Mechanical properties of composites based on geopolymers reinforced with sizal

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Abstract. The aim of the study was to evaluate the usefulness of composites based on alkali activated materials reinforced with natural fiber - sisal, as an ecological material for selected applications in the building industry. Microscopic analysis of the created structure and examination of compression and bending strength were carried out. Strength tests show a slight increase in compression and bending strength compared to a geopolymer matrix without fibers.

1. Introduction

Natural fibers used as a filler have many advantages over other fibers, including plastic ones. They are not only an environmentally friendly alternative, but also have lower density, lower cost and no toxicity [1, 2]. Additionally, these fibers are easy to use in processing and in many cases it is possible to use them in the technology park already owned by the companies [1]. At the same time, these fibers usually provide sufficient mechanical properties for most desirable applications in the field of construction [2,3]. In particular, due to the above-mentioned advantages, they are more and more widely used as a component of composites, inter alia, based on cements and geopolymeric materials [4,5]. Currently, research is conducted on natural materials such as cotton [1,6], flax [7,8], pineapple leaf [9], sorghum [10], coconut [2], raffia [2], wool [11], waste from the wood industry [12,13] and other organic fibers [2,14]. One of the possible additives to geopolymeric matrices are sisal fibers [2,9]. Sisal fibers come from the plant Agave Sisalana, which was originally found in Mexico [15,16]. Currently, the main producers of sisal fibers are Brazil, Mexico, Kenya, Tanzania, Colombia, Madagascar, China, Cuba, Haiti, Nicaragua, Angola, Indonesia, Mozambique, South Africa, and Thailand [15]. An unquestionable advantage of this plant is the possibility of growing all year round in hot climates and dry regions, which are often unsuitable for other crops. It is a low-maintenance plant and can be grown on most types of soils, it is also relatively resistant to diseases. The plants can be harvested from 2 years after planting, and their life span can be up to 12 years, producing 180 to 240 leaves depending on the conditions of cultivation. The yield per hectare is about 1 tone, although yields in East Africa can reach as much as 4 tons per hectare [16,17]. The fibers are made from plant leaves, contain about 90% moisture, are stiff and the fleshy flesh is very hard [15]. The fibers are deposited lengthwise in the leaves, especially near their surface. The first step in obtaining them is to separate them from the rest of the leaves as soon as they have been cut. This aims to avoid the risk of damage during the cleaning process. The fibers are removed either by mechanical peeling or by hand by separating the fibers from the rest of the leaf.
Sisal fibers have traditionally been used for cordage products. Nowadays, they are mainly used in the automotive industry, as a filler for plastic composites and in the paper industry. These fibers are also used in the production of: massage articles, orthopedic equipment, fabrics, as well as furniture or wallpapers [17,18].

It is also worth noting that sisal is a renewable source par excellence. During its entire life cycle, sisal absorbs more carbon dioxide than it produces. During processing, the plant generates mainly organic waste and leaf residues, which can be used to generate bioenergy, produce animal feed or fertilizer [19]. It is 100% biodegradable. In addition, sisal, as a plant with an extensive root system, is used to reduce soil erosion, as well as a barrier to protect farmland and forests from animals.

2. Material and methods

2.1. Material

Fly ash from the Skawina CHP plant was used as the material to create the geopolymer matrix. The oxide composition of the ash used is shown in Table 1.

| Property  | Value |
|-----------|-------|
| LOI       | 2.44  |
| SiO₂      | 55.89 |
| Al₂O₃     | 23.49 |
| Fe₂O₃     | 5.92  |
| CaO       | 2.72  |
| MgO       | 2.61  |
| Na₂O      | 0.59  |
| K₂O       | 3.55  |
| SO₃       | 0.16  |
| TiO₂      | 1.09  |
| P₂O₅      | 0.82  |
| BaO       | 0.20  |

Sisal fibers were added to the composite as a filler. The basic chemical properties of these fibers are known from the literature [20]. The basic component of the fiber is cellulose and it constitutes about 45.3% by volume of the fibers, the other components are: hemicellulose about 20.4%, lignin about 15.1% and other components about 15.5%. The basic physical and mechanical properties are presented in Table 2.

| Property       | Value         |
|----------------|--------------|
| Density        | 1.5 g/m³     |
| Young's modulus| 9.0–38 GPa   |
| Tensile strength| 363–700 MPa  |
| Elongation     | 2.0–7.0%     |

The added fibers had a diameter of about 0.5 mm and were mechanically shredded into pieces of 3 mm in length. The fibers were added in the volume of about 1% by weight in relation to fly ash used as the base for the geopolymer matrix. The amount of added fiber was determined on the basis of previous research on artificial and natural fibers [4, 22].

Crushed sisal fibers in 3% by weight were added to fly ash. Sodium hydroxide (NaOH) solution with a molar concentration of 8M containing sodium water glass was introduced into the mixture prepared in this way. 50 x 50 x 200 mm samples were prepared for flexural strength tests. To produce geopolymers flakes of technical sodium hydroxide were used and an aqueous solution of sodium silicate (R-145) whose molar ratio was 2.5 and density was about 1.45 g/cm³. The tap water was used instead of the distilled one. The alkaline solution was prepared by means of pouring the aqueous solution of sodium silicate over the solid sodium hydroxide. The solution was thoroughly mixed for 15 minutes in a low-speed mixer and allowed to equilibrate until a constant concentration and temperature. Next, the obtained paste was poured into cubic molds 50 x 50 x 50 mm. The solidification was conducted on the vibratory table. Then the molds were heated for 24 hours at 75°, cooled to the ambient temperature, taken out of the molds and stored for 28 days.
2.2. Research methods
The morphology of the samples was analyzed on the material remaining after the strength tests. The JEOL JSM-820 scanning microscope was used for the tests. Samples were previously properly prepared. Small amounts of materials dried to the constant mass, put on the coal tape to carry the electric charge of the sample away, and covered with thin layer of gold with the JEOL JEE-4X vacuum evaporator. Observations were carried out at various magnifications (50 - 2000 x).
Compressive strength tests according EN 12390-3, using Matest 3000 kN, were conducted on cubic samples of 50 x 50 x 50 mm conditioned at room temperature for 28 or 90 days. Five repetitions were carried out for each type of sample.
The bending strength tests were conducted according to EN 12390-5 on Instron Type 4465 Universal Testing Machine on 50 x 50 x 200 mm cubic specimens stored at ambient temperature for 28 days.

3. Results and discussion
Microscopic investigations allowed to observe the microstructure of the fiber and the obtained composite. The fiber structure (Fig. 1) and the filler-matrix connections (Fig. 2-3) are presented in the images.

![Figure 1. SEM image of used sisal fibers.](image)

Figures 2 and 3 show the fibers in the geopolymer matrix. The fibers are evenly distributed in the whole volume of the composite, they are dispersed - distributed without a defined directional order. Such a way of fibers arrangement allows to obtain mechanical properties of the product similar in all planes.
Figure 2. SEM image obtained for a geopolymeric composite reinforced with 1% sisal fibers showing the distribution of fibers in the composite.

Figure 3. SEM image obtained for a composite on geopolymer matrix reinforced with 1% sisal fibers showing the cohesion of the fibers with the matrix.

SEM analysis allowed to observe the uniform distribution of fibers in the whole composite and good fiber - matrix cohesion (Fig. 2 – 3).

3.1. Results of strength tests
The results of compression and bending strength tests were carried out on previously prepared composite samples. Geopolymer without fiber addition was used as a material for comparison. The tables show average values for particular materials. The results of compressive strength tests for geopolymer with added fiber are slightly better compared to the material of geopolymer matrix itself (Table 3).
Table 3. Results of the compressive strength tests [2].

| Sample                      | Compressive strength [MPa] | Standard deviation |
|-----------------------------|----------------------------|--------------------|
| Geopolymer without fibers  | 24,78                      | 1,89               |
| Geopolimer with 1% sizal fibers | 25,16                | 3,43               |

The bending strength was also improved with the addition of fibers. The results of the bending strength tests for geopolymer with added fiber are slightly better than for the material of the geopolymer matrix itself (Table 4).

Table 4. Results of flexural strength tests [2].

| Sample                      | Flexural strength [MPa] | Standard deviation |
|-----------------------------|-------------------------|--------------------|
| Geopolymer without fibers  | 5,55                    | 0,72               |
| Geopolimer with 1% sizal fibers | 5,90               | 0,14               |

Strength properties tests indicate a slight increase in the strength properties of composites with 1% addition of sisal fiber.

Conclusions
The paper presents the results of preliminary research works concerning the influence of the addition of sisal fibers in 1% weight volume on the geopolymer properties. The presented results confirm the potential of new material for selected building applications. Microscopic observations indicate good quality of connections between geopolymer matrix and sisal fiber. Strength tests show a slight increase in compression and bending strength compared to the geopolymer matrix.

There is now a demand on the market for new environmentally friendly composite materials, in particular those based on renewable raw materials. These materials should provide an environmentally friendly alternative to traditional construction materials used in the widely perceived construction industry. Modern composites allow to reduce the emission of substances harmful to the environment and at the same time save natural resources. Geopolymeric composites with natural fiber fillers are part of the sustainable development policy, which is currently a guideline in the policy of many countries in Europe and worldwide.

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