Mechanical Properties of Raffia Fibres Reinforced Geopolymer Composites

Kinga Korniejenko, Michał Łach and Janusz Mikuła

Abstract Geopolymer composites are "green" alternative to the traditional cementitious materials. They have good compressive strength, durability and other properties such as highly resistant to flame and heat and corrosion resistance. However, these composites have relatively low tensile and flexural strength, which limits their use in many areas, especially in construction industry. This paper describes possibilities to improve this mechanical properties by fibre addition. The study is intended to analyse the influence of addition of various raffia fibres on the mechanical properties of the geopolymer based on fly ash. The empirical part of the research was based on the compressive strength tests, flexural strength tests and detailed microstructure examination. The samples were prepared using sodium promoter and raffia fibres (the 1% by mass of the composite). The research involved the samples reinforced by raffia and artificial fibre—PP (polyprophylene) for comparison. PP is the traditional additive for building materials such a cement. The results show the possibility to produce the composites of reasonable properties from the industrial wastes (fly ash) and renewable resources—raffia fibres, which makes them a new class of environmentally friendly materials.

Keywords Geopolymer composites · Raffia · Fly-ash based geopolymers

Introduction

Cements have been reinforced with natural fibers for many years, particularly in developing countries that have used local materials such as bamboo, sisal, jute and coir with some success [1]. There are also same investigation with using the raffia fibres [2, 3]. It is well established that the choice of fibers used to reinforce concrete

K. Korniejenko (✉) · M. Łach · J. Mikuła
Institute of Material Engineering, Faculty of Mechanical Engineering,
Cracow University of Technology, Cracow, Poland
e-mail: kinga.korniejenko@mech.pk.edu.pl

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can affect its mechanical properties. The type of fibers, its form, surface properties and matrix properties, all need to be considered [1].

Geopolymer composites reinforced with the chosen natural fibres have relatively short history. They are interesting and eco—friendly alternative to the traditional construction materials such as Portland cement [4]. Natural fibers have special advantages when compared to their synthetic counterparts, where the former represents an environmentally friendly alternative, with lower density, lower cost, non-toxicity, ease of processing, renewability and recyclability, ready availability high strength-to-mass ratio and good tensile strength [5]. These properties make them attractive alternatives to the synthetic fiber composites used in more industrialized countries [1]. In addition, the use of natural fibres in geopolymer composites has the potential to produce materials with higher specific strength and specific modulus, due to their lower density [5, 4]. So far as a reinforcement of geopolymers were used and researched a following fibers:

- Cotton fibre; The use of cotton fibers has several advantages which include low cost, renewability, and low weight when compared to synthetic fibres, good intrinsic mechanical properties [1]. Results show that the enhancement of mechanical properties was achieved at an optimum fibre content of 2.1 wt%. Results of thermal analysis show that fly-ash based geopolymer can prevent the degradation of cotton fabric at elevated temperatures [5]. Results show that the appropriate addition of cotton fibres can improve the mechanical properties of geopolymer composites. In particular, the flexural strength and the fracture toughness increase at an optimum fibre content of 0.5 wt%. However, as the fibre content increases, the density of geopolymer composites decreases due to an increase in porosity and tendency of fibre agglomeration [1].
- Sisal fibre. The results of the research show that the appropriate addition of sisal fibres can improve the mechanical properties of geopolymer composites, especially flexible strength. Sisal fibres has good coherences with geopolymer matrix [4].
- Flex fibres. The mechanical properties of the geopolymers reinforced by fibre-reinforced composites improve with increasing fibre content. This represents a significant improvement on the flexural strength of the unreinforced geopolymer matrix, and all the composites show graceful failure, unlike the brittle failure of the matrix. Despite the formation of microcracks due to water loss from the geopolymer matrix, the fibres are thermally protected by the matrix up to 400 °C. The flax fibres do not appear to be compromised by the alkaline environment of the matrix, suggesting new possible applications for these low-cost simply prepared construction materials [6].
- Coir (fibres from coconut). The results of the research show that the appropriate addition of coir can improve the mechanical properties of geopolymer composites, especially flexible strength [4, 7].
- Sorghum fiber. The results indicate that the unit weight of the sweet sorghum fiber–geopolymer composite decreases with higher fiber content. Although the inclusion of sweet sorghum fiber slightly decreases the unconfined compressive

strength, the splitting tensile, and flexural strengths as well as the post-peak toughness increase with the fiber content up to 2% and then start to decrease. The splitting tensile tests also clearly show the transition from the brittle failure of the plain geopolymer specimen to the "ductile" failure of the geopolymer specimen containing sweet sorghum fiber [8].

– Wool fibres. The composites reinforced with natural protein-based (wool) have approximately 40% improvement in ultimate flexural strength compared with the unreinforced geopolymer matrix [9, 10].
– Other fibres such as jute, corn husk, pineapple leaf fibre and cellulose [11].

The Raffia palms (called also Raphia) are a genus of twenty species of palms [12] native to tropical regions of Africa, especially Madagascar, with one species also occurring in Central and South America. The raffia is especially popular in: the Province of Bohol in the Philippines, Kuba of Democratic Republic of the Congo, Nso of Cameroon, the Igbo and Ibibio/Annang of South-Eastern, the Urhobo and Ijaw people of Niger delta Nigeria and the Yoruba of South-Western Nigeria, and among several other West African ethnic nations [2, 13]. The raffia palm tree belongs to the multifunctional plant family. It is the largest palm and one of the most useful economically [14, 15]. In their local environments, it is used for ropes, sticks to tying up plants that require support and supporting beams, including binding together vegetables to be marketed, weaving baskets, and various roof (branches as well as leaves). Traditionally, it is used also to beds, shoes, handbags, carpets, hats and other native cloth, mats and food (sap/wine) and also to traditional art such as crafts, decoration, braces and sculptures [12, 16]. Its nuts are source of food and cosmetic oil, whereas the petioles and raw leaves are used as construction materials [17]. Contemporary, the fibres are used to reinforce composites, clay bricks and concrete, or to make panels and geotextiles [17–19]. It is sometimes combining with polymer materials [20, 21], including composites for automotive industry [22] and it is solicited in the protection of the environment (water and soil conservation) and nutrition [23]. The plant can be also potential source for bioethanol production [24].

The raffia palms grow in the swampy and semi-swampy areas of the equatorial rainforest or derived savannah [14, 25]. The plants are monocarpic or hapaxanthic, usually they flowering once and individual stems dying after fruiting but the root system remaining alive and sending up new stems. The palms grow up to 16 m tall and are remarkable for their compound pinnate leaves. The raw fibres are extracted from the upper surface of the leaflets [17, 3]. The raffia palm is crowned with enormous leaves that may be up to 25 m long, up 3 m wide (and composed of 80 to 100 leaflets [2]. The raffia fibres are made from leafs. The membrane on the underside of each individual frond leaf is taken off to create a long thin fiber which can be dyed and woven as a textile. Fiber from these leaves is torn into small strips and dried in the sun. The fibers are soft, pliable, and have "strong nature". Mechanical properties of fibres: Young's modulus approx. 30 GPa, tensile strength approx. 500 MPa, total elongation between 2 and 4% and density 0.75 [17, 26]. The raw fibre has semi-crystalline and that the allotrope form is I_b cellulose [17].

Additionally, the raffia has very good thermal properties. The research results which confirm its effectiveness as an insulation material having good heat storage capacity. The overall transverse thermal conductivity of anhydrous raffia bamboo gives an average of 0.07 W/m K [23]. This fact makes the raffia fibre attractive material for isolation.

Materials and Methods

The geopolymer matrix was made from fly ash from the CHP plant in Skawina (Poland). The fly ashes were thoroughly investigated as a possible raw material for the production of the geopolymer matrix being a base for various composites. SEM observations, EDS analysis and the previous research confirmed its suitability for such matrix. The chemical composition of the mentioned ash consists of approx. 56% SiO_2, 23.5% Al_2O_3, 6% Fe_2O_3, 3.5%, K_2O, below 3% CaO and MgO, and less than 1% of other components e.g., TiO_2, Na_2O, P_2O_5 and BaO [4]. High value of SiO_2 and Al_2O_3 is advantageous for creating geopolymers, additionally low amount CaO confirm the usability of this particular fly ashes for the prosecco alkali activation. The fly ash density amounted to 2.22 g/cm^3. The morphology of the particles of fly ash was typical of such by-products of coal combustion. Regarding the particle size distribution of the examined fly ash, the size of approx. 60% particles was <56 μm [4].

The matrix of the composites was 8 M sodium hydroxide solution combined with the sodium silicate solution (liquid glass at a ratio of 1:2, 5). In order to manufacture the composites flakes of technical sodium hydroxide were used and water solution of sodium silicate R–145 whose modulus was 2.5 and density 1.45 g/cm^3. Tap water was used as batched water instead of the distilled one. The alkaline solution was prepared by means of pouring the aqueous solution of sodium silicate and water over solid sodium hydroxide. The solution was mixed and left until its temperature became stable and the concentrations equalized.

The samples were prepared using sodium promoter, fly ash and raffia fibres (the 1% by mass of the composite). To reinforce the geopolymer matrix raffia fibres were used whose length was approx. 3 mm and diameter approx. 1 mm. The research involved the samples reinforced by raffia (Fig. 1) and artificial fibre—PP (polypropylene). PP is the traditional additive for building materials such a cement. The fly ash was mixed with fibres about 5 min by using mixing machine. Then, the solution was mixed with fly ash and raffia fibres about 15 min (to receive the homogeneous paste). Next, it was poured into two sets of plastic moulds. The first set consisted of the moulds dedicated to undergo compressive strength tests and the second set consisted of the moulds dedicated to undergo flexural strength tests. The samples were hand-formed and then subjected to vibratory removal of air bubbles. Tightly closed moulds were heated in the laboratory dryer for 24 h at 75 °C. Then, the samples were unmoulded. They were investigated after 28 days.

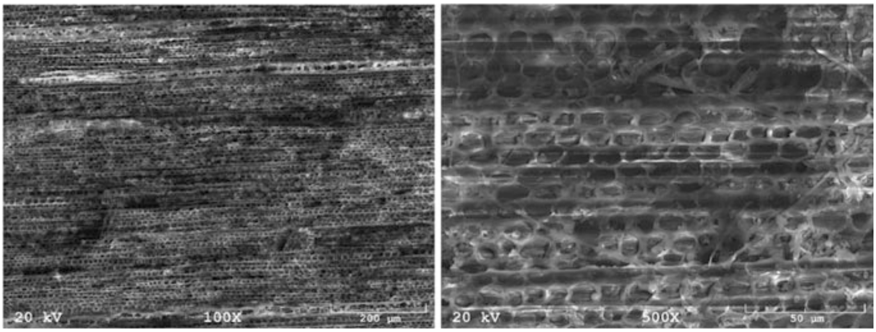

Fig. 1 Exemplary SEM images for raffia fibres

Microstructure research has been performed by means of scanning electron microscopy (SEM) type JEOL JSM 820 with EDS (The observations were made for raffia fibers and composites (geopolymer and fibres: raffia and PP). The investigation regarded the samples previously broken while compressive strength tests (in case of composities). The samples were sprinkled with a thin layer of gold with JEOL JEE-4X vacuum sputter. The observation was made at various magnifications (between 20–1000×). For the samples geopolymer—PP also the polished specimen were prepared.

Due to the lack of separate standards for geopolymer materials, the 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'). Samples used in the flexural strength tests had cuboid shape and dimensions (approx.): 50 mm × 50 mm × 50 mm. The tests involved at least 6 samples. They were performed with a concrete press (MATEST).

Due to the lack of separate standards for geopolymer materials, the flexural strength tests were carried out according to the methodology described in the standard EN 12390-5 ('Testing hardened concrete. Flexural strength of testspecimens'). Samples used to the flexural strength test had cuboid shape and dimensions (approx.): 200 mm × 50 mm × 50 mm. Tests were performed with a universal testing machine—single-point load (Instron type 4465).

Results

The SEM observations were made form composites and raffia fibres. The investigations for raffia fibres confirm the literature data about these fibres [17]. There are composed of superimposing layers. The top layer is composed of strands, themselves constituted by scales aligned in the longitudinal direction of the fibre and the bottom one has an alveolus structure resembling a honeycomb [17] and Fig. 1. These structure could serve as mechanical bonding in a composite matrix [17].

The observation of microstructure for composities gives a preliminary information about the coherency of fibers (filler) and the geopolymer matrix as well as lets to evaluate of the fiber distribution.

The results from the scanning electron microscopy analysis are shown in Figs. 2 and 3. They presents the raffia fibres in geopolymer matrix. The investigation in low magnification 20× allow to estimate the fibres distribution (Fig. 2).

The investigation in high magnification 100–1000× allow to estimate the fibres coherency with matrix (Fig. 3).

The fibre distribution in the case of natural fibres as well as artificial is regular (Fig. 4). The fibre distribution in the matrix heavily influences the properties of the specific composite, as the fibres aggregation can decrease its mechanical properties. Here, in the same sample one could notice some fibre agglomerations and it was connected with a concomitant decrease of mechanical properties of the composite.

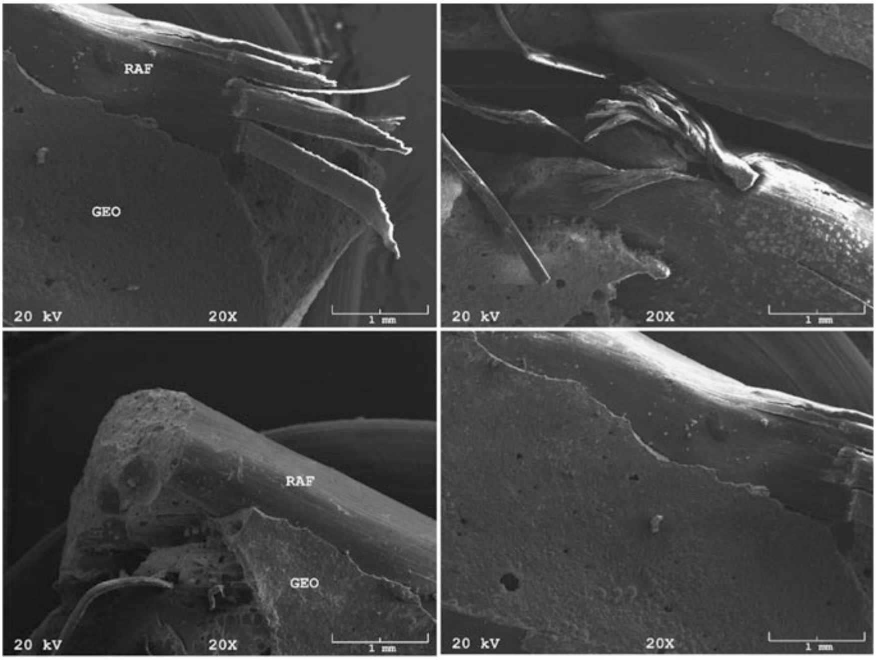

Fig. 2 Exemplary SEM images for composite: geopolymer matrix reinforced by raffia fibres in low magnification 20×

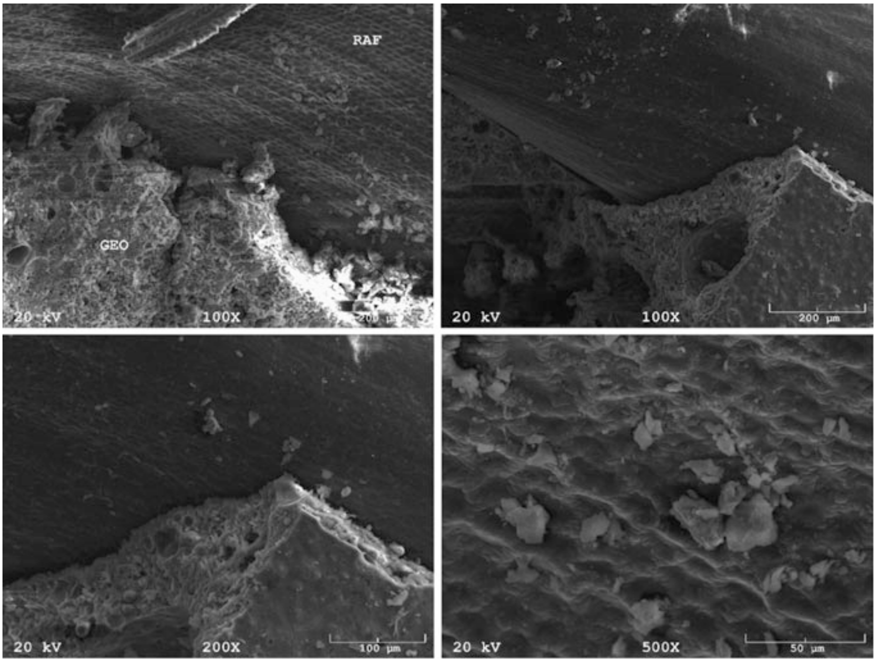

Fig. 3 Exemplary SEM images for composite: geopolymer matrix reinforced by raffia fibres in low magnification 100–500×

The coherency between the filler and the matrix not always exists. In the case of the composites reinforced with PP the observation confirms their cohesiveness (Fig. 4). But in the case of other natural fibres such as raffia the structure is not always coherent with the matrix: most fibres are surrounded by well-visible empty spaces. The exemplary ones are shown in the Fig. 3. The incoherent structure has a negative impact on the mechanical properties of the composites. However, even with such structure the presence of the fibres significantly reduces cracks propagation (SEM observation was made on the samples after the compressive strength test).

The results from the compressive strength test and flexural strength tests are shown in Tables 1 and 2.

The composites with raffia had worse mechanical properties as material with PP fibres additive, however they are still reasonable for some potential application. The addition of the raffia fibres decreased the mechanical properties of the samples comparison with other naturals fibres [4]. It is caused by the lack of cohesiveness between the fibres and the geopolymer matrix.

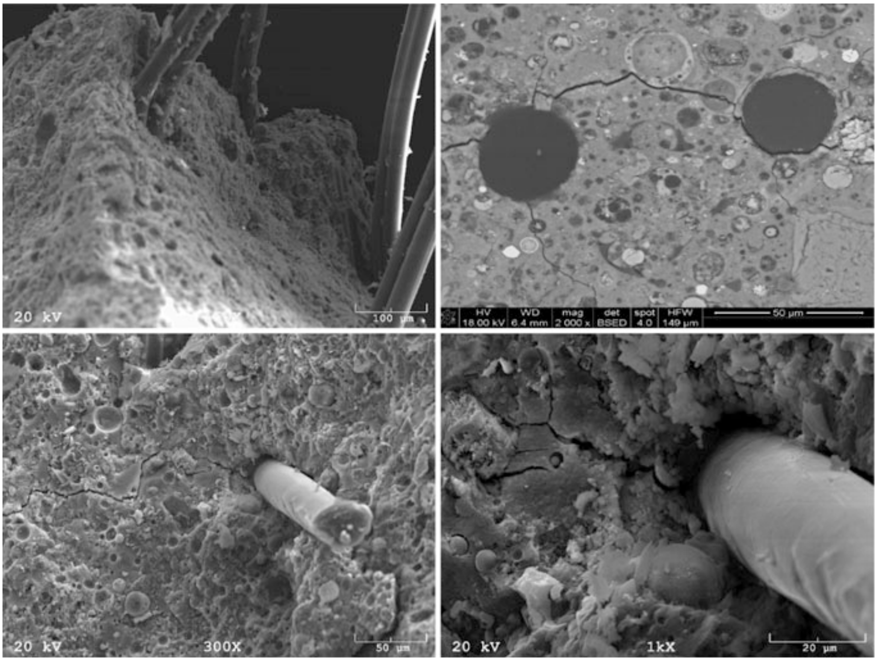

Fig. 4 Exemplary SEM images for composite: geopolymer matrix reinforced by PP fibres

Table 1 Compressive strength test after 28 days

Sample	MPa	StD
Geopolymer with raffia fibers (1%)	13.66	1.71
Geopolymer with PP fibers (1%)	16.14	3.52

Table 2 Flexural strength test after 28 days

Sample	MPa	StD
Geopolymer with raffia fibers (1%)	3.05	0.35
Geopolymer with PP fibers (1%)	3.95	0.21

Conclusions

Geopolymer composites reinforced with the raffia fibres and PP fibres have been produced and characterized. The samples were prepared using sodium promoter and four various types of fibre additive (each time it amounted to the 1% by mass of the composite (8 M)). The research involved both reinforced samples with natural and artificial fillers (for the sake of comparison).

The microstructure observations shows the difference between coherence natural and artificial fibres with geopolymer matrix that have an influence for mechanical properties. The composites with artificial fibers have better properties, however there are not such beneficial for environment. This study shows that it is possible to produce the composites of reasonable properties from the industrial wastes (fly ash) and renewable resources—raffia fibers, which makes them a new class of environmentally friendly materials. Further tests should be performed in order to optimize the composite properties.

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