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REVIEW ARTICLE

The overview of mechanical properties of short natural fiber reinforced geopolymer composites

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ABSTRACT

In the EU there is a pressing need for the change of the current economy into a so-called circular economy in recent years. The rational management of natural resources and the use of waste materials are becoming more and more important. It is also supported by the growing ecological awareness of society, including the consciousness of sustainable development. Nowadays, it is the construction industry that has the most significant impact on pollution. Therefore, numerous attempts are made to reduce energy consumption and the amount of waste generated by it. These are the main issues stimulating the research on new innovative materials such as geopolymer composites. They have a significantly lower carbon footprint than traditional construction materials. Moreover, the synthesis of geopolymers requires 2-3 times less energy than traditional Portland cement, not to mention the fact that 4-8 times less CO_2 is generated. In addition, the above process has another environmental benefit i.e. the possibility of using anthropogenic raw materials (minerals) such as slags and fly ashes for the production. One of the limitations for the wide use of such materials is their relatively low brittle fracture behaviour. Nowadays, one of the most important research areas is the improvement of their mechanical properties. To improve the mechanical properties it is possible to reinforce the matrix by fibres addition, especially natural fibres that are renewable resources. The main objective of the article is to analyse the mechanical properties of new composites and assessment the possibility to replace traditional building materials within eco-friendly alternatives.

Keywords: Composite, geopolymer, natural fibre, short fibre

1. INTRODUCTION

In the EU there is a pressing need for the change of the current economy into a so-called circular economy in recent years. The rational management of natural resources and the use of waste materials are becoming more and more important. It is also supported by the growing ecological awareness of society, including the consciousness of sustainable development. Nowadays the construction industry has the most significant impact on pollution. Therefore, numerous attempts are made to reduce energy consumption and the amount of waste generated by it. These are the main issues stimulating the research on new innovative materials [1, 2].

The current technology of Portland cement, developed in the 20th century, has many disadvantages. First of all, the durability of this material is questioned in many scientific studies. At the same time, its production has an adverse environmental impact, which includes both the emission of a very high amount of CO_2 and highly toxic nitrogen oxides as well as the overwhelming consumption of energy and natural resources [2, 3]. Significant energy consumption is associated with high temperature (between 1400 and 1500°C) necessary to carry out the clinker burning process. This process hardly belongs to the technologies that support the sustainable development economy [2, 4].

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The most promising alternative solutions are technologies based on alkali materials and geopolymers [5, 6]. Such technologies have a significantly lower carbon footprint than traditional construction materials. It is estimated that the production of one ton of cement is accompanied by a release of nearly a ton of CO_2 to the atmosphere. The synthesis of geopolymers requires 2-3 times less energy [1, 7], not to mention the fact that 4-8 times less CO_2 is generated. In addition, the above process has another environmental benefit i.e. the possibility of using anthropogenic raw materials (minerals) such as slags and fly ashes for the production. Modern energy, mining, and metallurgical industries produce huge amounts of post-processing waste whose deposition may cause serious ecological problems related to soil and water contamination. The geopolymer synthesis enables one to use such waste as a raw material for manufacturing new products in low energy and low emission processes [1, 3].

However, it should be noted that geopolymers are much more than environmentally friendly materials. They exhibit notable properties as construction materials. Apart from significant chemical and thermal resistance, they have excellent mechanical properties, in particular, compressive strength [8, 9]. Their main advantages are: high initial strength [10], [11], low shrinkage and dimensional stability during the production process [12, 13], good fire resistance up to 1000°C and lack of emission of toxic fumes during the burning process [14, 15], high resistance to a wide range of acids and salts [10, 16], including resistance to different environmental conditions [17], [18], good abrasion resistance [19], good adhesion to concrete, steel, glass, and ceramics [8], easiness of subjecting them to surface mapping, duplication of mould patterns [8, 12], no corrosion of steel reinforcement inside the geopolymer matrix [17], [18], availability of necessary raw materials and their cost-efficiency, including the possibility of producing geopolymer materials based on wastes such as fly ash from industrial combustion [20, 21], the possibility of immobilizing hazardous waste by enclosing it in geopolymer composites [22, 23].

One of the limitations for the wide use of such materials is their relatively low brittle fracture behaviour and their relatively low tensile and flexural strength [5, 24]. Contemporary, one of the most important research area is improving this mechanical properties by reinforce the matrix trough fibres addition [2, 3]. In mechanical point of view the reinforcement by fibres is an efficient method to improve such mechanical properties as fracture toughness. The presence of fibres reduces the general effects of cracking, limits the widths of the occurring cracks (for example reduction of the propagation of microcracks), suppresses all brittle behaviour and enhances ductility [3, 5]. It also increases the flexural strength of composites. The fibres can also improve those properties of geopolymers that are connected with their energy absorption and resistance to deformation [25, 26]. The most common additives for the composites are: fabric, long fibres (usually directional) and short fibres (usually unidirectional) [3].

Nowadays, the geopolymers reinforced by fibres are fast growing topic of research. On the Fig 1, there are presented the fibres that have been tested as a reinforced for geopolymer composites [2].

In the environmental point of view, the addition of natural fibres will be especially beneficial [2, 5]. The replacement of the synthetic fibres with their natural counterparts reduces significantly the environmental impact (closing important life cycles, including CO_2). The natural fibres have also other features such as [27-29]:

- low cost of production,
- low density,
- they are usually renewable in short time,
- non-toxic,
- easy to process.

The main objective of the article is to analyse the possibilities of using new composites in practical applications, especially taking into consideration the mechanical properties. The article presents the mechanical properties of new composites and assesses the possibility to replace traditional building materials within eco-friendly alternatives.

2. RESEARCH METHODOLOGY

The research was focused on natural fibres, such as: plants, animal and mineral one. The research was conducted with scientific articles databases such as ScienceDirect, Scopus and Google Scholar. The research was focused on geopolymers, inorganic polymers and alkali-activated materials, taking into consideration their mechanical properties. During research keywords such as: "natural fibres reinforced geopolymer" and "geopolymer composites with natural fibre" were used. Next the additional search phrases were applied. They were connected with particular kind of fibres, exemplary "flax fibres". Additional information for articles based on contemporary conducted research in the framework of project supported by the ERANet-LAC 2nd Joint Call (http://www.eranet-lac.eu) and funded by National Centre for Research and Development, Poland, the Romanian National Authority for Scientific Research and Innovation, CCCDI – UEFISCDI, project number ERANET- LACFIBER 17/2017, within PNCDI II and the Türkiye Bilimsel ve Teknolojik Araştırma Kurumu (TÜBİTAK), under grant: "Development of eco-friendly composite materials based on geopolymer matrix and reinforced with waste fibers".

2.1. Cellulose / Lignocellulose fibres

Among natural fibres, the most common are different types of plant fibres based on cellulose and lignocellulose. On a global scale, there are currently about 2,000 species of fibre plants, of which around 1,000 are currently used [3, 30].

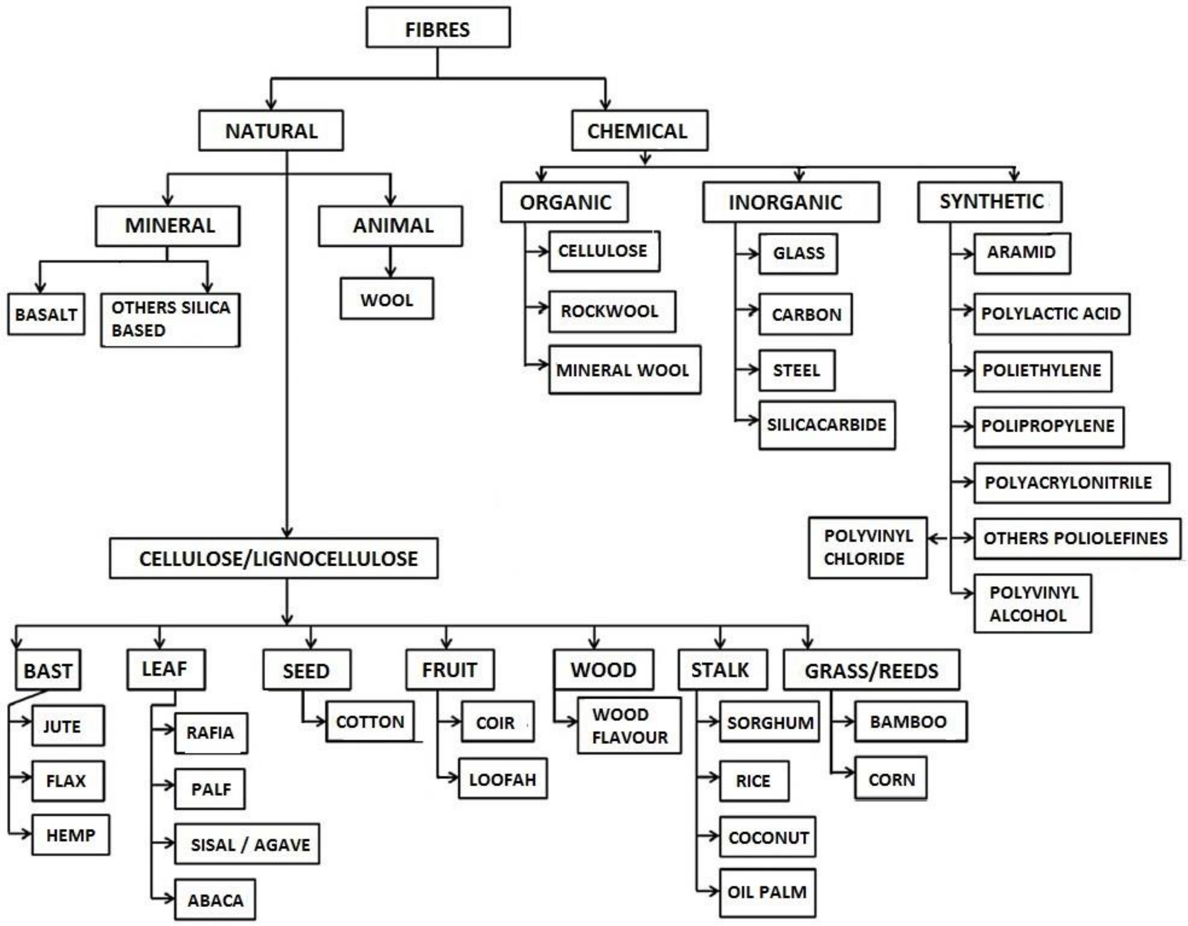

Fig 1. Classification of fibres used for reinforcment the geopolymer composities [2]

A lot of research work connected with geopolymers reinforced by cotton fibres has been conducted in years 2013-2014. The cotton was introduced to geopolymer matrix based on fly ashes (class F, collected from the Collie power station in Western Australia), as a short fibres as well as fabric layers [28, 31]. The results show that the content of cotton fibres up to 0.5 wt% increases the compressive and flexural strength, as well as fracture toughness of the materials. The content more than 0.5 wt% caused a decrease in the mechanical properties due to poor workability (mainly voids formation caused by poor dispersion of fibres within the matrix) and fibre agglomerations. [32, 33]. The other works with the short cotton fibres reinforced geopolymers based on fly ash from Skawina, Poland were conducted. They show that 1% of fibre addition improves mechanical properties in comparison with geopolymers without admixture [5]. The research with cotton fabric shows optimum value of fibre addition 2.1 wt% according to mechanical properties of the composite [33, 34]. However the mechanical properties can decrease as a result of water absorption [35]. The research results also show the dependence of properties on the fabric layers orientation [32]. The thermal stability of this kind of composites was also investigated. They have stable properties in elevated temperature thanks to geopolymer matrix [34, 36].

Other popular fibre for application in composites dedicated for construction purposes is abaca, called also as manila hemp. This fibre has very good mechanical properties [37]. The research was connected with the utilization of scrap abaca fibre as reinforcement (long fibre ca. 25 cm) for fly ash-based geopolymer matrix (fly ash from power plant situated in Luzon, Philippines). The research was focused on the abaca fibres to geopolymer matrix. The results show that proper pre-treatment of the fibre significantly increases the mechanical properties of the composites [37].

The research was made also on sisal fibres (Agave sisalana). The two types of geopolymers based on metakaolin [38] and fly ash [5, 39, 40] were manufactured. The metakaolin based matrix was reinforced by 3 wt% sisal fibres (25 mm length). The results show significant improvement of the mechanical properties in comparison with matrix without fibre addition [38]. The other research has been performed based on geopolymer based on fly ash from Satpura Thermal power station Sarni, District-Betul [40]. The short sisal fibres (length ca.1 cm) were added in the amount of 0.5, 1, 1.5, 2, 2.5 wt%. The best results for mechanical properties were obtained for 2 wt% [40]. The investigation for short sisal fibres was also conducted for geopolymers based on fly ash from Skawina, Poland [5, 39]. The results show that 1 wt% fibre addition improves mechanical properties [5, 39].

Correia et al. [38] also investigated pineapple leaf as a waste product of pineapple cultivation as a potential additive to geopolymer composites. The metakaolin based matrix was reinforced by 3 wt% leaf fibres (25 mm pineapple length) [38]. The results show that mechanical properties increases. Although the tests results for samples with pineapple leaf fibres are lower than the ones with sisal one [38]. Other research was made on geopolymer matrix based on fly ash class-C reinforced by short fibre (ca. 5.0 mm) - 0, 0.2, 0.4, 0.6, 0.8 and 1.2 wt% [41]. The results show that addition the pineapple fibres improves the compressive and flexural strength of the composites and do not change the nature of geopolymers as a fire or acid resistance material [41].

Contemporary, the flax is one of the most popular fibres used as an additive to geopolymer matrix. The research was made on different matrix based on i.a.: dehydroxylated kaolinite-type clay (New Zealand halloysite - Imerys Premium grade) [42], low calcium fly-ash (from the Eraring power station in NSW) [43], [44], fly-ash with nano-assitions [45, 46]. The flax fibres were added in amount: 4-10 wt%. The research results pointed improving mechanical properties by fibre addition, especially flexural strength. Also the research conducted in the framework of the ERANet-LAC project shows that flax is promising reinforcement for geopolimers based on clay as well as fly-ash [47, 48].

After flax and sisal, hemp (Cannabis sativa) is one of the most widely used cellulosic fibres as reinforcement in different kind of composites [38]. The research with this fibre was conducted with matrix based on foamed geopolymer. The two amounts of hemp fibres were applied 1.13 and 4.53% [49]. The results show good bonding between matrix and reinforcement, good stability to the thermal variation and improvement of mechanical properties [49]. Another research was made on geopolymer based on: fly ash from the PEGO Thermal Power Plant in Portugal, calcium hydroxide, waste glass, ordinary Portland cement (OPC), recycled aggregates and a sodium hydroxide solution [50]. The geopolymer mortar was reinforced by short hemp fibres (ca. 20–30 mm) up to 8 wt%. It caused decreasing of mechanical properties - about 50% in the compressive strength. Despite this fact, the authors stress the environmental benefits – reduce the carbon footprint, connected with using the natural fibres (the use of at least 8% hemp fibres leads to carbon negative emissions -19.7 kg CO_{2eq} m^{-3}) [50]. The research with hemp addition has also been made in the framework of the ERANet-LAC project, they show that hemp could be valuable addition to geopolymer matrix, but the properties depend on the amount and form of fibres [48].

The investigation for short coir fibres was conducted for geopolymers based on fly ash from Skawina, Poland with 1 wt% fibre addition. The result show that fibres admixture improves mechanical properties in comparison with geopolymers without fibre addition [5]. Similar research was made with coir addition between 0 to 1% and geopolymer mortar based on fly ash and silica fume [51, 52]. The research shows that optimum amount of coir is about 0.75 wt% according to mechanical properties. Additionally, a coir improves the crack resisting capacity on the mortar [52]. Other type of research was made with using short (3 – 5 cm) coconut trunk fibre and geopolymer matrix based on fly ash from Bosowa power plant in Jeneponto, South Sulawesi [53]. The results show also that mechanical properties increase up to some amount of fibres and then decrease [53]. Trindade et al. [53] also investigated the jute fibre as reinforcement for the geopolymer cement (metakaolin and sand). The test results present that the incorporation of jute fibres in geopolymers appears a viable solution to overcome its initial brittle behaviour [53].

The research for short raffia fibres was conducted for geopolymers based on fly ash from Skawina, Poland [5, 54]. The results show that the composites reinforced by raffia fibres has worse properties than synthetic fibre (PP). However they still have reasonable mechanical properties for some construction purposes [54].

Some investigations were also conducted with sweet sorghum. To the geopolymer matrix based on fly ash was implemented bagasse (waste form production) in 1, 2, 3 wt% as a fine fibre (below 10 mm) [55]. The results show that the compressive strength slightly decreases and the tensile and flexural strength increase with the content of sweet sorghum fibres up to 2% and then decrease to be lower than that of the geopolymer without fibres addition [55]. There is also change the behaviour during failure from the brittle failure (samples without fibres) to “ductile” (for samples with fibres) [55].

Not typical reinforcement is luffa (kind of tropical and subtropical vines in the cucumber family). The fibres were obtained from dried matured fruits. The composite includes about 10 vol% natural Luffa Cylindical fibres arranged as a layers [56]. The results show that the compressive and flexural strength of the final geopolymeric products respectively increase and the composites are durable (no significant deterioration in mechanical performance over a duration of 20 months) [56]. Other not typical addition used for geopolymer composite production was an Amazonian tropical bamboo - Guadua angustifolia. Geopolymer based on metakaolin was reinforced by bamboo fibres and strips [57]. The results confirm that the proper bamboo preparation allow gain the flexural tests results comparable with synthetic fibres such as polypropylene - PP [57].

Also some investigations connected with different fraction of wood waste [25, 58], including sawdust addition [59] to the geopolymers were conducted. The geopolymer matrix based on fly ash and metakaolin. The different kinds of wood aggregates were applied as an reinforcement [58], including: wood particles, wood fibres and wood flour. The research result shows that the shape and size of wood aggregates affect the properties of the geopolymer composites [58]. The wood flour show the best cohesion with matrix among investigated additions. The research with sawdust addition (0–20% by mass with an interval of 5% were investigated) was made on the fly ash based matrix [59]. The results show that 5% of sawdust addition is optimal taking into consideration all mechanical properties. However, the flexural strength increases with the content of sawdust - the highest flexural strength was for 20% of sawdust regardless of curing ages [59].

The other possibilities of reinforcement geopolymers composites are offered by some plant waste such as corn husk [60], rice husk [61] and coffee grounds [62], [63]. The research in this area is valuable not only because of designing a new composite, but also because of new possibilities of utilization some industrial waste. Moreover there is a lot of natural fibres such as: henequen, ramie, sunn, kenaf that have not been investigated yet as a reinforcement for geopolymers composites [2], [3]. It creates new research opportunities and new possibilities for application this class of composites in civil engineering [2].

2.2. Animal fibres

Other possibilities are offered by animal fibres such as wool and related mammalian fibres [4, 64, 65]. Among the animal fibres the widest test were conducted on wool [65, 66]. The research was carried out using high-quality wool (merino wool), as well as low-quality wool, for example carpet wool and wool from waste [65]. The matrix was a geopolymer made of kaolinite type halloysite clay originating from New Zealand, while the reinforcement was made of 2 types of high quality merino wool (18-25 μm) and low quality wool - mixed carpet wool (30-35 μm). The fibres were added in an amount of 5% by weight of the composite. In addition, the fibres were subjected to various types of pre-treatment - they were applied in three forms to composites [64]: in the form received without any action, after purification and pre-prepared by soaking in a solution of formaldehyde. After 14 days, flexural strength tests were carried out on the prepared samples. This strength for the matrix material was 5.8 MPa. For composites with the addition of fibres, the best properties were obtained for pre-prepared low-quality wool and treated high-quality wool - 8.7 MPa and 9.1 MPa, respectively. Studies have also shown a change in the nature of the fracture from brittle to ductile [65].

The research conducted on waste wool was carried out on a metakaolin matrix with the addition of 23% and 31% by volume of fibre (which gave 10% and 15% by weight, respectively) [66]. Obtained mechanical properties for the matrix, after 4 days, are respectively 1.4 MPa bending strength and 5.5 MPa compressive strength, 4.7 MPa bending strength and 8.6 MPa compressive strength were obtained for the composite with 10% wool, and 4.0 MPa and 8.3 MPa, respectively, for composite with 15% fibre [66]. The results also show that the obtained insulating properties at the level of k = 0.20 W mK^{-1} and the mechanical strength of the new composites are comparable with other commercial products, such as calcium silicate boards, and can be used in similar applications [66].

Other types of animal-derived fibres have not yet been studied as reinforcements of geopolymers. Therefore, it is possible to conduct research with accessories, such as animal hair (e.g. pigs), silk or bird feathers.

2.3. Mineral fibres

The mineral fibres such as basalt and diatomite when there are applied as reinforcement they usually give better results than plant fibres, but using this kind of fibres is not so beneficial for environment as plant ones [3], [4]. Among the mineral additives, the widest research was conducted on basalt fibres. They were implemented to geopolymer matrix as fabrics [66], [67], long fibres [68], as well as short fibres and microfibers. The short basalt fibres were investigated in different types of matrix, including: metakaolin, slag and fly ash.

For example the research was conducted on matrix based on fly ash from Raichur Thermal Power Station, Karnataka, India, with the addition of slag, basalt fibre, plasticizer (MYK Remicrete PC 5) and two types of aggregates (fine and coarse) [69]. The composition with fibres had higher values than basic matrix. The best result for compressive strength was achieved for 2% fibre content - 58.4 MPa after 28 days [69]. This composition gives also the best values for tensile strength - 3.6 MPa [69]. Tests on the mechanical properties of composites with the addition of basalt fibres were also carried out on the basis of a matrix consisting of fly ash, slag after processing of steel and sand [70]. The basalt fibres (diameter: 7-30 μm and lengths: 12 mm), were added in following amount: 0.0, 0.1, 0.2, 0.3, 0.4 and 0.5% by volume [70]. The compressive strength test shows that all composites achieved higher values than the plain matrix material. The highest values were obtained for 0.4% volume addition of basalt fibres, it was 40.3 MPa, compared to values around 35 MPa for basic matrix [70]. For bending strength, the highest values were obtained for 0.3% by volume of fibres, it was 7.3 MPa [70]. The research with basalt fibres was also carried out on the basis of a geopolymer matrix composed of metakaolin, slag from the Bolu Cement Company in Turkey, sand and collemanite waste (borate mineral) from the Eti Mining Company mine in Turkey [71]. The tests were carried out with 0.4, 0.8 and 1.2% fibres (diameter - 20 μm and lengths - 12 mm) addition by volume. The best results for mechanical properties were obtained for a sample containing 1.2% of basalt fibres: 64.8 MPa after 28 days, compared to the sample without reinforcement - 61.6 MPa for compressive strength and - 12.6 MPa, compared to the basic matrix - 8.8 MPa for flexural strength [71].

Another tests were carried out on a metakaolin matrix reinforced with basalt microfibers up to 10 μm, 5, 10 and 15% of microfibers by weight were used [72]. The composite with 15% microfibers showed the highest strength properties. Its compressive strength was 38.1 MPa, compared to 28.4 MPa for the plain matrix [72]. Similar works with the addition of short basalt fibres were carried out on a geopolymer matrix based on fly ash from the Gladstone power plant in

Queensland, Australia [19]. The fibres (diameter - 13 µm and length - 12.7 mm) were added in amounts of 0, 0.5, 1 and 1.5% by weight. [73]. The results of the compressive strength at ambient temperature showed an increasing for samples with short fibres compared to the material without additives. Studies [72, 73] confirmed also the resistance of basalt fibre geopolymers to elevated temperatures. It is also worth paying attention to the research on the addition of basalt fibres to fly ash from the power plant in Thailand. In these studies, a very high weight proportion of basalt fibres was used: 0, 10, 15, 20, 25 and 30% [74]. The results show that all composites with the addition of basalt fibres obtained higher compressive strength than the basic matrix. The optimal addition was 10 - 15% of fibres [74].

Another tested mineral additives in geopolymers were composition: silica, alumina and zirconium (diameter about 3.5 µm and length 20 - 35 mm) [75]. These fibres were introduced into a geopolymer matrix based on metakaolin with the addition of particles after grinding bricks (so-called refractory bricks) in amounts: 0.5 and 1% by weight. [75]. The highest compressive strength values were obtained for a matrix with the addition of 15% ground refractory brick about 56 MPa and for the same matrix reinforced with 1% fibres. For bending strength, the values obtained for reinforced composite are significantly better. In this case, the crack modulus was compared, which was 8.4 MPa for the matrix material, and 14.4 MPa for the composite with 1% fibres [75]. Other mineral additives used in geopolymer composites include diatomaceous earth [76], however, this additive was not introduced in the form of fibres, but grains with a diameter of 1.2 µm and wollastonite, also introduced in the form of micro-additives [77, 78].

Test results for mineral fibres give interesting results (mechanical properties are usually better than for reinforcements in the form of plant fibres), but the use of this type of fibre does not have so many advantages for the environment. First of all, these fibres are not quickly renewable, have a higher density than vegetable fibres and do not give benefits in the form of CO2 reduction during the product's life cycle, including the production process.

3. DISCUSSION

The undisputed advantages of geopolymer materials are good compressive strength and good thermal properties (high fire and heat resistance), as well as resistance to corrosive environments. The weaknesses of this type of composites is brittle cracking, which limits their use in many areas [55], [79]. That is main reason why the research into introducing fibres as a reinforcement into a geopolymer matrix is conducted.

The research shows the addition of fibres is an efficient method for improving such mechanical properties as fracture toughness [3]. The presence of fibres reduces the general effect of cracking, limits the widths of the occurring cracks (exemplary reduction of the propagation of microcracks), suppresses all brittle behaviour and enhances ductility. The fibers can also improve those properties of geopolymers that are connected with their energy absorption and resistance to deformation. Fibres increase the amount of energy absorbed by geopolymer before damage occurs [3, 55]. In particular, the introduction of short fibres, due to their easy fibre dispersion and fibre shape factor, is an effective way to strengthen geopolymer materials [3].

Research carried out so far for fiber-reinforced geopolymer composites show that their addition is an effective method of improving mechanical properties. Most of the research has shown both an improvement in compressive strength and bending of composites (Table 1).

Table 1. Mechanical properties for the natural fibres reinforcement geopolymers

No.	Fibres	Matrix	Mechanical properties	Mx. vs com.	Time	Reference, comments
1	Cotton 0.5 wt. (10 mm x 0,2 mm)	Fly ash	Bending (B): 10.4 MPa matrix (mx) 11.7 MPa composite (com)	+12.5%	28 days	[36]
2	Cotton 0.5 wt. (10 mm x 0.2 mm)	Fly ash	Compressive strength (CS): 19.1 MPa mx 48.0 MPa com	+151.3%	28 days	[32]
3	Cotton 1.0 wt. (30 mm x 1 mm)	Fly ash	B: 5.5 MPa mx 5.8 MPa com CS: 24.8 MPa mx 28.4 MPa com	+5.4% +14.7%	28 days	[5]
4	Abaca 8% wt. (0.1-0.2 mm)	Metakaolin	B: 2.5 MPa mx 27 MPa CS: 7.0 MPa mx 50 MPa com	+980% +614.3%	28 days	[37]; very high value for com – needs to be verified.

5	Sisal 3% wt. (ca. 25 mm)	Metakaolin	CS: 6.9 MPa mx 6.0 MPa com B: 1.4 MPa mx 2.7 MPa com	CS: Decreasing (D), B: +96.4%	Lack of informati on	[38]
6	Sisal 3% wt. (ca. 10 mm)	Fly ash	B: 3.3 MPa mx 4.5 MPa com CS: 27.2 MPa mx 41 MPa com	+36.4% +50.5%	14 days	[40]; low value for B.
7	Sisal 1% wt. (3 mm x 0,5 mm)	Fly ash	B: 5.5 MPa mx 5.9 MPa com CS: 24.8 MPa mx 25.2 MPa com	+6.3% +1.5%	28 days	[5]
8	Pineapple leaf 3% wt. (ca.25 mm)	Metakaolin	CS: 6.9 MPa mx 3.3 MPa com B: 1.4 MPa mx 2.0 MPa com	CS: D B: +42.8%	Lack of informati on	[38]
9	Pineapple leaf 1.2% wt. (ca.50 mm)	Fly ash	B: 6,0 MPa mx 7.1 MPa com CS: 23.3 MPa mx 58.2 MPa com	+17.8% +149.6%	28 days	[41]
10	Flax 10% wt. (0.01-0.08 mm)	Clay	B: 5.8 MPa mx 70.2 MPa com	+1110,3%	28 days	[42]; results required verification
11	Hemp 8% wt. (20-30 mm)	Fly ash, waste glass, OPC, recycled aggregates	B: 3.4 MPa mx 2.1 MPa com CS: 45 MPa mx 12 MPa com	D	28 days	[50]; low value for B.
12	Coir 1% wt. (3 mm x 0.5 mm)	Fly ash,	B: 5.5 MPa mx 5.2 MPa com CS: 24.8 MPa mx 31.4 MPa com	B: D, CS: +26,5%	28 days	[5]
13	Coir 0.75% wt. (25 mm)	Fly ash, silica	CS: 45.5 MPa mx 51.2 MPa com	+12,5%	28 days	[51]
14	Coir 0.5% wt. (30-50 mm)	Fly ash	B: 74.4 MPa mx 76.4 MPa com CS: 80.7 MPa mx 89.4 MPa com	+2,7% +10,8%	28 days	[52]; very high value for B.
15	Raffia 1% wt. (3 mm x 1 mm)	Fly ash	B: 5.5 MPa mx 3.0 MPa com CS: 24.8 MPa mx 13.7 MPa com	D	28 days	[5]
16	Sorgum 2.0% wt. (< 10 mm)	Fly ash	B: 3,4 MPa mx 5.4 MPa com CS: 27.7 MPa mx 22.9 MPa com	B: +58.8% CS:	7 days	[55]
17	Bamboo 5% wt. (12.5-40 mm & <1,25 mm)	76% metakaolin, 24% silica	B: 4.5 MPa mx 27.6 MPa com CS: 55.7 MPa mx 33.1 MPa com	B: +513.3% CS: D	7 days	[58]; 4 points B
18	Wood 10% wt. (0.7 mm)	Fly ash and metakaolin	CS: 76.5 MPa mx 30 MPa com	D	28 days	[59]

19	Wool 5% wt. (18-35 μm)	Clay	CS: 5.8 MPa mx 9.1 MPa com	+56.9%	14 days	[65]; 4 points B
20	Wool - waste 10% wt. (ca. 50 μm)	Metakaolin	CS: 5.5 MPa mx 8.6 MPa com B: 1.4 MPa mx 4.7 MPa com	+56.4% +235.7%	4 days	[66]; very low value of compressive strength
21	Basalt fibre 2.0% wt.	Popiół lotny	CS: 43.3 MPa mx 58.4 MPa com	+34.7%	28 days	[69]
22	Basalt fibre 1.0% wt.	Metakaolin	CS: 39.5 MPa mx 36.9 MPa com	D	28 days	[71]
23	Basalt fibre 15% wt. (10μm)	Metakaolin	CS: 28.4 MPa mx 38.10 MPa com	+74.61%	28 days	[72]
24	Silica, alumina & zirconium, 1% wt. (3.5 μm x 20-35 mm)	Metakaolin and clay bricks	CS: 56 MPa mx 56 MPa com	Without change	15 days	[75]; tested at 60oC.

Contemporary, the reinforcements used in geopolymer composites are often based on inorganic fibers, such as carbon or glass fibres [3, 80] or synthetic fibres [81]. However, the research direction is clearly visible, undertaking work on reinforcements from natural fibres [5, 82]. This solution is to be an environmentally friendly alternative. However, it is worth noting that the reinforcements with natural fibre give lower mechanical properties, which does not always allow their desirable applications. In addition, only selected from these fibres are tested in terms of providing materials with other properties, i.e. resistance to temperature or corrosive environments. A separate problem is the lower dimensional repeatability of natural fibres.

4. CONCLUSIONS

The main motivation of research work is growing environmental awareness and importance of development of sustainable construction materials for decreasing environmental impact of building industry. Nowadays, the geopolymer composites are most promise alternative for traditional building materials based on concrete. One of the limitations for these materials is brittle behaviour. To improve their mechanical properties it is possible to reinforce the matrix by fibres. In the environmental point of view, the addition of natural fibres is especially beneficial. The article presents exemplary solution in this area based on up-to-date literature.

Various types of fibers, both natural and chemical, were tested as geopolymer reinforcements. The results show that the geopolymer composites based on natural fibres could be a low-cost and an effective construction material with comparable properties as composites reinforced by synthetic fibres. In many cases, however, these studies were only a preliminary analysis of the subject, limited to basic microstructure and mechanical tests on a small number of samples.

The natural fibres could replace the conventional additives. They could have similar mechanical properties and positive environmental effects - reduce greenhouse gas emissions and negative environmental impacts. The contemporary research gives promising results, but the further research are required. The practice applications require further tests to optimize the mechanical properties of the composites as well as investigate the other properties such as absorptivity and resistance for different environment, including long-durability issues and the LCA analysis for the chosen products.

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