples (without fibers) for both compressive strength and bending strength. The samples did not show a significant increase in the strength values over time [17]. The best results were obtained for the compressive strength after 28 days, it was about 61 MPa for the sample with 0.4% PP fiber content, compared to the strength of 60.5 MPa obtained by the reference samples. The flexural strength for the samples with fiber reinforcement was: 9.7 MPa, compared to 8.5 MPa for the control sample [17].

The mechanical properties of geopolymers with the addition of PP fibers were also tested based on a matrix from class C fly ash, slag after steel processing, and sand [18]. The PP fibers added to the composites had the following dimensions: diameter: 18–30 μm and length: 12 mm; they were added in 0.0%, 0.1%, 0.2%, 0.3% and 0.4% by volume. The samples were tested after 3, 7, and 28 days [18]. The compressive strength increased over time for all composites, after 3 days it was about 12 MPa, after 7 days about 22 MPa, and after 28 days above 35 MPa. All composites achieved higher values than the matrix material. The highest values were achieved for 0.2% by volume of PP fiber addition, it was 39.0 MPa, compared to about 35 MPa for the matrix material. The compressive strength values of composites reinforced by PP fiber was compared with basalt and steel reinforcement. It was lower than for composites reinforced with basalt fiber but slightly higher than for steel reinforcement [18]. The increase in flexural strength was also observed over time. This value after 3 days was about 3 MPa, after 7 days about 3.5 MPa, and after 28 days about 6.5 MPa. Composites with 0.1%, 0.2%, and 0.3% additions achieved higher values than the matrix material, while the material with 0.4% PP fibers was slightly lower. The highest values were achieved for 0.2% of PP fiber addition; it was 7.0 MPa, compared to about 6.5 MPa for the matrix material. The values obtained were slightly lower than for materials with basalt or steel reinforcement [18].

The influence of the PP fiber type on the mechanical properties was also investigated [19]. The tests were carried out on a matrix made of sand and slag with the use of two types of PP fibers. The fibers had different properties and methods of production. The first, defined as “split fiber”, was created by cutting tapes of split yarns and had the dimensions of 20 μm in diameter and 12 mm in length. The other fiber, called “multi-fiber”, was a conventional spun fiber (there were aggregations of fiber in the material) with dimensions: 38 μm in diameter and 20 mm in length. Fibers were added to the composite in an amount of 2% by volume. The samples were investigated after 7 and 28 days [19]. The flexural strength for both fibers used in the tests increased. It was approx. 8 MPa for matrix material up to 31 MPa for “split fiber” and about 32 MPa for “multi-fiber”—after 28 days. The compressive strength after 28 days was about 80 MPa for reference samples, about 75 MPa for “split fibers” and almost 100 MPa for “multi-fibers” [19].

The other research studies conducted in this field show slight changes in the mechanical properties of materials, both for composites based on fly ash as well as slag with various fiber additives [20][21]. The interesting phenomenon in the case of the addition of PP fibers is the decrease of compressive strength over time, occurring in about half of the presented research works in this field. This phenomenon is mostly explained by the authors by the presence of additional spaces between the reinforcement and the matrix in the matrix material curing process [15][16][17][19][21]. Zhu et al. confirmed that if the amount of fibers in composites is properly selected, both compressive and flexural strength should increase [22].

The different types of PP fibers have been tested also by Noushini et al. [23]. They added three types of PP fibers: 18, 19, and 51 mm length with a volume fraction of 0.5% to a geopolymer based on fly ash and slag. The results show a decrease in compressive strength for all types of fiber. After 28 days for the reference samples, the compressive strength was 50.4 MPa, and samples with PP fibers were between 46.7 and 47.3 MPa [23]. The authors investigated also tensile strength that slightly increases from 4.1 MPa for the matrix to 4.3 MPa for the composite with 19 mm PP fibers [23].

The trials were also provided on a geopolymer based on zeolitic tuff and fine aggregates—river sand reinforced by PP fibers (length 12–19 mm) [24]. The PP fibers were implemented in 0.5% and 1.0% by weight. The compressive strength was investigated, however, received results are very low and required further works. The best results were achieved for 0.5% fiber additions; it was barely 4.6 MPa [24].

Much higher results for mechanical properties were achieved by Pham et al. [25]. Two kinds of PP fibers (the length of 10 and 15 mm, the diameter of 50 μm) were added in amount 0.5, 1.0, and 1.5% by volume to geopolymer matrix based on fly ash with aggregates [25]. The results show improvement compressive strengths as well as flexural strengths for both types of PP fibers. The better results were achieved for shorter PP fibers of 10 mm lengths. The best results for compressive strength was for 0.5 vol.% PP fibers achieved 43.3 MPa, compared with 32.0 MPa for a plain matrix [25]. The flexural strength had a higher value for 1.5% vol. PP fibers addition achieved almost 8 MPa, compared with 5.9 MPa for the material without reinforcement [25]. The authors also compared results for PP fibers with steel fibers. The slightly better mechanical properties were noted for the composites reinforced by steel fibers [25]. These works also show the possibility of computer modeling the predicted values for this kind of composite [25].

The metakaolin based geopolymers with aggregates were reinforced by PP fibers of length 6 mm and diameter 20 μm [26]. The PP fibers were added to the mixture at 0.3%, 0.5%, and 1.0% by mass. The results show a lack of changes in compressive strength—the strength of the control sample was 52.6 MPa which increased by less than 1.0% upon adding 1% PP fibers and increasing the flexural strength. The flexural strength of the control sample was 3.6 MPa which improved to 3.8, 4.2, and 4.9 MPa when 0.3%, 0.5%, and 1.0% PP fibers were added [26].

The decrease of compressive strength of the geopolymer composites after PP fibers addition was also observed by Yuan et al. [27]. The matrix was made from fly ash with different slag addition. The PP fibers (length 12 mm and diameter 40 μm) were added to the mixture in an amount of 0.15%, 0.30%, and 0.45% by volume [27]. The compressive strength decreased from 80 MPa for the matrix to 74.8, 72.1, and 46.3 MPa for the composites with fibers [27].

Among the various types of fiber, PP fiber is the most commonly used for thermal insulation purposes and as lightweight materials [28][29][30]. The fibers in the geopolymer matrix are also resistant to high temperatures up to 900 °C [31]. Other reasons for the greater usage of PP fibers also include economical advantage and excellent resistance to environmental aggressiveness [31][32].

7. Polyvinyl Alcohol (PVA)

A large amount of research has also been conducted with a polyvinyl alcohol (PVA) fiber-reinforced geopolymer matrix. These tests compared composites with PP fibers and PVA fibers have been conducted [17]. The matrix based on fly ash class F from the Catalagzi/Zonguldak power plant in Turkey and slag from the Bolu cement plant were used for this research. PVA fibers were added to the matrix in 0.4%, 0.8%, and 1.2% by vol. (fibers dimensions: 0.04 mm in diameter and 8 mm in length). The composite was cured at 80 °C for 24 h. The samples were tested after 7 and 28 days [17]. The test results show an increase in the mechanical properties of the samples with fibers compared to the control samples (without the fibers content) [17]. The best results were for compressive strength for composites with 1.2% fibers content of 63.1 MPa, compared to 60.5 obtained for reference samples and strength bending of 11.8 MPa, compared to 8.5 MPa for the control samples [17].

Tests with PVA fibers were also carried out based on a geopolymer matrix composed of metakaolin, slag from the Bolu Cement Company in Turkey, sand, and colemanite waste (a mineral from the borate group) from the Eti Mining Company mine in Turkey [4]. The tests were carried out with 0.4%, 0.8%, and 1.2% by volume of PVA fibers. The added fibers had a diameter of 39 µm and a length of 8 mm [4]. The research results show an increase in the compressive strength; the best results were obtained for the samples containing 1.5% by volume of PVA fibers of 66.2 MPa, compared to the value of the sample without reinforcement of 61.6 MPa. The highest value for flexural strength was achieved for the composite with 1.2% fiber content of almost 12.2 MPa, compared to the matrix material of about 8.8 MPa (according to the data presented in the diagram, which they are consistent with the data found elsewhere in the article, according to which the strength reached almost 12 MPa) [4]. The composite results were compared with basalt, polyolefin, and PA composites. The composites with PVA fibers had the best compressive strength and were second (after the composites with basalt fibers in terms of flexural strength) [4].

The other research shows the potential applications for geopolymer composites reinforced by PVA fibers for different kinds of engineering applications, including structures [33][34], fire resistance products for the construction industry [35], and for maintained work, including repair of concrete structures [36].

8. Polyvinyl Chloride (PVC)

Research with the use of PVC fibers was carried out based on a metakaolin matrix with the addition of slag from the Italian company Acciaieria di Rubiera SpA, in the town of Casalgrande [37]. The bending properties of composites with 1.0% by weight of PVC fibers (diameter of 400 µm, length of 7 mm) were tested. The flexural strength for the plain matrix was 6.9 MPa, and for composites with reinforcement 10.0 MPa [37]. These values were slightly lower than for composites with PVA fibers [37].

9. Other Polymer Fibers

Tests with polyolefin fibers (PO), with the type of fibers not specified, were also carried out based on a geopolymer matrix composed of metakaolin, slag from Bolu Cement Company in Turkey, sand, and colemanite waste (a mineral from the borate group) from the Eti Mining Company mine in Turkey [4]. The PO fibers (diameter of 63 µm and length of 10 mm) were added with 0.4%, 0.8%, and 1.2% by volume. The studies were conducted after 3, 7, and 28 days [4]. The best results of compressive strength were after 28 days, for the sample containing 0.8% by volume addition of PO fibers, of about 61.6 MPa. The result was slightly better than for the plain matrix. The highest result of flexural strength was obtained for the composite containing 1.2% fiber addition of 11 MPa, compared to the matrix material of 8.8 MPa [4]. The composites reinforced by PO fibers were compared with composites based on the same matrix with the addition of basalt fibers, PVA, and PA. Compared to other composites, they obtained the lowest mechanical values [4].

The polyolefin fibers have been tested also by Noushini et al. [23]. They added two types of fibers: 48 and 55 mm length with a volume fraction of 0.5% to geopolymer based on fly ash and slag. The results show a decrease in mechanical properties for both types of PO fibers. After 28 days for the reference samples, the compressive strength was 50.4 MPa, and for samples with PO fibers it was 43.8 and 43.6 MPa, respectively [23]. The tensile strength also decreased from 4.1 MPa for the matrix to 3.9 and 3.5 MPa for the composite with PO fibers [23].

A matrix based on metakaolin was used for testing the addition of PLA fibers. Research work in this area was mainly related to the use of these fibers as an additive generating pores in the material [38][39].

10. Use of Synthetic Fibers in Hybrid Reinforcement

Another type of reinforcement used in composites based on geopolymers is the so-called hybrid reinforcement—containing two different types of fiber. For this type of reinforcement, fibers with different properties are most often used to obtain the synergy effect [4]. Steel fibers combined with plastic fibers are most often used in this type of reinforcement. An example of this type of reinforcement is the use of short steel and PP fibers [21][40][41][42][43].

The research was carried out on a geopolymer matrix based on fly ash and silica fume, the ingredients came from a power plant in Lampang province in Thailand. Curved steel fiber (60 mm long) and PP fiber (58 mm long) were used for the composite [21]. Two types of experiments were conducted. In the first, PP fibers were replaced with steel fibers with an increment of 0.2% until a full replacement was achieved. In the first case, an increase in compressive strength was observed with an increasing amount of steel fibers in the composite. For the composite with PP fibers, the compressive strength after 28 days was 35.44 MPa, and with subsequent additions of steel fibers, it increased: 80:20—40.5 MPa, 60:40—45.2 MPa, 40:60—51.7 MPa, 20:80—56.8 MPa and 100% steel fibers 60.57 MPa (for the same period, the compressive strength for the material without the addition of fibers was 40.08 MPa) [21]. In the second experiment, steel fibers were added to the composite with an increase of 0.2%, until the total volume fraction reached 2%. The amount of PP fibers was constant at 1% [21]. The compressive strength also increased with an increasing amount of steel fibers and was for the addition of 1% of steel fibers and 1% of PP fibers: 73 MPa. For the remaining composites it was, respectively: 1% PP fibers and 0% steel fibers 35.4 MPa, 1% PP fibers and 0.2% steel fibers 39.4 MPa, 1% PP fibers and 0.4% steel fibers 43.7 MPa, 1% PP fibers and 0.6% steel fibers 56.5 MPa, and 1% PP fibers and 0.8% steel fibers 68.4 MPa [21]. The research also determined the behavior of the composites in terms of flexural strength, which was similar to the compressive strength [21].

The research with the usage of PP and steel fiber reinforcement was also made on a geopolymer matrix based on fly ash class C. The fibers were applied in 0.5 and 1% by volume. The fibers were used in a 4:1 ratio, including steel macro fibers (length 30 mm, 0.5 mm diameter) and PP microfibers (length 12 mm, 18 µm diameter). The tests were carried out after 28 days at temperatures ranging from −30 °C to 300 °C [44]. The research results showed a decrease in the mechanical properties of composites when temperature increase. The best results, both in terms of compressive strength and flexural strength, were for negative temperatures [44]. For the compressive strength, the best results were obtained for samples without reinforcement—about 45 MPa, for 0.5% fiber addition about 38 MPa, and for 1% 30 MPa. The flexural strength for samples with 1% addition of fibers was 9 MPa and for samples without reinforcement and with 0.5% fibers addition it was below 7.2 MPa [44]. Recently also the hybrid composition included PP and glass fibers [45] and compositions with PP and PO fibers are investigated [46].

The second most popular polymeric fiber for hybrid geopolymer composite is PE incorporated with steel [47][48][49][50][51][52]. This kind of composite was widely studied by Khan et al. [47][48][49][50]. The tests were carried out with the use of two types of steel fibers—spiral and curved fibers of the same length 25 mm and diameters of 0.55 and 0.3 mm, respectively. The PE fibers were 12 mm long and had 12 µm in diameter [47]. The fibers were introduced into a geopolymer matrix composed of fly ash and slag. Fly ash class F came from Gladstone Power Station in Queensland, Australia, and BGC slag came from a cement plant in Australia [47]. Four types of samples were prepared, including two types of samples containing 1% fibers (80% steel fibers using both types of fibers in a 50:50 ratio and 20% PE fibers, 80% spiral steel fibers and 20% PE fibers), and two types of samples containing 2% fibers (90% steel fibers using both types of fibers in a 50:50 ratio and 10% PE fibers, and 80% steel fibers using both types of fibers in a 50:50 ratio and 20% PE fibers). The samples were tested after 28 days [47]. The results show a decrease in the compressive strength of samples with mixed fibers in comparison to samples with the same content of steel fibers. Composites with hybrid fibers obtain comparable values as a matrix of 72 MPa [47]. The hybrid fibers significantly improved the flexural strength. The flexural strength for samples without reinforcement was 3.89 MPa, and then it increased with the addition of steel fibers, for the subsequent contents it was, respectively: 1%—6.1 MPa, 1.5%—6.7 MPa and 2%—9.6 MPa. For samples with 1% addition of steel fibers and PE, the following values were obtained: 6.9 MPa for composites with the addition of 80% steel fibers using both types of fibers in the 50:50 ratio and 20% PE fibers, and 4.9 MPa for composites with the addition of 80% spiral steel fibers and 20% PE fibers. The highest values were obtained for composites with 2% mixed fibers, it was: 9.8 MPa for 90% steel fibers using both types of fibers in the 50:50 ratio and 10% PE fibers and 11.3 MPa for 80% steel fibers with using both types of fibers in a 50:50 ratio and 20% PE fibers [47].

The hybrid reinforcement of steel and PE fibers was also investigated in a geopolymer matrix composed of fly ash from Hong Kong, Chinese slag, and sand. Steel fibers had 13 mm long and 180 µm in diameter and PE fibers had 13 mm long and 17 µm in diameter. Fibers were added to the composites in the amount of 2% by volume, changing the proportions of between steel and PE fibers (100% steel fibers, 75:25, 50:50, 25:75, and 100% PE fibers). The samples were tested after 28 days [51]. The results of the compressive tests show improvement with an increase in the steel fiber content. The values for particular samples are as follows: 100% steel fibers—78 MPa, 75:25—77 MPa, 50:50—68.2 MPa, 25:75—63.8 MPa and 100% PE fibers—64.8 MPa [51]. At the same time, the positive effect of the addition of PE fibers on the inhibition of the cracking mechanisms has been observed. The change of the crack character from a brittle fracture to a more ductile one was confirmed [51].

Cui et al. decided to add to hybrid reinforcement additional fibers. The reinforcement includes: 1% copper-coated micro steel fiber, 1% high-strength PE fibers in volume fraction, and 0.4%, 0.8%, and 1.2% methylcellulose in weight fraction [52]. The geopolymer matrix was based on fly ash and slag. The steel and PE fibers had a positive influence on compressive strength. Additionally, the addition of the fibers changed the damage pattern from brittle to ductile. It effectively suppresses the development of multiple micro-cracks [52]. Moreover, the methylcellulose increased the ductility of the composite [52].

Another hybrid reinforcement, a 1% addition of PVA fibers and a 1% addition of steel fibers, was tested on a metakaolin matrix with the addition of class F ashes and various sand fractions [53][54]. The results were compared to the properties of traditional cement materials, as well as to composites with one type of fiber. The studies were conducted after 28 days [53][54]. The results show that the composites based on the geopolymer matrix achieved comparable values in terms of flexural strength as composites based on traditional concrete. Additionally, these composites achieved higher values compared to composites containing only PVA fibers (2%) and lower than composites with the addition of fibers steel (2%) [53][54].

Carbon fiber nanotubes (diameter 30–50 nm) and PA fibers (length 5 mm and diameter 12 μm) were also investigated as a hybrid reinforcement [55]. The geopolymer matrix was based on metakaolin activated with phosphoric acid. The fibers were added in the following percentages: 0.0%, 0.5%, 1.0%, 1.5%, 2.0%, 2.5% by weight [55]. The best mechanical properties were achieved for the hybrid reinforcement—the compressive strength was approximately 115 MPa for 1.5% of the additive (for the same amount of PA fibers it was 90 MPa, and 51.7 MPa for the plain matrix material) [55]. The best result for flexural strength was also for 1.5% addition of hybrid fibers—about 38 MPa (for the same amount of PA fibers the strength was about 27 MPa, and for plain matrix it was 9.9 MPa) [55].

The hybrid reinforcement is a very promising research area. It allows to increase compressive strength and flexural strength by using different types of reinforcement.

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