

Impact of Flax Fiber Reinforcement on Mechanical Properties of Solid and Foamed Geopolymer Concrete

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Abstract

The main objective of this study is to develop the advanced composites for civil engineering applications as material for the building industry, especially for an insulation purpose. The research processes include several steps. Firstly, the prototype elements, such as bricks and elevation elements were performed from eco-friendly composite -flax fiber reinforced geopolymer. The elements were designed to take into consideration for environment. Geopolymers are environmentally friendly, sustainable, and resource efficient, including energy demand. Next, the wall was built from these elements and exposed during the three months in a relevant environment. The main conclusion of the research is that the kind of fibers is important for the mechanical properties of the composite, including the fact that for those different fibers could be more beneficial for different raw materials, giving higher strength properties. The significant influence on the mechanical properties of the composites has the adhesion between fiber and material used as a matrix. The adhesion depends among others on the previous treatment of the fibers.

Keywords: geopolymer, mechanical properties, foamed material, flax fiber

1. Introduction

The background for the article is a pressure for the change of the traditional economy that is based on a linear approach to a so-called circular economy in recent years. The main principle of the circular economy is designing out waste and pollution. The rational management of natural resources and the usage of waste materials are getting more and more important. It is also supported by the growing ecological awareness of society, including the consciousness of sustainable development [1-2]. One of the most promising technologies for a circular economy is the geopolymerization with using waste streams. This technology is dedicated to the construction industry. It has a much lower carbon footprint than the technology of manufacturing traditional construction materials [1, 3]. The geopolymer synthesis also enables one to use waste, such as mining tiles or industrial by-products as a raw material for manufacturing new products in low energy and low emission processes [4-5].

One of the limitations for the wide usage of this technology in construction industry is the brittle fracture behavior of the received materials and their relatively low tensile as well as flexural strength [1, 6]. In order to improve tensile and flexural strength, it is possible to reinforce the geopolymer matrix by fibers [2-3]. From a mechanical point of view, reinforcement by fibers is an efficient method to improve material properties, for instance, fracture toughness. The fibers reduce the general effects of cracking, limit the widths of the occurring cracks, especially the propagation of micro-cracks, suppress all brittle

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behavior, and enhance ductility [1, 3]. The fibers additions also increase the flexural strength of composites. The fibers improve energy absorption and resistance to deformation [3, 7-9]. In particular, the introduction of short fibers due to their easy fiber dispersion and fiber shape factor; it is an effective way to strengthen geopolymer materials [3].

Currently, the reinforcements used in geopolymer composites are usually based on inorganic fibers, such as carbon or glass fibers [3, 10] or synthetic fibers [11]. However, the new research direction usage of eco-friendly materials is clearly visible. From the environmental point of view, the addition of natural fibers is particularly beneficial [1, 12]. This solution is an environmentally friendly alternative to inorganic fibers [1, 13].

Nevertheless, natural fibers usually have lower mechanical properties. It does not always allow their desired applications. Natural fibers have lower dimensional repeatability than artificial fibers, but these fibers have also many advantages [14-15]. The most important features are: reduction of the environmental impact (closing important life cycles, including CO₂), low cost of production, low density; the fibers are usually renewable in a short time, non-toxic, and easy to process [1, 16]. The research shows natural fibers could replace the conventional ones in many applications; and gives added value, especially reduction of greenhouse gas emissions and negative environmental impacts [1-2].

Contemporary, the flax is one of the most popular fibers used as reinforcement to geopolymer matrix [17]. The research was made on the matrix based on dehydroxylated kaolinite-type clay (New Zealand halloysite - Imerys Premium grade) [18], low calcium fly ash (from the Eraring power station in NSW) [19-20], fly ash with nano-clay particles [21-22]. The flax fibers were added in an amount: 4 - 10 wt%. The research results pointed out that mechanical properties are improved by fiber addition, especially flexural strength [17, 23]. The other research shows the possibility of using the geopolymers reinforced by short flax fibers in additive manufacturing technology [24-26].

There were several attempts to investigate foamed geopolymers reinforced by fibers. Most of the research was dedicated to reinforcement by artificial fibers such as carbon [27-28] or glass [29-30], including waste products [29-30]. Some of the investigations have been done on the composites with natural fibers such as hemp [31-32], abaca [33], cellulose [34-35] and jute [36]. The mineral fibers; for example, basalt have been also tested [28, 37].

The hemp (*Cannabis sativa*) fiber is one of the most widely applied cellulosic fibers as reinforcement in different kinds of composites [31]. The two amounts of short hemp fibers were applied 1.13 and 4.53% [32]. The results show good bonding between matrix and reinforcement, good stability to the thermal variation and improvement of mechanical properties [32].

The research conducted with abaca fibers shows its improving properties [33], including increasing compressive strength and flexural ranged from 19.6 MPa to 36.8 MPa and 2.4 MPa to 6.3 MPa, respectively [33]. The addition of jute fibers also positively influenced on mechanical properties, flame, and water resistance [37].

The investigation with cellulose shows the positive influence of this addition on pH and the possibility of applying this material for eco-friendly pots [34-35]. The flax fibers in foamed geopolymers were only investigated as an addition to long fibers [36]. The results show the positive effect of the addition to flax fibers on impact bending and flexural strength [38]. Additionally, the flax fibers were compared with basalt fibers (both were added in amount - 2.16 wt%). The results show a different pattern of failure mechanisms dependent on applied reinforcement [38].

The main purpose of the provided research is to develop the advanced composites for civil engineering applications, as material for the building industry. This paper shows the possibilities of using waste streams coming from energy industry (fly ashes and agriculture waste) and short flax fibers (residues for linen production), as raw materials to produce high-added value lightweight and low thermal conductivity geopolymer composites, including foamed products. These kinds of materials could be used as the advanced composites for civil engineering applications, as a construction material as well as insulation one and also for rehabilitating deteriorated concrete [39]. The previous study does not include semi-industrial tests for the foamed geopolymers reinforced flax fibers [40-41].

2. Materials and Methods

2.1. Materials

Two kinds of materials have been prepared: solid and foamed. The solid geopolymers based on the fly ash from the CHP plant in the city called Skawina (Lesser Poland region, Poland) and sand in ratio 1:1. This fly ash has the physical and chemical properties that support the geopolymerization process [42-44]. The second geopolymers according to the metakaolin and sand in ratio 1:1. Both kinds of samples were reinforced with 1% by mass of flax fibers. In order to reinforce, the following flax fibers were applied as compositions to solid materials:

- (1) Raw flax fiber - shortened (raw straw).
- (2) Long flax fiber after dew retting.
- (3) Cottonized flax fiber.

The foamed materials the following flax fibers were applied to:

- (1) Cottonized flax fiber - internal layer.
- (2) Shortened flex fiber after water retting - external and internal layer.
- (3) Short flax fiber - external layer.

2.2. Samples preparation

Samples were prepared using sodium promoter, fly ash or metakaolin, sand, and various flax fibers (each 1%, by mass of the composite). The process of activation has been made by a 10M sodium hydroxide solution combined with the sodium silicate solution (liquid glass at a ratio of 1:2.5). The geopolymers were produced using technical sodium hydroxide flakes and an aqueous sodium silicate solution of R-145 (module 2.5), with a molar density of about 1.45 g/cm³. The tap water was used instead of the distilled one. In the case of the foamed plated, the hydrogen peroxide has been used - 3.5% for metakaolin and 2% for fly ash based geopolymers. The alkaline solution was prepared by pouring the aqueous solution of sodium silicate over the solid sodium hydroxide. The solution was mixed and allowed to equilibrate until a constant concentration and temperature were achieved. It took nearly 2 hours. The fly ash or metakaolin, sand, alkaline solution, and fibers were mixed for about 15 minutes by using a low-speed mixing machine (to receive the homogeneous paste). On this stage for the foamed materials, a proper amount of hydrogen peroxide was introduced and continuously mixed for approximately 1 min. After the mixing process was complete, the material was poured into a mold and exposed to a temperature of 75 °C for 24 hours. After the heating process, the elements were dismantled and stored under laboratory conditions for a period of 28 days to obtain the full strength.

The following kind of samples were prepared (Table 1. and Table 2.):

(1) Bricks-solid material

- Metakaolin with a cottonized flax fibre.
- Metakaolin with a long flax fibre after dew retting.
- Metakaolin with a raw flax fibre - shortened (raw straw).
- Fly ash (FA) with a cottonized flax fibre.
- FA with a raw flax fibre-shortened (raw straw).

The detailed information about composition of prepared samples - solid bricks is included in Table 1.

Table 1 Composition of the solid samples - bricks

No.	Sample
1	Metakaolin with a cottonized flax fiber
2	Metakaolin with a long flax fiber after dew retting
3	Metakaolin with a raw flax fiber - shortened (raw straw)
4	Fly ash (FA) with a cottonized flax fiber
5	FA with a raw flax fiber - shortened (raw straw)

(2) Elevation plates-the internal layer (solid material, ca. 1 cm) and external layer (foamed material, ca. 4 cm)

A sketch of the elevation plate are presented in Fig. 1:

- External layer: metakaolin with the shortened flex fibre after water retting, internal layer: metakaolin with the shortened flex fibre after water retting (metakaolin: sand ratio - 0.85:0.15, hydrogen peroxide - 3.5%).
- External layer: FA with the short flax fibre, internal layer: FA with the cottonized flax fibre (FA: sand ratio - 0.75:0.25, hydrogen peroxide - 2.0%).
- External layer: FA with the shortened flex fibre after water retting, internal layer: FA with a shortened flex fibre after water retting (FA: sand ratio - 0.85:0.15, hydrogen peroxide - 2.0%).

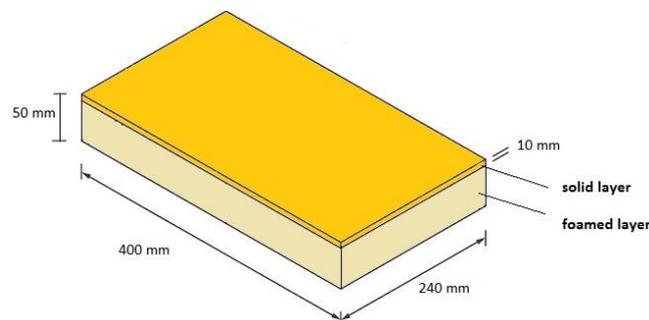


Fig. 1 Sketch of the elevation plate

The detailed information about composition of prepared samples-elevation plates is included in Table 2.

Table 2 Composition of the elevation plates

No.	Sample - external layer	Sample - internal (foamed) layer	H ₂ O ₂
1	Metakaolin with a shortened flex fiber after water retting	Metakaolin with a shortened flex fiber after water retting (metakaolin: sand ratio - 0.85:0.15)	3.5%
2	FA with a short flax fiber	FA with a cottonized flax fiber (FA: sand ratio - 0.75:0.25)	2.0%
3	FA with a shortened flex fiber after water retting	FA with a shortened flex fiber after water retting (FA: sand ratio - 0.85:0.15)	2.0%



Fig. 2 The wall made from bricks and elevation plates – first layer



Fig. 3 The wall made from bricks and elevation plates build on the university campus

The both prototype solutions are presented in Fig. 2 - bricks (small elements) and elevation plates (large elements). In Fig. 2, there were two solid bricks-lower based on metakaolin (white color), upper-based on fly ash (gray color). The brick size was:

25 cm × 12 cm × 5 cm. The plate's size was: 40 cm × 24 cm × 5 cm (Fig. 1). The gray elevation plates based on the fly ash reinforced by flax fibers and white elevation plates based on metakaolin reinforced by flax fibers are also shown in Fig. 2 (right site).

Eventually, the two products have been used for creating the prototype wall (Fig. 3) for testing in a relevant environment. The wall was placed on the campus of the Cracow University on Technology (Jana Pawła II Street, Cracow) and left on the open-air for 3 months. Next, it was demolished and the chosen parts were investigated according to mechanical properties.

2.3. Methods

Compressive strength tests were carried out according to the methodology described in the standard EN 12390-3 ('Testing hardened concrete. Compressive strength of test specimens'), because of the lack of separate standards for geopolymer materials. The tests involved cubic samples: 50 × 50 × 50 mm. The samples have been cut from large plates previously prepared (wall elements). Tests were performed on a concrete press - MATEST 3000kN with speed of 0.5 [MPa/s].

Bending tests were carried out according to the methodology described in the standard EN 12390-5 ('Testing hardened concrete. Flexural strength of test specimens'), because of the lack of separate standards for geopolymer materials. The tests involved prismatic samples: 50 × 50 × 200 mm (space between supporting points 150 mm). The samples have been cut from large plates previously prepared (wall elements). Tests were performed on a universal testing machine-MATEST 3000kN with speed of 0.05 MPa/s. The calculations were based on the following equation:

$$f_{cf} = \frac{Fl}{d_1 d_2^3} \quad (1)$$

Where

f_{cf} - compressive strength, MPa

F - maximal load, N

L - space between supporting points, mm (for conducted tests: 140 mm)

d_1, d_2 - sample dimensions, mm

3. Experimental Results and Discussion

3.1. Compressive strength

The results of the compressive strength tests are shown in Table 3 and Table 4.

Table 3 Results of compressive strength tests: bricks-solid material

No.	Sample	MPa
1	Metakaolin with a cottonized flax fiber	66.4
2	Metakaolin with a long flax fiber after dew retting	67.6
3	Metakaolin with a raw flax fiber - shortened (raw straw)	42.9
4	FA with a cottonized flax fiber	58.0
5	FA with a raw flax fiber - shortened (raw straw)	90.8

The tests were provided on minimum of 6 samples. The compressive strength test results achieved for bricks (solid material) were between 42.9 to 90.8 MPa. The received values for all types of materials are better than for conventional concrete. The best results were achieved for a fly ash based geopolymer with the raw flax fiber - 90.8 MPa. The results were drastically different than for the geopolymer concrete based on the metakaolin with the raw flax fiber-shortened (raw straw) -

1% by mass. In the case of the cottonized flax fiber, better results were received for the metakaolin based matrix than for fly ash based one. The reverse results were achieved for composites reinforced by raw straw fibers. The better results were for fly ash based geopolymer than metakaolin based material.

The investigation was also provided on elevation plates that consist of the foamed material. The plates included elevation part with the solid material and foamed one - isolation layer (Fig. 4). The grey elements are elevation plates based on the fly ash reinforced by flax fibers in Fig. 4. There are visible fibers agglomeration (marked in red arrow). The agglomeration is probably the consequence of not effective mixing process during material manufacturing. It could have an influence on material properties. The white elevation plates based on the metakaolin reinforced by flax fibers are also shown in Fig. 4. The layers have been produced with similar materials but based on the metakaolin. The material was also reinforced by flax fibers. The plates did not need additional joint between the layers - geopolymer binder bounded them.



Fig. 4 The elevation plates with visible layers and agglomeration of fibers

The mechanical properties for foamed samples are presented in Table 4.

Table 4 Results of compressive strength tests: elevation plates - foamed material

No.	Sample - external layer	Sample - internal (foamed) layer	H ₂ O ₂	MPa
1	Metakaolin with a shortened flex fiber after water retting	Metakaolin with a shortened flex fiber after water retting (metakaolin: sand ratio - 0.85:0.15)	3.5%	6.8
2	FA with a short flax fiber	FA with a cottonized flax fiber (FA: sand ratio - 0.75:0.25)	2.0%	6.9
3	FA with a shortened flex fiber after water retting	FA with a shortened flex fiber after water retting (FA: sand ratio - 0.85:0.15)	2.0%	4.3

The mechanical properties of foamed materials are much lower than solid ones. The same mechanism is presented for all formed materials. The results of compressive strength tests for elevation plates are in range: 4.3 - 6.9 MPa. The lowest results of compressive strength are for the geopolymer concrete based on fly ash with the shortened flex fiber after water retting - 1% by mass. It is almost 38% lower than for other investigated materials based on the metakaolin and fly ash. The pours in foamed layers are open.

3.2. Flexural strength

The results of the flexural strength tests are shown in Table 5 and Table 6. The best results were achieved for geopolymer concrete based on the metakaolin with different fibers. This value is definitely better than for traditional cements.

As the same as in the case of compressive strength, the foamed materials have much lower properties than solid ones. The flexural strength test results for bricks were between 7.2 and 10.7. The highest value was received for the metakaolin with the cottonized flax fiber - 10.7 MPa. The results of flexural strength tests for elevation plates are in the range 0.05 - 0.86 MPa. However, the results are comparable or even better than other foamed materials accessible on the market, especially foamed organic polymers. The provided research did not show any deterioration process.

Table 5 Results of flexural strength tests: bricks - solid material

No.	Sample	MPa
1	Metakaolin with a cottonized flax fiber	10.7
2	Metakaolin with a long flax fiber after dew retting	10.6
3	Metakaolin with a raw flax fiber - shortened (raw straw)	7.2
4	FA with a cottonized flax fiber	7.6
5	FA with a raw flax fiber - shortened (raw straw)	9.4

Table 6 Results of flexural strength tests: elevation plates - foamed material

No.	Sample - external layer	Sample - internal (foamed) layer	H ₂ O ₂	MPa
1	Metakaolin with a shortened flex fiber after water retting	Metakaolin with a shortened flex fiber after water retting (metakaolin: sand ratio - 0.85:0.15)	3.5%	0.86
2	FA with a short flax fiber	FA with a cottonized flax fiber (FA: sand ratio - 0.75:0.25)	2.0%	0.05
3	FA with a shortened flex fiber after water retting	FA with a shortened flex fiber after water retting (FA: sand ratio - 0.85:0.15)	2.0%	0.65

3.3. The effect of flax fibers addition

The article presents the impact of flax fiber reinforcement on the mechanical properties of solid and foamed geopolymer concrete. The prototype elements such as bricks (made from the solid material) and elevation elements (plates including solid and foamed parts) were manufactured and investigated. The two kinds of raw materials have been tested (fly-ash and metakaolin). The research on the mechanical properties compressive and flexural strength were conducted.

The compressive strength results for the new materials (solid) were between 42.9 and 90.8 MPa. These values were achieved for the samples with the raw flax fibers - shortened (raw straw). The results depended on used raw materials. The other tendency was observed for the samples reinforced by the cottonized flax fibers. In this case, the material based on the metakaolin had a higher compressive strength - 66.4 MPa, compared with the samples where fly ash was applied as a raw material - 58.0 MPa. The same tendency was noticed in the results of the flexural strength test. For the samples reinforced by the raw flax fibers-shortened (raw straw), better results were achieved for the material based on fly ash - 9.4 MPa than for based on the metakaolin - 7.2 MPa. The behavior of the material reinforced by cottonized flax fibers for the flexural strength test was similar to the results of the compressive strength test. The composite based on the metakaolin had higher values for the flexural strength - 10.7 MPa than the material based on fly ash - 7.6 MPa.

It shows that the kind of fiber is important for the mechanical properties of the composite, including the fact that for the different raw materials different fibers could be more advantages. The significant influence in this case has the adhesion between the matrix and reinforcement. The adhesion is depended among others on the previous treatment of the fibers. The significant meaning could have also the reaction between fiber and material used as a matrix.

The elevation elements (plates including solid and foamed parts) reinforced by the shortened flex fiber after water retting were also compared. The plates based on the metakaolin have better mechanical properties than based on the fly ash. The values for the plates based on the metakaolin were 6.8 MPa for compressive strength and 0.86 MPa for flexural strength. For the composition based on the fly ash, the relevant values were 4.3 MPa and 0.65 MPa, respectively. The different amount of hydrogen peroxide applied in these compositions was not consider, but a larger amount of hydrogen peroxide was added to the material based on the metakaolin; therefore, this material should potentially have lower mechanical properties.

4. Conclusions

The research shows the possibility of manufacturing the products for construction industry based on the eco-friendly materials. The composites comprise the waste flax fiber and the reinforced geopolymer concrete. The geopolymers includes

the fly ash as well as the metakaolin. The new products were designed to take into consideration for environment, including the energy efficiency, reduction of carbon footprint, waste reduction, and development of a circular economy.

The new composites have comparable properties with the results achieved for traditional foamed and solid building materials. The main conclusion of the research is the kind of fibers is important for the mechanical properties of the composite, including the fact that for that different fibers could be more beneficial for different raw materials, giving higher strength properties. The significant influence on the mechanical properties of the composites has the adhesion between fiber and material used as a matrix. The adhesion depends among others on the previous treatment of the fibers.

The contemporary research gives promising results, but further research is required. The practice applications need further tests to optimize the mechanical properties of the composites as well as investigate the other properties such as water absorption and resistance for a different environments, including long-durability issues. The LCA analysis of the chosen products will be also desirable.

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Conflicts of Interest

The authors declare no conflict of interest.

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