Review Article

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State of the art, challenges, and emerging trends: Geopolymer composite reinforced by dispersed steel fibers

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Abstract: The main aim of the article is to analyze the state of the art in short steel fiber-reinforced geopolymers, taking into consideration also waste fibers. Steel fibers are currently the most widely applied additive to composites in the building industry. The work is dedicated to the usage of short steel fibers and the mechanical properties of geopolymer composites. Research methods applied in the article are a critical analysis of the literature sources, including a comparison of the new material with other, traditional concrete materials used in similar applications, especially in the construction industry. The results of the research are discussed in a comparative context. They indicate that the addition of fibers is an efficient method not only for improving compressive and flexural strength, but also mechanical properties such as fracture toughness. The potential applications in the construction industry as well barriers and challenges for the effective application of geopolymer materials reinforced with steel fibers are presented. Further research directions are discussed.

Keywords: steel fiber, geopolymer, mechanical properties, fiber reinforcement, composite

1 Introduction

Nowadays, an important factor in the development of geopolymers is their environmental credentials. The rational management of natural resources and the use of waste materials, such as fly ash, are becoming increasingly important [1,2]. The development of sustainable structural materials for decreasing the environmental impact of the construction industry is the main motivator to research works on new, innovative materials' solutions [3–5]. These kinds of materials, based on geopolymers, allow reducing the emission of CO_2 and other substances harmful to the environment and at the same time save natural resources by using waste [6,7]. The estimations show that geopolymer concretes are reportedly able to produce between 50 and 80% less CO_2 emissions compared to ordinary Portland cement products [2,8,9]. Moreover, geopolymer production allows the use of different wastes streams (hazardous and non-hazardous) [10,11]. These kinds of admixtures could improve the geopolymer properties, for example, coke dust increases the mechanical properties of the composite, and at the same time, it is a pro-ecological direction aimed at the management of industrial waste [12]. Geopolymer composites, in particular with short fiber reinforcement, intended for advanced engineering applications, are part of the sustainable development policy, which is currently a guideline for the creation of legal standards in many countries in the world [1].

The main advantages of geopolymers are high compressive strength, good thermal properties (fire- and heat resistance), and resistance to corrosive environments. The weakness of this type of composite is a brittle fracture, which limits its use in many areas [13,14]. Therefore, the reinforcement of the geopolymer by short fibers is desirable. This should improve the flexural strength and fracture toughness of these materials [13,15]. Fibers can also increase the amount of energy absorbed by the material before damage occurs [16,17]. The addition of fibers changes the nature of the fracture from brittle to more ductile [17]. Moreover, the number of cracks in the material is reduced and the width of the cracks is limited [18].

Steel fibers are currently the most widely applied addition to composites in the building industry [6]. Different types are used for reinforcement of the

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composites (Figure 1). The hooked-end and curved fibers are used for obtaining better bonding strength between the geopolymer matrix.

The composites based on a geopolymer matrix has good compressive strength and the steel fibers have good tensile and flexural strength; hence, the main goal of the addition of steel fibers is increasing the mechanical properties, in particular, tensile and flexural strength [19,20] and reducing the propagation of cracks in the material (micro-cracks are intercepted before they are developed) [19]. Additionally, steel fibers in geopolymers do not show any problems with corrosion [20].

2 Research methodology

The main topic of the research was the mechanical properties of short steel fiber-reinforced geopolymer composites. The study was conducted with scientific article databases, including ScienceDirect, Scopus, and Google Scholar. It was focused on the keyword "geopolymer" and supported by similar ones, for example: "inorganic polymer" and "alkali-activated material," taking into consideration the phrases "mechanical properties" and "steel fiber." In the field of steel additives, only the articles with the addition of short fibers were considered in this research. The scientific works carried out on the use of long fibers, bars, and some kind of "mesh" reinforcement were not taken into consideration in this article. All the listed types of reinforcement have a significant application potential but their usage gives different effects on the material.

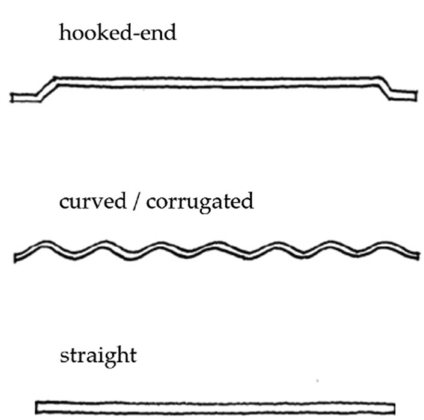

Figure 1: Types of most popular steel fibers used for reinforcement of composites.

3 Composites reinforced with steel fibers

3.1 Steel fiber-reinforced geopolymer composites for traditional structure applications (solid material)

The research on the mechanical properties of composites with the addition of steel fibers was carried out, among others based on a matrix consisting of fly ash class C, slag after processing steel and sand [21]. The steel fibers had a diameter of 0.2 mm and a length of 13 mm. The following percentages of fibers were used: 0.0, 0.1, 0.2, 0.3, 0.4, and 0.5% by volume. The samples were tested after 3, 7, and 28 days [21]. The compressive strength increased over time for all composites: it was about 14 MPa after 3 days, about 22 MPa after 7 days, and above 32 MPa after 28 days. All composites achieved higher values than the plain matrix material. The highest compressive strength was achieved for the composite containing 0.4% by volume of steel fibers (38.6 MPa). The compressive strength of the composite containing steel fiber was slightly lower than for other tested fibers, including basalt and polypropylene (PP) fibers [21]. The flexural strength also increased over time: it was about 3 MPa after 3 days, about 4 MPa after 7 days, and about 6.5 MPa and after 28 days. For the addition of 0.2 and 0.3% of steel fibers, a decrease in value was observed compared to the plain matrix material. The highest values were achieved for the composite containing 0.5% by volume addition of steel fibers: it was 7.9 MPa compared to about 6.5 MPa for the plain matrix material. Compared to composites reinforced with basalt and PP fibers, slightly higher values of flexural strength were obtained [21]. Additionally, it is worth noting that other fibers such as basalt or glass degrade in the alkaline environment, which is a geopolymer and gives a significant advantage over the steel fiber [22].

Ranjbar et al. investigated the composites based on fly ash class F from Lafarge Malayan Cement Bhd of Malaysia [23]. The following amounts of short steel fibers were added: 0.0, 0.5, 1.0, 2.0, 3.0 and 4.0% by weight (solid precursors). The steel fibers had a diameter of 0.2 mm and a length of 22 mm. The steel fiber-reinforced composites were compared with composites reinforced with PP fibers. The studies were conducted after 7 and 56 days [23]. The results show a favorable effect of fibers on flexural strength and compressive strength [23]. The best results for flexural strength were achieved for the composites with the addition of 3.0% steel fibers: it was 27 MPa after 7 days and 35 MPa after 56 days; for comparison, the values for the plain matrix material were 4 MPa and 11 MPa, respectively [23]. In the case of compressive strength for all dosages of fibers, the initial strength after 7 days was higher than that of the matrix material itself. The best result was for 3.0% addition of fibers was about 55 MPa compared to 31 MPa for the base material. After 56 days, the value for the plain matrix material was about 58 MPa, the same as for the 2.0% addition of steel fiber. For the addition of 3.0%, it was slightly lower, i.e., about 57 MPa [23].

Other studies were carried out based on a matrix made of fly ash class F from the Catalagzi/Zonguldak power plant in Turkey and slag from the Bolu cement plant [24]. The following amounts of steel fibers were added: 0.4, 0.8, and 1.2% in a volumetric ratio. The fibers had dimensions of 0.17 mm in diameter and 6 mm in length. The samples were tested after 7 and 28 days [24], and the results showed an increase in the mechanical properties of the samples with fibers compared to the control samples (without the fiber content). The compressive strength improved slightly but the flexural strength significantly. The samples did not show a significant increase in strength over time [24]. The best results were obtained for the compressive strength after 28 days, for samples with 1.2% of fibers. These values were 62.5 MPa for the compressive strength compared to 60.5 MPa for the reference samples, and 11.1 MPa for the flexural strength, compared to 8.5 MPa for the control samples, respectively [24].

A significant increase in compressive strength was observed for 0.5 and 1.0% addition of steel fibers, by volume, with a length of 60 mm to a matrix based on fly ash and fume silica. The components came from a power plant in the Lampang province in Thailand [25]. The samples were tested after 28 days. The compressive strength for the composite containing 0.5 wt% of steel fibers was 56.6 MPa, and for the composite containing 1.0 wt% steel fibers, it was 61.7 MPa. For the matrix material, the compressive strength after the same period was 40.1 MPa [25].

The addition of short steel fibers was tested also using a fly-ash-based geopolymer matrix. The steel fibers were 13 mm long and 0.6 mm in diameter. The amount of fibers used was 1.5% by volume [26]. The matrix material reached a value of compressive strength of 70 MPa, and that of the composites with the addition of steel fibers was 76.7 MPa [26]. The flexural strength increased significantly: it was 12.6 MPa for the composite with 1.5 wt% fiber content compared to 7.1 MPa obtained for the plain matrix material [26]. The tensile strength tests were also carried out, and an increase from 3.1 MPa for the plain matrix material to 9.1 MPa was observed for the fiber-reinforced composite [26].

Shaikh investigated the composites based on a metakaolin matrix with the addition of fly ash class F and sand [27,28]. These composites were compared to traditional concrete materials [27,28]. In this research, a 2.0 wt% addition of steel fibers was used. The fibers had a diameter of 0.12 mm and a length of 10 mm [27,28]. The samples were tested after 28 days. The results show that the composites based on the geopolymer matrix achieved higher values in terms of flexural strength than the composites based on the cement matrix; in addition, the geopolymer composites were characterized by a more ductile cracking mechanism [27,28].

The study of steel fibers on a geopolymer matrix was also investigated based on fly ash. The properties of geopolymer concrete were compared to traditional concretes [29]. Steel fibers were 30 mm long and had a diameter of 0.5 mm. The amount of fibers added were 0.0, 0.25, 0.5 and 0.75 wt% [29]. The results show the positive effect of fiber addition on compressive strength. For 0.75% addition of steel fibers, the compressive strength of 43.7 MPa was obtained; it was higher for both the plain geopolymer matrix (39 MPa) and for traditional concrete with the same fiber content (40.2 MPa) [29]. These studies were continued with the use of the same fibers; composites with 1.0% fiber content were also made [30]. The following results of compressive strength were achieved: plain matrix material – 37 MPa, and for fiber-reinforced composites: 0.25% – 38.4 MPa, 0.5% – 41.2 MPa, 0.75% – 42.5 MPa, and for 1.0% – 42.8 MPa. Thus, the value of the compressive strength increased with the amount of fiber added. The results were compared to traditional concrete, which obtained lower values than materials based on geopolymers. It was 35 MPa for the plain matrix material and 39.5 MPa for the traditional concrete with the addition of 0.5% fibers [30]. The flexural strength was also tested and it behaved similarly to the compressive strength, i.e., it increased with the amount of reinforcement. It was 4.10 MPa for the plain matrix material, and for composites containing fibers: 0.25% – 4.3 MPa, 0.5% – 4.6 MPa, 0.75% – 4.9 MPa, and 1.0% – 5.1 MPa, respectively. For the concrete, it was 3.8 MPa for the matrix material and 4.2 MPa for the composite with the addition of 0.5% fiber [30].

This research was also carried out at the Cracow University of Technology, Poland [31,32]. The amount of short steel fibers used as an additive to geopolymer composite was 5% by weight. The fly ash from the CEZ Skawina power plant (Małopolskie, Poland) mixed with sand in a 1:1 ratio was used as the matrix material. The studies were conducted after 28 days [31,32]. The results showed an increase in mechanical properties both in terms of compressive strength and flexural strength. As a result of the addition of the dispersed fibers, the composite was strengthened from 9.2 MPa for the matrix material to 14.5 MPa for the fiber-reinforced composite in the case of flexural strength. For the compressive strength, an increase in the value from 55.4 MPa for the matrix material to about 69 MPa for the fiber-reinforced composite was also noted [31,32]. The microstructure investigations showed good cohesion of steel fibers with the matrix material [31,32].

Other studies on the addition of steel fibers to the geopolymer matrix were carried out based on a matrix made of fly ash and sand [33]. Fibers were added in the following amounts: 0.0, 0.1, 0.2, 0.3, 0.4, and 0.5%. The best results were obtained for the addition of 0.2% of steel fibers: it was 37.5 MPa for the compressive strength and 4.2 MPa for the flexural strength. For the matrix material, these values were 28.9 and 3.2 MPa, respectively [33]. The slightly different behavior of the composites was observed in studies using geopolymer composites based on the fly ash from Mettur Thermal Power Plant in Tamil Nadu, India, and sand [34]. Crushed steel fibers, 30 mm long and 0.45 mm in diameter, were used as reinforcement in amounts of 0.0, 0.25, 0.5, 0.75, and 1.0%. The studies were conducted after 28 days [34]. The results showed an increase in mechanical properties with the addition of fibers. The compressive strength increased from 45.4 MPa for the plain matrix material to 49.2 MPa for the composite with 1% of steel fibers. The flexural strength improved from 2.6 MPa for the plain matrix material to 4.2 MPa for the composite with 1% of steel fibers [34].

Ng et al. investigated the behavior of various types of fibers in geopolymers; depending on the shape of the steel fibers, different types of cracking mechanisms were observed [35]. The two types of steel fibers were applied: curved at the end, in amounts of 0.0, 0.5, 1, 1.5% (diameter of 0.55 mm, length of 35 mm) and straight ones, in an amount of 1.5% by weight (diameter of 0.2 mm, length of 13 mm) [35]. The geopolymer matrix was prepared based on the fine basalt aggregate (10 mm), fly ash from Eraring Power Station in the New South Wales region of Australia, ground blast furnace slag, and kaolite ash from Callide Power Station in Queensland, Australia [35]. The compressive strength of the composites was tested after 7 days. The results show that for both types of fibers there was a decrease in compressive strength; a greater decrease in the percentage of fibers. The compressive strength for the plain matrix material was 63.1 MPa, and for composites with curved fibers, it was 0.5% – 58.2 MPa, 1.0% – 55.0 MPa, 1.5% – 53.4 MPa, respectively. It should be noted that when we compare curved fibers with straight fibers, the decrease is slightly lower for composites with straight fibers. It was 55.1 MPa (composite with 1.0% by weight of straight steel fibers) [35].

Research on the dependence of mechanical properties on the type of steel fibers used as reinforcement was also carried out on a geopolymer matrix consisting of fly ash, slag, and sand. Steel fibers were added at 1.0, 2.0, and 3.0% by volume. Three types of fibers were used: straight fibers 6 mm long and 0.16 mm in diameter; straight fibers 13 mm long and 0.16 mm in diameter; and curved fibers 50 mm long and 1 mm in diameter. After the preparation of samples, the materials were tested after 3, 7, 14, and 28 days. An increase in the mechanical properties of composites was observed over time [36]. The results of the compressive strength after 28 days show a significant increase compared to the plain matrix material (about 45 MPa). The best results that about 60 MPa were obtained for 2.0% addition of 6 mm straight fibers and 3.0% addition of 13 mm straight fibers [36]. The best result, about 6.5 MPa for the flexural strength, was obtained for a 3% addition of 13 mm straight fibers. The obtained results were compared with reinforcement made from glass and polyvinyl alcohol (PVA) fibers. The composites with steel fibers achieved better results [36].

Tests with curved steel fibers were also carried out based on a fly ash matrix from the Mae Moh power plant in Lampang, Thailand, and silica dust [37]. The experiment included the addition of steel fibers, 0.5 and 1.0%, and different proportions between fly ash and silica. Fibers with a length of 35 mm were used. The samples were tested after 28 days [37]. The flexural strength of composites increased with the percentage of added fibers. The best results were obtained for 1.0% addition of steel fibers with a matrix composed of about 90% fly ashes supplemented with silica – 10.7 MPa. For the same matrix with 0.5% fiber content, the flexural strength value was 6.7 MPa, and that for the plain matrix it was 5.7 MPa [37].

The differences between the behavior of steel fibers of the same type but with different dimensions, lengths, and diameters, were investigated by Bashar et al. [38]. The research was conducted on a geopolymer matrix based on the waste from palm oil production and metakaolin. Two types of curved steel fibers were added to the matrix: for the first one, length of 60 mm, the diameter of 0.75 mm; and for the second one, a length of 35 mm and diameter of 0.54 mm. Additionally, the hooked-end type steel fibers of length 60 mm and 35 mm with aspect ratios 80 and 65, respectively, were used. The steel fibers were added in amounts of 0.25, 0.50, and 0.75% by volume [38]. The compressive strength was tested after 3, 7, 14, and 28 days and flexural strength after 28 days. Compression test results show a slight improvement in mechanical properties. The best results were obtained after 28 days for the 0.50% content of fiber (31.9 MPa). It was a slight improvement compared to the plain matrix (30 MPa) [38]. The best flexural strength was obtained for the content of 0.75% of steel fiber (5.1 MPa) compared to the value for the plain matrix (4.3 MPa) [38].

The curved steel fibers were also investigated by Yuvaraj and Srinivasan [39]. The fibers were 30 and 60 mm long. Fibers were added in an amount of 1% by weight to the geopolymer matrix based on slag. Both types of fibers were used as an additive in the following proportions: 50/50, 40/60, and 60/40 [39]. The samples were tested after 1, 7, and 28 days [39]. The compressive strength increased with time. The best results were obtained for a mixture containing 60% of 30 mm long fibers and 40% of 60 mm long fibers: it was 41.2 MPa; the plain matrix material achieved 30.4 MPa. Also, the composite with only one kind of fiber had lower values, the addition of only 30 mm long fibers (34.8 MPa) and only 60 mm long fibers (31.3 MPa) [39]. The best results of the flexural strength were obtained for the mixture containing 60% of 30 mm long fibers and 40% of 60 mm long fibers; it was 7.5 MPa. For the plain matrix material, it was 3.7 MPa, and for the 30 mm fibers – 5.0 MPa, and for the 60 mm fibers – 4.5 MPa [39].

The research was also carried out with the use of steel fibers with the following dimensions: diameter of 0.2 mm, length of 13 mm; and diameter of 0.16 mm, length of 6 mm [40]. The matrix was geopolymer concrete based on fly ash and slag class F with two types of filler: lime and sand [40]. The fibers were added in the following proportions: 0.0, 0.25, 0.5, 0.75, and 1% for each type of fiber, and in the following proportions of both fiber combinations: 80/20, 60/40, 40/60, and 20/80 (1% by weight of the composite). The samples were tested after 7 and 28 days [40]. The results of the compressive strength tests show an increase in the value over time and with the fiber content (the highest values were obtained for 1% of the fiber addition). Among composites with one type of fiber, the highest value was obtained for longer fibers (13 mm) – about 95 MPa (compared to about 81 MPa for the plain matrix material). The best results for the composition of two types of fibers were obtained for the proportion of 60% fibers with a length of 13 mm and 40% with a length of 6 mm – about 95 MPa. All compositions with two types of fibers achieved higher compressive strength values than the composite with one type of fiber. The synergy effect was visible for the simultaneous use of both types of fibers in the composite [40].

Research works based on different types of fibers, spiral and curved, with the same length of 25 mm and different diameters (0.55 and 0.3 mm, respectively) were carried out on a geopolymer matrix composed of fly ash and slag. The fly ash class F was obtained from Gladstone Power Station in Queensland, Australia, and slag from a cement plant in Australia [41]. The composites were prepared with fibercontents of 1.0, 1.5, and 2% by volume. Both types of fibers were used in the tests in a 50:50 ratio. The samples were investigated after 28 days [41]. The compressive strength increased with the amount of fibers. The compressive strength for the plain matrix was 72 MPa, and for the composites with contents of 1.0 and 1.5%, it was about 75.1 and 74.7 MPa, respectively. The best results, about 82 MPa, were obtained for a 2.0% fiber content [41]. Similarly, flexural strength increased. It was 3.9 MPa for samples without the addition of fibers. It increased with the addition of steel fibers; for the subsequent contents, it was 1.0% – 6.1 MPa, 1.5% – 6.7 MPa, and 2.0% – 9.6 MPa, respectively [41]. The tests were also were carried out with curved steel fibers with a diameter of 0.75 mm and a length of 35 mm. Fibers were added in amounts of 0.0, 0.25, 0.5 and 0.75%. The geopolymer matrix based on fly ash and slag was used. Samples were tested after 7 and 28 days [42]. The mechanical properties increased over time and with the content of steel fibers [42].

The tests were also carried out on copper-coated steel fibers in a fly ash-based matrix from Lafarge Malayan Cement Bhd in Malaysia [43]. The steel fibers were added to the composite in amounts of 0.0, 0.5, 1.0, 2.0, 3.0, and 4.0%. The studies were conducted after 28 and 56 days [43]. The results indicated a change in the cracking mechanism from brittle to ductile and improvement of flexural strength for composites containing 1% and a higher percentage of steel fibers. The flexural strength for the composites with 3.0 and 4.0% steel fibers was about 30 MPa, while for the plain matrix material it was about 10 MPa [43]. The compressive strength was also improved by the addition of fibers, with the best result of 58 MPa obtained after 56 days with the addition of 2.0 and 3.0% fibers. The results show that the addition of fibers caused higher initial strength (a faster binding mechanism) [43]. However, not all research works confirm the existence of such a mechanism, showing slightly better results for the matrix material than for the material with the addition of steel fibers [44].

The investigation was made on a matrix based on fly ash, slag, and sand. Two kinds of fibers were added: with 0.25 mm diameter and 13 mm length; and 0.75 mm diameter and 50 mm length [45]. The fibers were added as 1% of each type of fibers and in a mixed proportion as 2%. The best results were achieved for 2% of fibers. It was 43.8 MPa for compressive strength and 8.6 for flexural strength, compared to the plain matrix, which was 33.4 MPa and almost 6.0 MPa, respectively [45].

Srinivas et al. investigated the geopolymer based on fly ash from Kothagudem Thermal power station, Bhadradri Kothagudem Dt, Telangana, India, and sand [46]. The fibers were added in amounts of 0.0, 0.5, 0.7, 0.9, and 1.0% by volume. The low carbon steel fibers had a length of 30 mm and a diameter of 0.6 mm [46]. Only the tensile strength was investigated. The results showed an increase of the tensile strength over time (samples were cured 7 and 28 days) and with the amount of the fibers [46].

Steel fiber-reinforced fly ash geopolymer concrete was also investigated in a geopolymer matrix based on Malaysia fly ash. The geopolymer concrete was produced by mixing fly ash class F from Manjung power station, Lumut, Perak, with river sand and granite (aggregates) [47]. Steel hooked fibers were added into the geopolymer concrete as reinforcement with different weight percentages: 0.0, 0.5, 1.0, 1.5, and 2.0%. The fibers had a diameter of 0.60 mm and a length of 0.75 ("steel wool") [47]. The results showed that the flexural strength of samples increased with the addition of hooked steel fibers until 1% and slightly decreased when the amount of fibers added was more than 1%. The flexural strength for the addition of 1% of fibers was 11.1 MPa compared to the plain matrix was 4.6 MPa [47]. The compressive strength was not investigated.

The fracture parameters including flexural strength were also investigated by Gomes et al. [48]. The geopolymer was based on metakaolin. It was reinforced by hooked-end steel fibers with 30 mm in length and a diameter of 0.62 mm. The volume ratios of fibers were 0, 0.25, and 0.50% [48]. The results show increasing mechanical properties with the amount of fibers. The compressive strength for the plain matrix was 32.5 MPa and that for the composites was 32.9 MPa for the addition of 0.25% fibers s and 38.9 MPa for 0.5 fibers [48]. The flexural strength obtained in the matrix specimen was 3.1 MPa. For volume ratios of 0.25 and 0.50%, the mean flexural strength was 3.6 and 4.3 MPa, respectively [48].

The steel fibers were also investigated in the fly ash/slag-based matrix [49]. Three different lengths of steel fibers (diameter 0.75 mm) were applied in the geopolymer matrix: 35 mm, 50 mm, and 60 mm [49]. The following proportions were added: 0.0, 0.25, 0.50, and 0.75%. The samples were tested after 28 and 56 days [49] and the results showed increasing compressive as well as flexural strength over time and with the amount of fibers. The compressive strength increased from about 27 MPa for the plain matrix to 44 MPa for the composite with the addition of 0.75% fibers. The flexural strength increased from about 4 to 5.5 MPa, respectively [49].

Liu et al. studied the influence of fiber's shape on the mechanical properties of geopolymer concrete based on blended granulated blast furnace slag, fly ash class F, silica fume, and sand as an aggregate [50]. The following fibers were investigated:

- Straight (length: 6 mm, diameter: 0.12 mm)
- Straight (length: 8 mm, diameter: 0.12 mm)
- Straight (length: 13 mm, diameter: 0.12 mm)
- Straight (length: 13 mm, diameter: 0.20 mm)
- Hooked-end (length: 13 mm, diameter: 0.20 mm)
- Corrugated (length: 13 mm, diameter: 0.20 mm).

The amounts of the fibers were 0, 1, 2, and 3% by volume of the concrete [50]. The achieved results were very high. The best results for compressive and flexural strengths were for the sample with 3% of straight steel fibers (length: 13 mm, diameter: 0.12 mm) [50]. The compressive strength was 170.4 MPa and flexural strength was 24.6 MPa. These results are significantly higher than those presented in other articles [50].

This kind of research was also conducted for micro steel fibers [51]. The matrix is based on fly ash and nanosilica. The microfibers were added in amounts of 0.0, 0.5, 1.0, 1.5, and 2.0% by volume [51]. The compressive strength was investigated after 28 days. The highest increase was shown in 1% of micro steel fiber (ca. 78 MPa) and was higher than the reference mix (ca. 70 MPa). The flexural strength was not studied [51].

3.2 Applications of steel fiber-reinforced composites in a corrosive environment and high temperatures

An important aspect of research on composites with steel fibers is also their resistance to various environments. The research in this area was carried out based on a geopolymer matrix based on slag reinforced with curved steel fibers with a diameter of 0.5 mm and length of 35 mm [52]. Composites with 0, 0.5, 1, and 1.5% of steel fibers were prepared for the tests. The research was conducted after 180 days (durability assessment). The mechanical properties for the composition were determined under the conditions of [52]:

- Ambient temperature

- Alternating soaking the sample in water and drying it at 100°C in 24 h cycles
- Acidic environment (soaking the sample in hydrochloric acid and drying it at 100°C in 24 h cycles)
- Increased temperature (cyclic heating of samples and cooling for 90 days to temperatures of 100, 200, and 800°C).

The research showed the beneficial effect of steel fibers on the mechanical properties and durability of composites. The highest values were obtained for composites containing 1.5% of steel fibers. For the plain matrix material, which was not influenced by any additional factors such as temperature, the value was 52.6 MPa, and for composites with 1.5% fiber content, it was about 65.4 MPa. The introduction of additional factors affecting the samples reduced the properties of both the plain matrix as well as fiber composites. For variable humidity, these values were 46.7 and 62.4 MPa; those for the acidic environment were 46.4 and 61.6 MPa, and for temperatures they were as follows: 100°C – about 48 and 53 MPa, 200°C – about 41 and 44 MPa, 800°C – about 17 and 29 MPa (values for reference samples after 90 days: about 50 and 55 MPa). The research showed a significant resistance of composites with steel fibers to environmental conditions [52].

Other research works were carried out to confirm the obtained results of tests at high temperatures, showing the possibilities of using composites with a reinforcement of dispersed steel fibers at elevated temperatures (up to 800°C). The research showed that composites at 200–400°C had better mechanical properties than at ambient temperature. Additionally, the addition of fibers reduces cracking at higher temperatures [53].

The resistance against seawater exposure was also investigated on the fly-ash-based geopolymer concrete with the addition of steel fibers [54]. Fly ash class F was obtained from Cement Industries of Malaysia Berhad (CIMA), Perlis, Malaysia. For comparison, the ASTM Type I Portland cement was used. The material was reinforced by low carbon steel with a straight end – a length of 5 mm and a diameter of 0.13 mm for 3% of the total weight [54]. The results showed that the compressive strength of the composite was in a decreasing trend as the time of seawater immersion increased. The highest compressive strength obtained for the geopolymer concrete was 76.9 MPa at 28 days, whereas the lowest compressive strength obtained was 51.6 MPa. These values were significantly better than for reference samples made from Portland cement [54].

3.3 Application of recycled steel fibers in geopolymer composites

The research was also carried out with the use of recycled reinforcement, in particular with the use of waste steel cord from used car tires. The geopolymer is based on a fly ash matrix from the Matra Power Station in Hungary [55] and fly ash from the combined heat and power plant in Skawina, Poland [56,57]. The work confirmed the possibility of using the used metal as reinforcement for geopolymers, which will improve their mechanical properties. It is also possible to use other components of the tire, i.e., textile cord, and rubber as an additive to geopolymers, but they do not significantly improve the mechanical properties of composites or cause their slight decrease [56,57].

3.4 Application of steel fiber-reinforced geopolymer composites in additives' manufacturing

Methods of strengthening composites printed with 3D technology by steel fibers are currently the subject of research [58,59]. The study includes short steel fibers [60] and long steel fibers [61–63].

Al-Qutaifi et al. conducted studies on the effect of spacing in the formation of successive layers and interlayer bonding [60]. They used a 3D printing extrusion method for samples' preparation. The composition was based on a geopolymer matrix (fly ash) reinforced with steel fibers 40 mm long (1 vol%) and polypropylene (PP) fibers 5 mm long (0.5 vol%) After the samples were produced, they were subjected to a three-point bending test. The flexural strength of elements with steel fibers was 6.3 MPa, and that with PP fibers was 5.1 MPa, and of reference elements, it was about 5.0 MPa [60]. Additionally, research confirms the positive impact of reducing the time intervals between the layers of reinforcement admixtures on the flexural strength, the bond strength between successive layers depends on the effect of fibers [60].

The research of Lin et al. concerns hybrid composites reinforced during 3D printing, where the matrix is a geopolymer with the composition: fly ash, blast furnace slag, and microsilica with a stainless steel continuous cord. The cable lengths were 1.0, 1.5, and 2.0 mm, respectively [61]. The composite includes also polyvinyl alcohol fibers (8 mm length) in a volume of 0.5% by weight. A four-point bending test of the produced samples was carried out, which showed the efficiency of the hybrid method by 290% compared to the control sample [61].

Ma et al. made geopolymers (containing fly ash, slag, silica dust, and a mixture of quartz sand) reinforced with steel fibers [62]. The production involved three configurations of printing paths with fibers arranged: obliquely, rectangular in shape, and orthogonally crossed [62]. The obtained samples were subjected to a four-point bending test. The results showed that the flexural strength of the samples with the cross-angled fiber was the best, approximately 48.9 and 200% dominant, then that remaining arrangement of the fibers. Also, for ordinary samples, the bending results with cross filament exceeded the value even up to 600% [62].

3.5 Use of steel fibers in hybrid reinforcement in the geopolymer matrix

The hybrid reinforcement contains two different types of fibers. There is a very often combination of steel fibers with plastic fibers such as polypropylene (PP) [25,64–68], polyethylene (PE) [41,69–73], and polyvinyl alcohol (PVA) [27,28]. The hybrid reinforcement is a very promising research area. It allows us to increase both compressive as well as flexural strength by using different types of fibers.

The most popular hybrid reinforcement joins steel and PP fibers. These kinds of composites were investigated on a geopolymer matrix based on fly ash and silica fume, the components came from a power plant in the Lampang province in Thailand. The curved steel fibers (length of 60 mm) and PP fibers (length of 58 mm) were applied [25]. Two types of tests were made:

- PP fibers were substituted with steel fibers with an increment of 0.2% until a full replacement. The compressive strength increased with the amount of steel fibers in the composite. The compressive strength after 28 days was 35.4 MPa for the composite with PP fibers, and it increased with steel fibers addition: 80:20 – 40.5 MPa, 60:40 – 45.2 MPa, 40:60–51.7 MPa, 20:80 – 56.8 MPa and 100% of steel fibers – 60.6 MPa (the compressive strength for reference sample was 40.1 MPa) [25].
- The steel fibers were applied to the composite with an increase of 0.2% until the total volume fraction reached 2% (the volume of PP fibers was constant – 1%) [25]. The compressive strength increased with the amount of steel fibers. The maximum value of 73 MPa was achieved for the addition of 1% of steel and 1% of PP fibers. For the other composites, it was 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, respectively [25].

The hybrid composite containing the steel macro fibers (length 30 mm, 0.5 mm diameter) and PP microfibers (length 12 mm, 18 μm diameter) was also investigated on a geopolymer matrix based on fly ash class C. The fibers were added n the amount of 0.5 and 1% by volume, in a 4:1 ratio. The research was made after 28 days at temperatures from −30 to 300°C [68]. The results showed a decrease in the mechanical properties of composites when the temperature increased. The best results were for negative temperatures [68]. The best results in compressive strength were achieved for plain matrix – about 45 MPa, for 0.5% fibers addition – about 38 MPa, and for 1% – 30 MPa. The flexural strength has the following results: composite with 1% addition of fibers – 9 MPa and plain matrix as well as a composite with 0.5% fibers addition – below 7.2 MPa [68].

The second most popular polymer fibers used together with steel fibers are PE fibers [41,69–73]. Khan et al. studied this kind of composites on a geopolymer matrix composed of fly ash and slag [69–72]. Fly ash class F came from Gladstone Power Station in Queensland, Australia, and slag from a cement plant in Australia [41]. The research was made with the usage of two types of steel fibers – spiral and a curved one. The fibers had the same length 25 mm and slightly different diameters 0.55 and 0.3 mm, respectively. The PE fibers had a length of 12 mm and a diameter of 12 μm [41]. The following samples were prepared:

- two types of samples containing 1% of 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);
- 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 investigated after 28 days [41]. The results showed a decrease in the compressive strength of samples with mixed fibers in comparison to samples with the same content of only steel fibers [67]. The hybrid fibers were beneficial for the flexural strength. It was 3.9 MPa for samples without reinforcement, and increased with the addition of steel fibers: 1% – 6.1 MPa, 1.5% – 6.7 MPa, and 2% – 9.6 MPa, respectively. For the hybrid reinforcement (1% steel fibers and 1% PE), the subsequent results were achieved [41]:

- 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,
- 4.9 MPa for composites with the addition of 80% spiral steel fibers and 20% PE fibers,
- 9.8 MPa for 90% of steel fibers using both types of fibers in the 50:50 ratio and 10% PE fibers,
- 11.3 MPa for 80% of steel fibers with using both types of fibers in a 50:50 ratio and 20% PE fibers.

The hybrid reinforcement containing steel fibers (13 mm long and 180 μm in diameter) and PE fibers (13 mm long and 17 μm in diameter) were investigated in a geopolymer matrix composed of fly ash from Hong Kong, Chinese slag, and sand [72]. Reinforcement was introduced into the composites in an amount of 2% by volume. The proportions between steel and PE fibers were changeable: 100% steel fibers, 75:25, 50:50, 25:75, and 100% PE fibers. The composites were tested after 28 days [72]. The compressive strength increased with the steel fiber content [72]:

- 100% steel fibers – 78 MPa
- 75:25 – 77 MPa
- 50:50 – 68.2 MPa
- 25:75 – 63.8 MPa
- 100% PE fibers – 64.8 MPa.

The PE fibers worked as inhibition of the cracking. The change of the crack character from a brittle fracture to a more ductile one was observed [72].

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 were applied into the geopolymer matrix based on fly ash and slag [73]. The steel and PE fibers had a positive influence on compressive strength and changed the damage pattern from brittle to ductile [71]. Furthermore, the methylcellulose improved the ductility of the composites [73].

The hybrid reinforcement containing steel and PVA fibers was also investigated. The research was made on a metakaolin matrix with the addition of fly ash class F and various sand fractions reinforced by the addition of 1% of PVA fibers and 1% of steel fibers [27,28]. The results were compared with traditional cement materials. The samples were investigated after 28 days [27,28]. The results showed that the composites based on the geopolymer matrix had similar properties of flexural strength as composites based on traditional concrete. The composites reinforced by both types of fibers obtained higher values compared to composites comprising only PVA fibers (2%) and worse than composites with the addition of only steel fibers (2%) [27,28].

Contemporary research are provided by using more advanced polymer fibers such as melamine [74]. Using these fibers combined with steel could not only improve the mechanical properties but also thermal and fire resistance [74].

3.6 Other applications of short steel fiber-reinforced geopolymer composites

The steel fiber-reinforced geopolymers were also investigated for nontypical applications such as material resistance against explosion [75], multifunctional conductive composites [76], and lightweight materials [77].

Meng et al. investigated the possibility of using the geopolymer composite reinforced by short steel fibers as a material for buried utility tunnels used to carry different items such as electricity, steam, water supply pipes, sewage pipes, and gas pipes [75]. They were applied as a matrix material geopolymer concrete based on fly ash, ground granulated blast-furnace slag powder, silica fume, and three grades of quartz sand. The material was reinforced by 2% of steel fibers with a dimension of 12 mm in length and a diameter of 0.12 mm [75]. The mechanical properties were tested. The plain geopolymer concrete had a compressive strength of 61 MPa and the steel fiber-reinforced composite had 74 MPa. Moreover, the methane gas explosion test conducted in a full-scale tunnel showed that the fiber-reinforced geopolymer concrete slab had a good capacity to resist methane gas explosion load [75].

The selected electrical properties of fly ash geopolymers with steel microfibers in the range of 5–30 wt% were investigated by Mizerová et al. [76]. They found that steel fibers caused an improvement in all assessed electrical properties but only above certain frequency values. Additionally, they observed increased in both compressive and flexural strength as well as reduced shrinkage of the material [76].

The possibilities of using geopolymers as lightweight composites were studied [77]. The research was made on a geopolymer matrix based on fly ash from ISKENment-Turkey power station and two types of aggregates. Sand was used as a fine aggregate. As a coarse aggregate, the artificial lightweight aggregate from bentonite clay and water glass (sodium silicate) was used; it minimalized the weight of the composite [75]. High tensile steel hooked end fibers were used as the reinforcement. The fibers had a length and diameter of 30 and 0.5 mm, respectively. The reinforcement was applied in percentages of 0.25, and 0.5% by volume [77]. The results showed that the steel fibers increased the density but also had a positive influence on mechanical properties, including compressive strength, splitting tensile strength, and flexural strength [77].

4 Influence of the addition of short steel fibers on mechanical properties of geopolymers

Different types of steel fibers had been applied (Table 1). The research carried out in the area of steel reinforcement for geopolymer composites was usually based on different fibers dedicated to cementitious materials. The fibers had different shapes (straight, curved, and hooked-end), length (between 6 and 60 mm), and diameter. Different percentages were also applied, up to 0.1–2.0%. Some authors added according to weight and others according to volumes [78,79]. However, the range of changes in the kind of fibers is significant, and the achieved results showed a lot of similarities with geopolymer composite's behavior.

Different lengths of fibers are applied as short fibers from 0.75 to 80 mm. The most popular fibers are between 20 and 30 mm (Figure 2).

Table 1: Characteristics of the short steel fiber-reinforced geopolymers

Length [mm]	Diameter [mm]	wt%	Reference
6	0.17	0.4, 0.8, 1.2 vol%	[22]
13	0.16	1.5 vol%	[26]
30	0.5	0.0, 0.25, 0.5, 0.75, 1.0%	[30]
Short	Not specified	0.0, 0.1, 0.2, 0.3, 0.4, 0.5%	[33]
30	0.45	0.0, 0.25, 0.5, 0.75, 1.0%	[34]
35	Not specified	0.5, 1.0%	[37]
65	0.035	0.25, 0.5, 0.75 vol%	[38]
80	0.06		
30	Not specified	1.0 vol%	[39]
60	Not specified		
25	0.55	1.0, 1.5, 2.0%	[41]
25	0.3		
13	0.25	1.0, 2.0%	[45]
50	0.75		
0.75	0.60	0.0, 0.5, 1.0, 1.5, 2.0%	[47]
30	0.62	0.25, 0.5 vol%	[48]

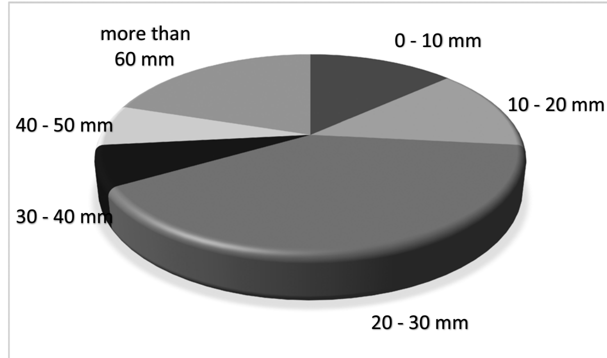

Figure 2: Research number percentage regarding the length of the steel fibers.

The research conducted so far for steel fiber-reinforced geopolymer composites showed that their addition is an effective method of improving mechanical properties (Table 2). Mechanical properties depended on a lot of issues such as the shape of the fiber or matrix composition and coherence fibers to the matrix. The best mechanical properties are usually achieved for the addition between 1 and 2% by weight (Table 2). Good mechanical properties are also achieved for composites with a mix fine fiber and biggest one. Compressive strength improvement is usually between 3.4 and 43.8%. The fibers have a more significant influence on flexural strength. The improvement is between 18.7 and 243.1% (Table 2). However, the improvement of more than 200% needs to be verified [47].

The addition of fibers is an efficient method not only for improving compressive and flexural strength,but also for mechanical properties such as fracture toughness. The presence of fibers reduces the general effect of cracking, limits the widths of the occurring cracks (exemplary reduction of the propagation of microcracks), suppresses all brittle behaviors, and enhances ductility [78,79]. It could be observed during microstructural research [77]. Steel fibers usually enhance toughness and ductility of materials. The mechanism of reinforcement in case of geopolymers is quite similar to concrete materials and show ductile or quasi-ductile behavior [80,81]. The fibers can also improve properties of geopolymers that are connected with their energy absorption and resistance to deformation. The improvement of early stage properties is also observed, including reduction of shrinkage [76,79].

The values of the obtained mechanical properties can be compared to other geopolymer composites reinforced by fibers as well as traditional building materials [82,83]. The values given for the fiber-reinforced geopolymer concrete are usually the compressive strength of more than 40 MPa and the flexural strength above 5 MPa. It defines

Table 2: Mechanical properties of the composites – short fiber-reinforced geopolymers

Fiber	Geopolymer matrix	Test time	Compressive strength (matrix) [MPa]	Flexural strength (matrix) [MPa]	Compressive strength (composite) [MPa]	Flexural strength (composite) [MPa]	Reference
Steel (1.2 vol%)	Fly ash, slag, sand	After 28 days	60.5	8.4	62.5 (+3.4%)	11.1 (+31.4%)	[22]
Steel (1.5 vol%)	Fly ash	After 7 days?	70.0	7.1	76.7 (+9.6%)	12.6 (+77.5%)	[26]
Steel (1.0%)	Fly ash	After 28 days	37	4.1	43.8. (+18.4)	5.1 (+24.4%)	[30]
Steel (0.2%)	Fly ash, sand	Not specified study time	28.9	3.2	37.5 (+30%)	4.2 (+30%)	[33]
Steel (1.0%)	Fly ash, sand	After 28 days	45.4	2.6	49.2 (+8.5%)	4.2 (+61.6%)	[34]
Steel (1.0%)	Fly ash + silica fume	After 28 days	—	5.7	—	10.7 (+87.9%)	[37]
Steel[1]	Metakaolin + wastes from palm oil production	After 28 days	30	4.3	32 (+6.3%)	5.1 (+18.7)	[38]
Steel[2] (1.0%)	Slag	After 28 days	30.4	3.7	41.2 (+35.5%)	7.5 (+100%)	[39]
Steel (2.0%)	Fly ash, slag	After 28 days	72	3.9	82 (+13.9%)	9.6 (+145.8%)	[41]
Steel (2.0%)	Fly ash, slag, sand	Not specified	33.4	6.0	43.8 (+76.2%)	8.6 (+69.7%)	[45]
Steel "wool" (1.0%)	Fly ash, granite, sand	After 28 days	N/A	4.6	N/A	11.1 (+241.3%)	[47]
Steel (0.5 vol%)	Metakaolin	After 21 days	32.5	3.1	38.9(+19,7%)	4.3 (+38.7%)	[48]

[1]Different proportions of fibers 1 and 2 were tested. The best results were obtained for 60% of fiber 1 and 40% of fiber 2; [2]Both types of fibers were used in a 50:50 ratio.

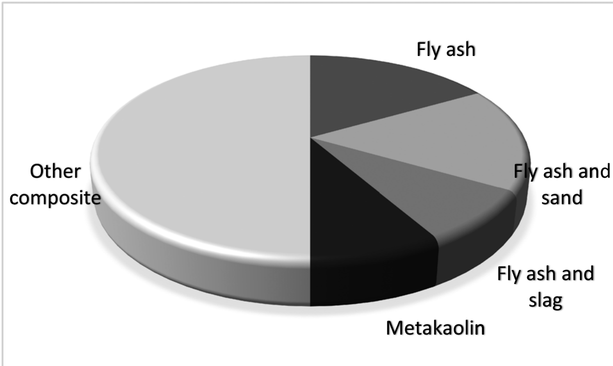

Figure 3: Research number percentage regarding the used matrix.

some applications for these kinds of composites in the building industry as well as for special applications, including increasing of seismic performance [82–84]. Steel fibers could have also some negative influence, i.e., on processing properties. One of the most important influences is decreasing the workability [85,86] and also limitation in some manufacturing methods as 3D printing [59]. However, the steel fibers are investigated in additive manufacturing technology; they are not used as a traditional bars but rather as microcable or short, dispersed fibers [60,61].

Nowadays, the main challenge for this kind of material is research on their durability. It requires standards definition and appropriate data from long-term research. This will define the possibilities of its applications in more advanced products [75,87]. Durability research shows that the geopolymer composites have better properties than traditional concrete. Most of all, there is lack of corrosion steel reinforcement in the geopolymer matrix [88,89]. Also, the long-term investigation confirms the positive effect of steel reinforcement on materials' properties [90].

The current research challenges for short steel fiber-reinforced geopolymer composites are also environmental aspects [1,8]. Geopolymers are a "green" alternative to the traditional concrete [6,91]. It may be achieved by using waste-based matrix, for example, fly ash. Recently, the steel fibers were mainly investigated in fly ash based matrix, also with addition other wastes such as slag (Figure 3). Additionally, the positive influence could be achieved by using recycled raw materials such as steel from used tires [55,92].

Moreover, it is estimated that the production of geopolymers generates 4–8 times less carbon dioxide than that produced by Portland cement [8,93]. The process needs twice less energy and causes low emissions of CO_2, SO_2, and NOx [1,8].

5 Conclusion

The geopolymer composites with the addition of steel fibers are up-to-date research topics. These kinds of composites had significantly better properties than with the use of other fibers such as synthetic polymer or natural. Because of that, they could be an important construction material for replacing traditional concrete in many applications. This material could be used also for special applications, namely in areas where the heat and fire-resistance are required, for example, in power stations (construction material) and in heat shields for the space shuttle.

However, a lot of research on different kinds of matrix and different steel fibers have been made but there is still a lot of challenges in this area. For example, the available literature does not describe research connected with the long-term durability of such composites and it limited the application of these materials in many areas. There are still a lot of possibilities to conduct the research, both experimental work and theoretical considerations creating models of behavior of geopolymer composites. This area offers a lot of occasions for future scientific exploration of the subject and also new opportunities for the practical applications of these kinds of geopolymers reinforced by steel fibers.

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