Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal 2023, 17(2), 268–278
https://doi.org/10.12913/22998624/161449
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Received: 2022.11.04
Accepted: 2023.03.15
Published: 2023.04.01

Comparative Evaluation of the Selected Mechanical Properties of Polymer Composites Reinforced with Glass and Hemp Fabrics

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INTRODUCTION

The dynamically developing technology, as well as the constantly growing needs and requirements of the industry, force the development of new materials [1–6], which would reduce production costs and (at the same time) be characterized by better physical and/or chemical properties than traditional materials [7, 8].

One of the rapidly developing material groups includes fiber composites (FRPC – Fiber Reinforced Polymer Composite) [9–11], which covered almost all branches of the economy. This applies to the technology industry in the area of everyday items through the automotive, machinery, building materials, economics, aerospace, defense, and shipbuilding industries. The EU framework program called H2020, the universal application of technological process design (TRL – Technology Readiness Level), and the European Commission's package concerning the circular economy of December 2015, indicated the need to solve a global problem of disposal and/or recycling [10,12–15] for FRP (Fibre Reinforced Plastic) recreational watercraft that have been taken out of service [16–20].

Since the middle of the second decade of the 21st century, the Polish yacht industry has shown constant and rapid growth in the production and export of recreational units [13]. In these structures, composite materials are mainly used. Currently, it is the European leader in the most popular segment of GFRP (Glass Fiber Reinforced Polymer) boats – i.e. motor yachts with a length of 6–9 meters – taking second place in the world behind the USA [20–22]. According to EUROSTAT (the Statistical Office of the European Union), Polish export of vessels, mainly yachts and motor boats, in 2019 accounted for 60% of the total value of yacht export in the EU, and in the period 2014–2018, it increased from the amount of 184.8 million euros to the amount of 295.8 million euro [20–22].

In total, approximately 22.000 various types of GFRP vessels are produced in Poland each year. They are exported worldwide [20, 22]. In light of the applicable conventions and international regulations about natural environmental protection, it is important to meet the current requirements in the field of safe recycling [23] and/or disposal of end-of-life structures. It is largely related to the elimination of the composite reinforcement made of various forms, i.e. fabrics and glass mats, that has been used for many years. This leads to the consideration of using natural fibers as an alternative to glass fibers (as reinforcement of polymer structural composites) [24–26].

These materials were used in various industries as early as the turn of the 1980s. In the United States and Europe, mainly in Germany, polymer composites reinforced with natural fiber (NPFC) are used in automotive components [24, 27, 28], i.e. jute, flax, and hemp. The literature [21, 29, 30] indicates that jute, hemp, and flax are the most cultivated globally. They have the largest share in the production of composites reinforced with natural fibers (Figure 1). An important criterion while considering the selection of fiber plants [21, 26, 30] in the context of the possibility of their industrial application and technical use of fibers is the place of their natural occurrence in a specific geographical region of the world.

For example, in Asia, tests on the selection of natural fibers in composites focus on cotton, hemp, sisal, or jute. Concerning Europe and its climatic conditions, there are two fiber plants – i.e. flax and fiber hemp. Flax is a common, commercially grown, and expensive natural resource. Compared to flax, hemp is relatively cheaper to cultivate and produce [31–33]. Currently, fibrous hemp is cultivated in over 50 countries in various geographical regions of the world [27, 32, 33]. This causes these plants to be used in many industries. It should be remembered that plant crops are very dependent on weather conditions. They are also sensitive to pest threats. Only good quality, healthy and well-dried fibers can ensure the best mechanical strength of products. Additionally, a gradual increase in the area of hemp cultivation leads to an increase in the possibility of applying this plant – also to the shipbuilding industry. Therefore, this work evaluates the selected mechanical properties of hemp fibers, i.e. impact strength, static tensile, and bending strength. These fibrous fillers in the form of fabric were used as an innovative solution for natural structural reinforcements. Previously, they have not been indicated in the literature.

Following the applicable regulations of the Polish Register of Shipping (PRS) [34−39] in the field of classification and construction of sea yachts, presented in Part II concerning the hull of a sea yacht, the main shells of the yacht's plating made of laminate (mainly reinforced with glass mats) should have a reinforcement content within the range of 28–33% concerning the laminate's weight, while reinforced mixed mats and other types of reinforcement, approx. 40% [40].

For yachts characterized with a classification length of fewer than 9 meters, the construction of the yacht's hull (according to the PRS regulations) may be performed without strength tests, provided that the following conditions are met:

- Confirmation of the correctness of the laminate's performance with the use of the visual method (VM).
- Use of plating with a better reinforcement (by 15%) and higher index of stiffening (by 10%) that the values presented in these regulations.
- Stating the content of reinforcement within the required limits (based on the obtained thicknesses of plating) [40].

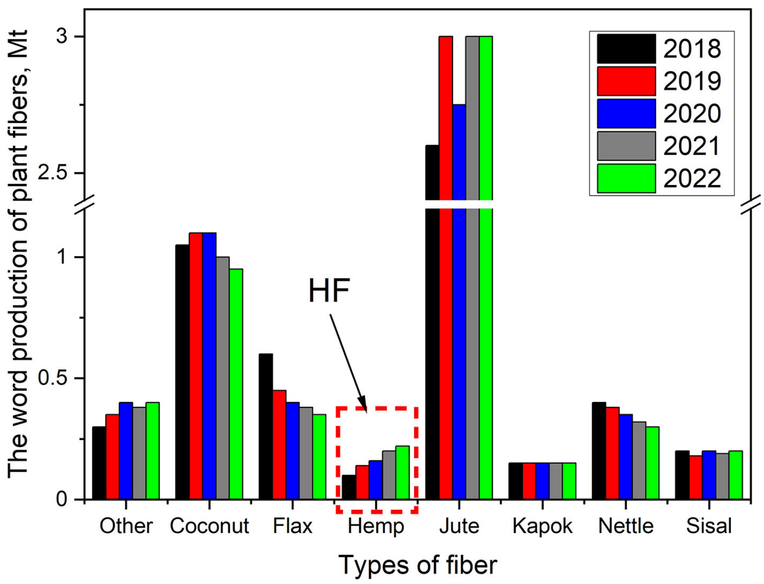

Fig. 1. World production of plant fibers in the years 2018–2022 (projected own study based on) [21, 29, 30]

Currently, applicable legal acts and standards in Poland [34−36, 38, 39, 41−43] concern the requirements that are not only connected with the safe production of FRP vessels but also (in the future) with the possibility of their recycling or disposal of, after reaching the EOL status, in an environmentally safe manner. However, these regulations are mainly related to composites reinforced with glass fiber, so in this study, it was assumed that the newly produced biocomposite can be used to build a vessel – if it shows properties that are similar to or better than the composite reinforced with glass fabric.

Therefore, the purpose of this work was to compare the selected mechanical properties of polymer composites reinforced with glass and natural fibers. Composites reinforced with glass fabric and hemp fabric were compared due to the lack of research concerning this form of reinforcement for hemp biocomposite in the literature. The use of natural reinforcements will bring tremendous benefits to the natural environment because it will largely reduce the amount of post-consumer waste.

MATERIALS AND METHODS

For the tests, composites in the form of a polyester composite panel reinforced with glass fabric (GFRP) and a polyester composite reinforced with fiber hemp fabrics (HFRP) were produced with the use of the HUL (Hand Lay-Up) method. In the production of composites, the following elements were used:

- Carcass in the form of a standard DCPD structural resin (the so-called improved polyester resin for yachts) with the trade name M 604 TBR produced by Ashland. Metox-50WR, produced by Oxytop Sp. z o.o., along with a polymerization accelerator based on cobalt octanoate 6% (dissolved in xylene) called BÜFA®Accelerator Co 6 were used as an initiator of copolymerization to resins. Components for the production of control panels were provided by the manufacturer of sail-motor yachts and motor boats (Technologie Tworzyw Sztucznych Sp. z o.o. Łozienica near Goleniów). Additionally, to increase the adhesion between the carcass and reinforcement, an adhesive agent in the form of maleic anhydride (MAH), in the proportion of 3 g per 100 g of resin, was used.
- Reinforcement 1, glass fiber fabric with an average weight of 452 g/m^2, Krosglass company, product code: STR 026–450–125).
- Reinforcement 2, hemp fabric with an average weight of 478 g/m^2, S.C. Cavvas Limited S.R.L. company from Romania.

Technology and parameters for the production of new composite materials

During the manufacturing process, the following conditions were maintained (by the provisions of PRS) [40]:

- the temperature in the range of 16÷25°C (average process temperature was 22±1°C),
- the relative humidity below 70% (average process humidity was 66±2%).

For the laminate production process, 430 × 280 mm pieces were cut out of the above-described fabrics. The use of larger formats was aimed at eliminating underfilling and delamination near the edges of the finished panels. As a result, control panels with dimensions of 250×400 mm were obtained. To produce the GFRP composite, approx. 26 g of resin/fabric layer was used, while for the HFRP composite approx. 75 g per layer. The composition

Table 1. Mass share (in %) of reinforcement and matrix in the laminate

No.	Designation	Number of reinforcement layers	Material thickness [mm]	Type of reinforcement phase	Mass share of reinforcement in the laminate [%]	Mass share of carcass in the laminate [%]
1	GFRP	6	2.478	Glass fabric (GF)	61	39
2	K1	3	2.478	Hemp fabric (HF)	41	59
3	K2	5	4.130	Hemp fabric	42	58
4	K3	7	5.780	Hemp fabric	42	58
5	K4	9	7.430	Hemp fabric	41	59
6	K5	11	9.080	Hemp fabric	40	60
7	K6	13	10.730	Hemp fabric	42	58

and designations of laminates are presented in Table 1. In the HUL method, subsequent layers were applied wet on wet. After the resin application process is complete the produced panels were seasoned at constant temperature and humidity for 72 hours from the gelation of the last layer of resin. After the panels were formed, test samples were cut out of them by the standards. WaterJet technology was used for cutting, the cutting was made at a working pressure of 3950 bar using an 80 mesh garnet. The cutting method was used for continuous cutting with piercing outside the area of finished elements. Five samples were cut from each material/panel for each test (PN-EN ISO 868:2003; EN ISO 527–2:2012; EN ISO 178:2019; EN ISO 179–2:2020).

To determine the properties of polymer structural composites of the base GFRP and HFRP, samples of these materials were tested:

- Static tensile strength was performed under EN ISO 527–2:2012 using a universal testing machine Shimadzu type AG-X plus with a crosshead speed of 10 mm/min, at a temperature of 22°C. Five samples of each material in the form of a cuboid with dimensions of 80×10×h mm were used for the tests. Where h is the thickness of the samples and depends on the number of layers in the material (Table 1).
- Flexural strength per EN ISO 178:2019 was carried out by a universal testing machine Shimadzu, type AG-X plus, load range: 0÷10 kN, with a bending speed of 10 mm/min. Five samples of each material in the form of a cuboid with dimensions of 80×10×h mm were used for the tests. Where h is the thickness of the samples and depends on the number of layers in the material (Table 1).
- Charpy impact strength by EN ISO 179–2:2020 on standard samples without a notch (swing hammer produced by VEB Werkstoffpruefmaschinen Leipzig-Betrieb des VEB „Fritz Heckert" with a maximum impact energy of 50 J. Five samples of each material in the form of a cuboid with dimensions of 80×10×h mm were used for the tests. Where h is the thickness of the samples and depends on the number of layers in the material (Table 1).
- The density of materials was tested according to the EN ISO 1183–1:2013–06 standard using the hydrostatic method using an electronic balance Type XA340 (Radwag) equipped with a set for determining the density of solids. Five samples of each material in the form of a cuboid with dimensions of 30×10×h mm were used for the tests. Where h is the thickness of the samples and depends on the number of layers in the material (Table 1).
- The macroscopic examination was carried out using an optical stereoscopic microscope by HAYEAR (model FHD216).

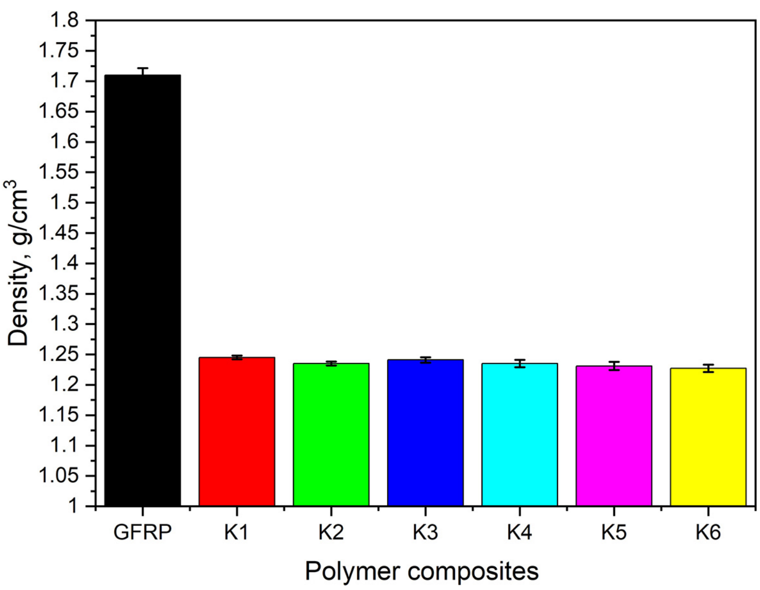

Fig. 2. Comparison of the density of HFRP (K1-K6) and GFRP composites.

RESULTS AND DISCUSSION

Analysis of the density of polymer composites with different types of reinforcement

The results of density tests of composites based on natural fabrics (HFRP) with polyester-glass composites (GFRP) are compared in Figure 2.

When analyzing the results of density (Figure 2) for individual composites (K1-K6), it was stated that the polymer composite reinforced with hemp fabric (HFRP) shows a decrease in density by 29% compared to the reference sample, GFRP composite. The lower density of the GFRP composite results from the lower density of natural fibers than glass fibers.

Analysis of the static tensile strength of polymer composites with different types of reinforcement

The results of static tensile tests for composites based on natural fibers (HFRP) and polyester-glass composites (GFRP) are compared in Figure 3.

After analyzing the results of tensile strength tests for the HFRP composite, concerning GFRP, it was found that composites reinforced with hemp fabric (K1-K6) show a reduction in the max. force by approx. 31% concerning the GFRP composite. As shown in Figure 3, the maximum force of the HFRP composite increases with the increase in the number of layers in the HFRP composite. Furthermore, it was observed that K5 can withstand of 9209 N – it is the closest to the value of 9541 N – the maximum force characteristic for GFRP composite. This indicates the applicability of this HFRP system for industrial applications, assuming that increasing the thickness of the element does not matter. Additionally, it was noted that the K6 material has a 6% reduction in the mean max. force concerning the K5 series and a 9% reduction concerning the GFRP base material. Based on the above-mentioned results, it can be assumed that 11 layers of the K5 series fabric constitute the upper limit of the quantitative use for the reinforcement of the polymer structural composite.

By analyzing the ultimate elongation of composite materials (Figure 4), composites reinforced with hemp fabric (K1-K6) show an increase in average elongations by approx. 74% concerning the GFRP material. This means that the HFRP material is relatively more durable and more prone to elongation than GFRP composite. From the point of view of average elongations of this material, the obtained test results do not disqualify this material in the category of construction materials;

The analysis of the ultimate tensile strength (Figure 5) of composites reinforced with hemp fabric (K1-K6) shows a reduction in the maximum stresses compared to the GFRP composite. This is due to the increase in the thickness of the materials compared to composites reinforced with glass fiber. While considering the obtained results in the context of the construction of small vessels, the thickness of plating depends on the following

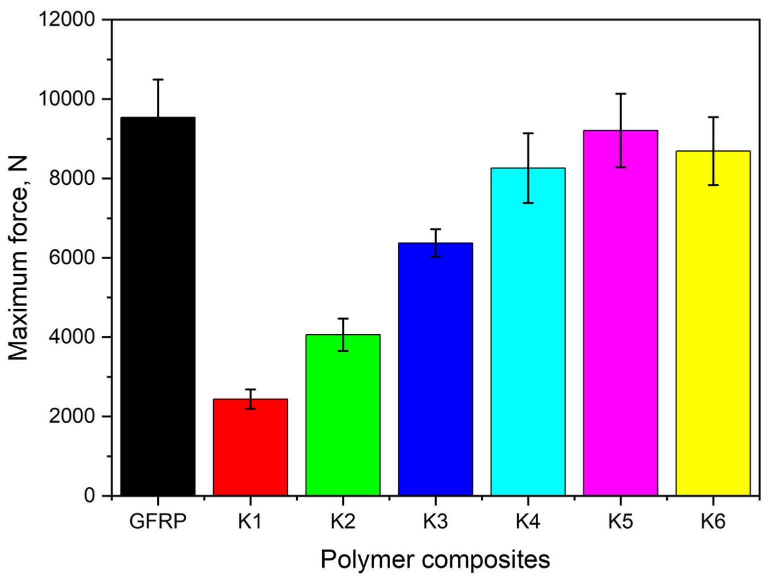

Fig. 3. Comparison of maximum force of HFRP (K1-K6) with GFRP composite.

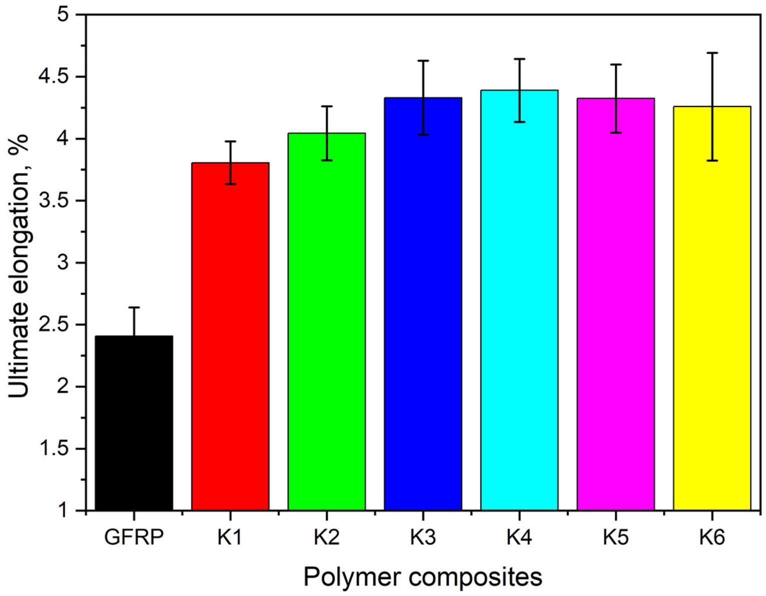

Fig. 4. Comparison of ultimate elongation of HFRP (K1-K6) and GFRP composites.

factors such as the size of the hull, the size, and arrangement of binders, as well as shape. Furthermore, different thicknesses are used in different places of the plating: the thickest at the bottom, and thinner, e.g. in superstructures. The thickness of the yacht's plating is limited only by the weight of the ready unit. This causes the plating's thickness to be not the most important parameter. The ability of the material to transfer loads is more important. From the point of view of the obtained results of maximum stresses, this only partially disqualifies the HFRP material in the category of alternative construction material, in particular for applications with elements characterized by increased strength properties.

Analysis of the flexural strength of polymer composites with different types of reinforcement

The results of bending strength tests for K1-K6 (HFRP) composites compared to the GFRP composite show that the maximum bending force of composites increases with an increasing number of HFRP fabric layers (Figure 6). Moreover, the HFRK in K3-K6 shows the ability to transfer higher static bending forces with the HFRP, e.g. K3 (756 N), and GFRP (525 N). This means that the number of 7 layers of hemp fabrics with 6 layers of glass fabrics (type E) meets the condition of the ability to transmit bending force of this construction material.

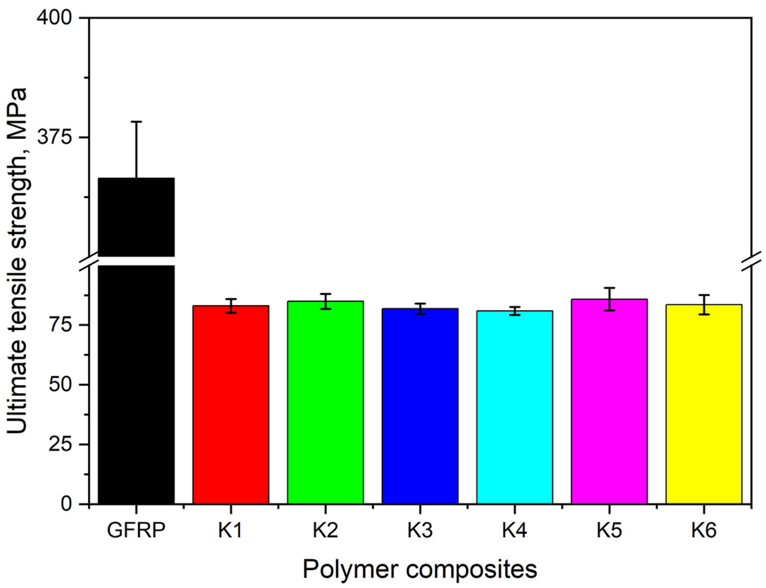

Fig. 5. Comparison of the ultimate tensile strength of HFRP (K1-K6) and GFRP composites.

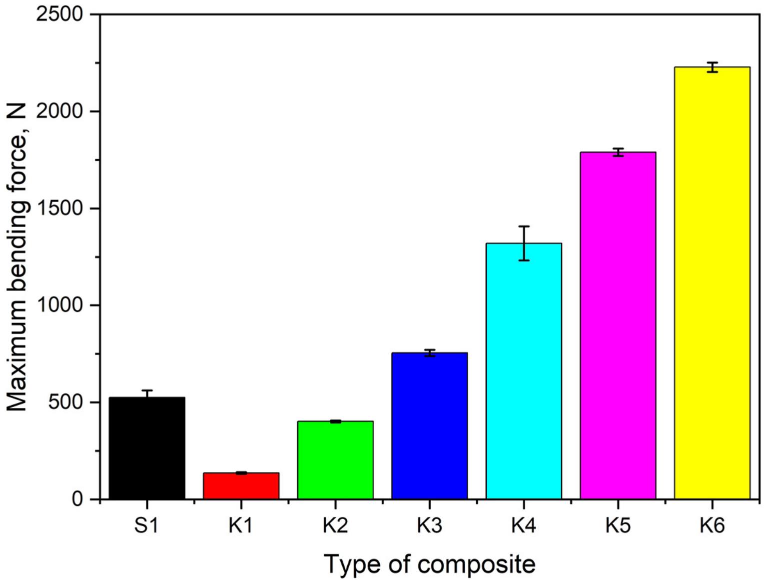

Fig. 6. Comparison of maximum bending force for HFRP (K1-K6) and GFRP composites.

As a result of the analysis regarding deformation during bending (Figure 7), it can be observed that composites reinforced with HFRP hemp fabric show a reduction in average deformation by approx. 28% concerning the GFRP composite. K2-K4 composites show the most similar deformation results. K1 composites presented a significant susceptibility to bending elongation (high flexibility) compared to the GFRP composite. Furthermore, it was observed that GFRP and HFRP composites do not break, as shown in Figure 8.

The analysis of the bending strength of these composites (Figure 9) showed an approx. a 14-fold decrease in the maximum stress of a composite reinforced with hemp fabric with the GFRP material. From the point of view of the obtained results, it disqualifies this material in the category of an alternative construction material that is exposed to bending.

Analysis of impact strength of polymer composites with different types of reinforcement

After a comparative analysis of the impact strength results for HFRP and GFRP composites – with the use of the Charpy method – it was stated (Figure 10) that the GFRP composite has

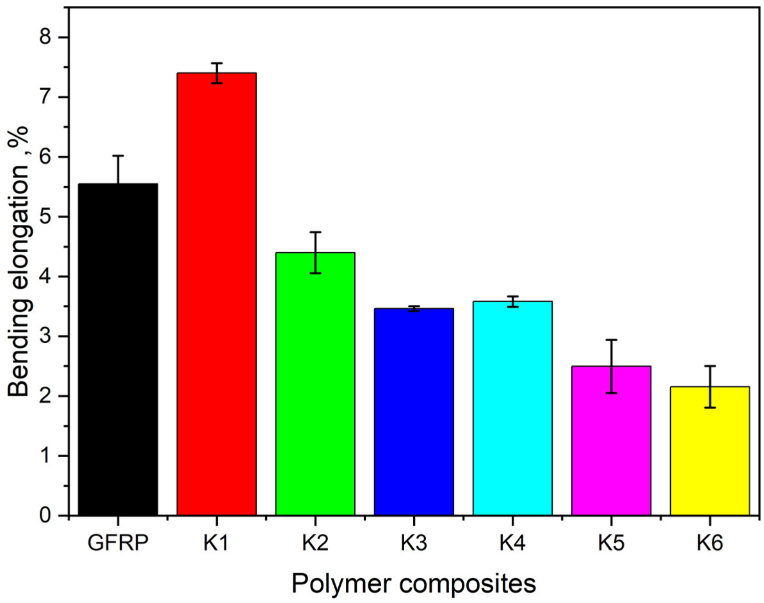

Fig. 7. Comparison of the bending elongation for HFRP (K1-K6) composites and GFRP composite.

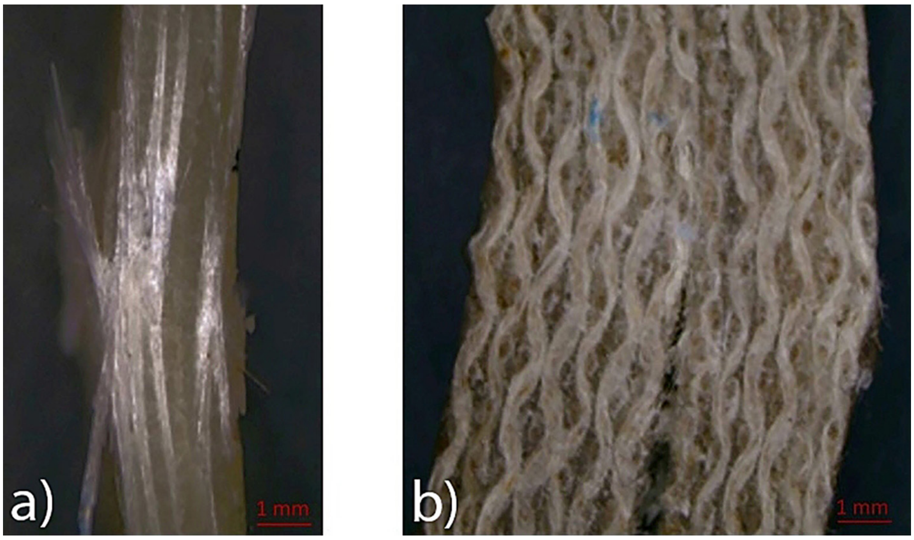

Fig. 8. Sample photo of the break (in a micro-scale): GFRP (a) and K6 (b) composites after the bending strength test.

the highest impact strength. For HFRP composites reinforced with hemp fiber, it was observed that impact strength increases with the increase of fabric layers (Figure 10).

However, composites reinforced with hemp fabric show a reduction in the impact strength of composites by approx. 38% to the GFRP composite. Furthermore, while considering the results of the K6 series tests, it can be stated that they are comparable with the results of the GFRP composite. From the point of view of the obtained results of average impact strength, this means that this HFRP composite is not disqualified in the category of construction materials for the shipbuilding industry. A summary of selected mechanical test results that may be useful in the simulation and/or design of polymer composite structural components for the construction of a vessel is presented in Table 2.

CONCLUSIONS

The paper compared the selected mechanical properties of classic GFRP composite with new polymer composite materials reinforced with hemp fabric (HFRP) for use in the construction of vessels. Based on the obtained results, it was concluded that it is reasonable to use an alternative bio-reinforcement in the form of hemp fabric (HF) instead of the common, non-biodegradable material such a glass fiber (GF).

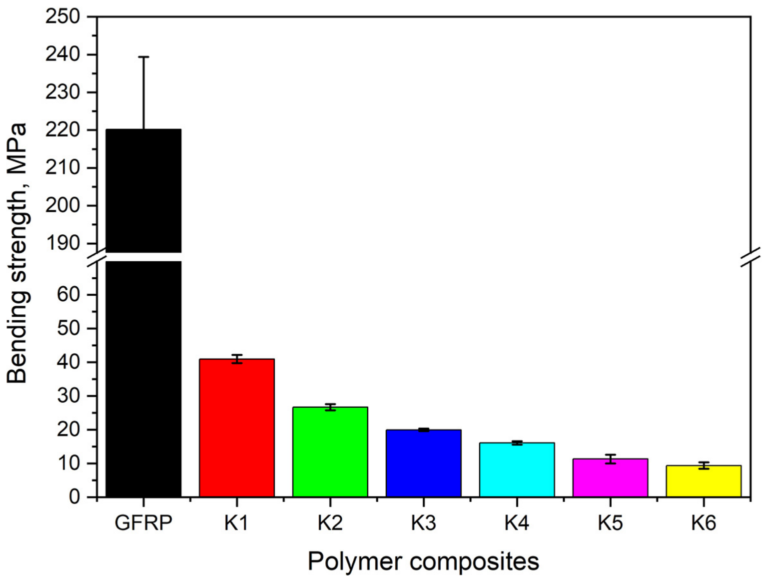

Fig. 9. Comparison of the bending strength for HFRP (K1-K6) composites and GFRP composite.

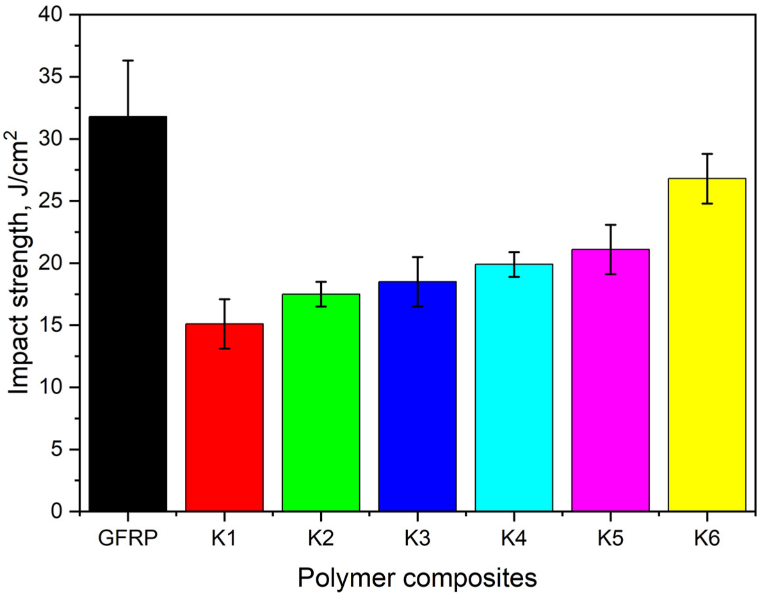

Fig. 10. Comparison of the impact strength for HFRP (K1-K6) composites and GFRP composite.

Table 2. Summary of the comparison of selected physico-chemical properties of polyester-hemp bio-composites (HFRP) and the classic polyester-glass composite (GFRP).

Polymer construction bio-composite	HFRP	GFRP	Possibility of industrial application
Density [g/cm^3]	1.2–1.3	1.7	The technical product will be lighter
Ultimate elongation [%]	3.8–4.4	2.4	The possibility of use in the shipbuilding industry
Bending elongation [%]	2.2–7.4	5.5	It does not exclude the application in the shipbuilding industry
Maximum bending force [N]	135–2228	525	The possibility of use in the shipbuilding industry
Maximum tensile force [N]	9209	9541	It does not exclude the application in the shipbuilding industry
Ultimate tensile strength [MPa]	81.0–86.0	366	It does not exclude the application in the shipbuilding industry – for less stressed elements
Bending strength [MPa]	9.0–41.0	220	It does not exclude the application in the shipbuilding industry for less stressed elements
Charpy impact strength [J/cm^2]	15.1–26.8	31.8	The possibility of use in the shipbuilding industry

Finally, the physical tests (see Table 2) showed that the obtained HFRP composite has a 41% lower density, almost twice as high stiffness, and a higher ability to absorb impact energy.

Moreover, from the economic point of view, HFRP composites with a low raw material price, as well as the production of mats and fabrics, were obtained. On the other hand, taking into account the aspect of environmental protection, the advantage of the produced new composites is the possibility of full recycling and recovery of these materials.

While, the tests have also shown some disadvantages of this material such is a low bending strength, which does not fully disqualify composites for industrial application. They only limit its potential use. It is also possible to use point reinforcement of the structure when designing the product.

The application of a new generation of HFRP composite structures in the shipbuilding industry, intended for the construction of hull sheathing, i.e. deck, superstructure, and other products, e.g. tanks, pipes, seems to be an adequate alternative to the currently produced small vessels and corresponds to the program concerning the implementation of pro-ecological measures recommended and required by the European Union.

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