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COMPOSITES THEORY AND PRACTICE

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THE IMPACT OF REINFORCEMENT MATERIAL ON SELECTED MECHANICAL PROPERTIES OF REINFORCED POLYESTER COMPOSITES

This work describes polyester matrix composite materials with diversified reinforcement materials, namely glass, carbon, and a natural material (jute). These reinforcement fibres were utilised in the form of fabrics with a canvas-like weave and basis weight ranging from 300÷400 g/m^2. The mass fraction was uniform in each of the materials that were produced, namely 40% of the baseline in comparison to the materials that were subjected to testing. The composites were produced by the vacuum pressure infiltration method, RTM (resin transfer moulding), thereby creating laminates. To assess the mechanical properties of the composites, static tensile strength tests were carried out according to PN-EN ISO 527-1:2016; the bending strength was determined according to PN-EN ISO 178:2011, and the impact strength was tested by the Charpy method according to PN-EN ISO 179-1:2010. The density of these composites was determined by the hydrostatic method according to standard PN-EN ISO 1183-1:2013-06.

Keywords: polymer composites, polyesters, ceramics, jute

WPŁYW MATERIAŁU UMOCNIENIA NA WYBRANE WŁAŚCIWOŚCI MECHANICZNE KOMPOZYTÓW POLIESTROWYCH

Przedstawiono materiały kompozytowe o osnowie poliestrowej ze zróżnicowanym materiałem struktury umocnienia, tj. włókna szklane, węglowe i naturalne (jutowe). Włókna tych umocnień występowały w postaci tkanin o splocie płóciennym i gramaturze tkaniny mieszczącej się w granicach 300÷400 g/m^2. Udział wagowy w każdym z wytworzonych materiałów był jednakowy i wynosił 40%, co stanowi punkt wyjścia przy porównywaniu badanych tworzyw. Kompozyty wytworzono metodą próżniowej infiltracji ciśnieniowej RTM - tworząc laminaty. W celu oceny właściwości mechanicznych kompozytów wykonano badania wytrzymałościowe przy próbie statycznego rozciągania (wg PN-EN ISO 527-1,2:2016), odporności na zginanie oznaczono wg PN-EN ISO 178:2003, udarności metodą Charpy'ego badano zgodnie z normą PN-EN ISO 179-1:2010. Gęstość wytworzonych kompozytów określano metodą hydrostatyczną wg PN-EN ISO 1183-1:2013-06.

Słowa kluczowe: kompozyty polimerowe, poliestry, ceramika, juta

INTRODUCTION

Composite materials are the most promising and quickly evolving group of modern construction materials [1-5], which are very popular in the fields of science, technology, industry, and business due to their desirable functional properties. The main idea behind the design of composites is to obtain a material with specific desired properties, which to a large extent depend on the applied technology. In order to obtain a desirable result, two or more materials with different properties are combined. As the composites are made of two or more constituents, it is possible to utilise the required beneficial characteristics of the constituents, while reducing their disadvantageous characteristics. Composite polymeric materials are commonly used because of their low density and high mechanical strength, as well as their high resistance to many acids and bases. The use of composites based on various materials, mass fractions, and types of reinforcement phase has a significant impact on reducing the mass of all types of structures being strengthened [5, 6].

A common means of reinforcing materials is to strengthen them with laminated materials. Materials reinforced in this way are called sandwich structures (or laminates), and are composed of a set of laminates and reinforced with a continuous fibre, mat, or fabric. This results in a three-dimensional structure with individual layers arranged in different directions or the so-called honeycomb structure. Instead of the "honeycomb" layer, it is also possible to use a foamed plastic layer covered on both sides with light-alloy sheets which are then glued to it. The first contemporary laminate composite was plywood, a board made of thin layers of wood, usually arranged transversely and glued together. Other examples of laminated composite materials are fibreboards laminated with plastics or OSBs (oriented strand board) commonly used in the furniture or construction industries. Structures (glass, carbon, or graphite fibres) are nowadays the most common materials used for reinforcement in laminates [1-8].

The development of layered composite materials in recent years has extended the range of applications of these materials, from general use to the automotive, aerospace, aeronautics and shipbuilding sectors, etc. This has generated a large volume of waste, the recycling problem of which has not yet been solved. According to data from the European Composites Industry Association (EuCIA) [6], in the EU in 2015 the total annual volume of waste composites filled with glass fibre will increase to 300,000 t. This has resulted in the search for natural reinforcements to replace the previously used materials. The use of natural reinforcements such as wood flour and vegetable fibres will contribute to the increase in the biodegradability of the waste mass component. Natural fibres, compared to synthetic fibres, are characterized by good availability, low cost, low density and biodegradability for renewable energy [6-14].

Among natural fibres we can distinguish plant stem fibres (flax, hemp, kenaf, jute, ramie), leaves (sisal) or fruits (coconut fibres). Many scientific and technological efforts have been made to find solutions to improve the natural variability in the quality of natural fibres and their poor compatibility with polymers. Unfortunately, their low strength, susceptibility to ageing, and low thermal stability still limit the production and application of these fibres [11-16]. One of the most widely used natural fibres is **jute fibre**. It is a valuable industrial raw material suitable for cultivation only in warm and humid climates. Jute fibres are durable, and coarse fabrics woven from them are both strong and flexible. Jute is used in the manufacture of sacks, carpets, upholstery, twines, linoleum, paper, and also electrical insulation materials. They are considered to be potential composite reinforcements to replace glass fibres. After cotton, jute is the most widespread fibre (due to its low cost and high yield). It is also highly desirable in the recycling of polymer composite materials. In the case of these materials, the issue of post-production and post-functional waste management is of paramount importance [9] due to their large quantity. Therefore, new materials with favourable environmental characteristics are still being sought. In this paper it was decided to create composites with a polyester matrix and reinforcement with different types of fibres: glass, carbon, and jute, in order to compare their mechanical properties and optionally to compare natural fibres with ceramic fibres. This study has also aimed to test the applicability of natural fibre laminate for constructing the hulls of small vessels.

RESEARCH MATERIAL

ESTROMAL 14 LM01 polyester resin was used to produce the laminates. In order to cure them, 1.5 wt.% METOX 50 hardener and 0.05 wt.% accelerating agent (cobalt naphthenate) were added to the polyester resin. The reinforcement materials were:

1. glass fibre with a plain weave: basis weight of Textilglass 1/1 fabric is 350 g/m^2 (Fig. 1a);
2. carbon fibre with a plain weave: basis weight of KrosGlass 1/1 fabric is 300 g/m^2 (Fig. 1b);
3. jute fibre with a plain weave: basis weight of Fibresco 1/1 fabric is 400 g/m^2 (Fig. 1c).

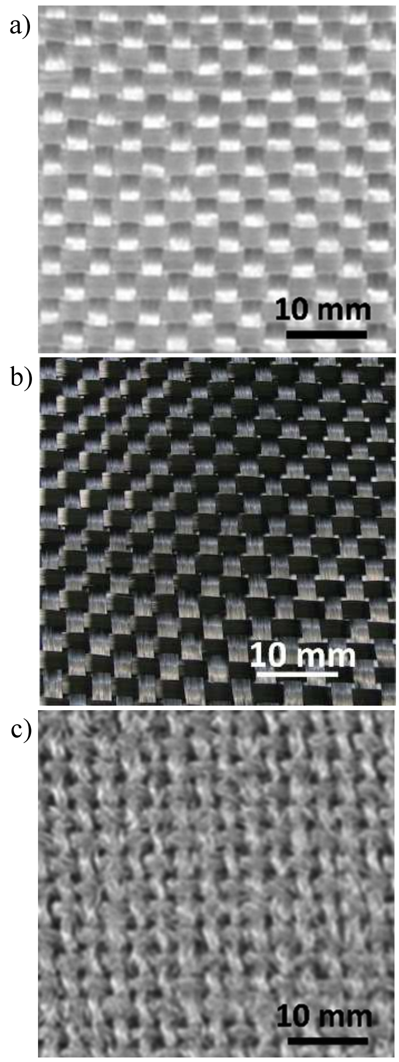

Fig. 1. Reinforcement materials: a) glass fabric, b) carbon fabric, c) jute fabric

Rys. 1. Materiał fazy umocnienia: a) tkanina szklana, b) tkanina węglowa, c) tkanina z juty

Before the saturation process of the jute fabric, it was chemically treated in 15% NaOH for 2 hours, and then the fabric was washed and dried at 110°C. The properties of the reinforcement phase materials that were tested are summarized in Table 1.

TABLE 1. **Selected properties of glass, carbon, and jute fibres [12-16]**

TABELA 1. **Wybrane właściwości włókien szklanych, węglowych i jutowych [12-16]**

Property		Glass fibre	Carbon fibre	Jute fibre
Density	[g/cm^3]	2.55	1.86	1.46
Tensile strength	[MPa]	2400.00	2600.00	800.00
Modulus of elasticity	[GPa]	73.00	160.00	26.00
Unit elongation	[%]	3.00	0.90	1.80
Price (December, 2017)	[PLN/m^2]	18.00	150.00	7.00

The technology for manufacturing the composites was chosen through experimentation. The RTM method was used due to its simplicity and the final quality of the composites. In this method, a suitably prepared resin is pressed under low pressure into a closed mould (Fig. 2) in which a fibrous reinforcement has been previously fixed. In addition to the pressure, the mould closing process can be supported with a vacuum to ensure better saturation of the reinforcement.

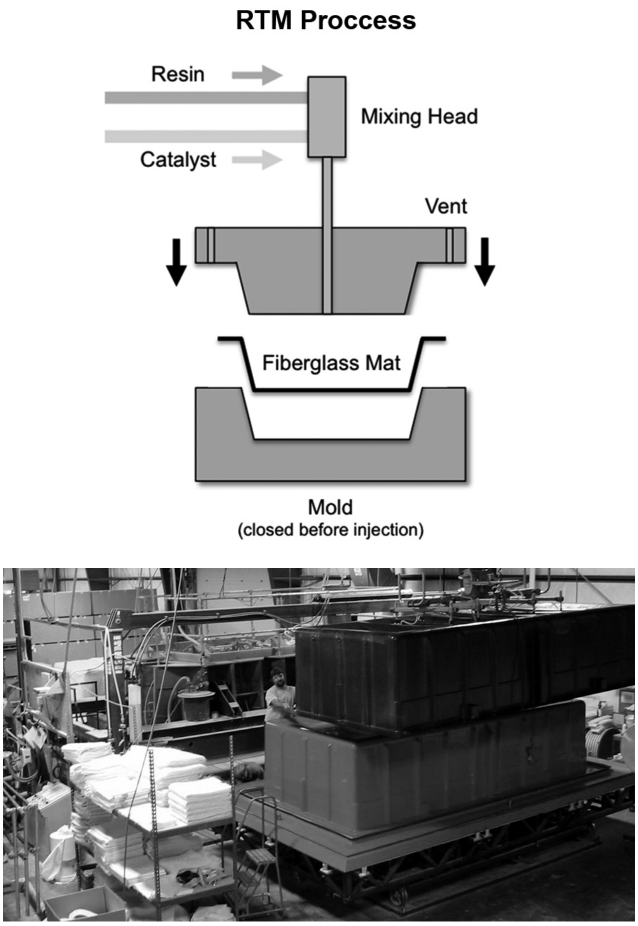

Fig. 2. Process diagram and example of a product manufactured by RTM method [17]

Rys. 2. Schemat procesu i przykład wyrobu wytworzonego metodą RTM [17]

The values of the pressures applied in the moulding of the products are much higher than when using a vacuum only and the two-sided moulds need to possess significant rigidity and precision [2, 3, 17], as this affects the quality of the products. The RTM method is a very efficient way of forming composites.

In this study 600 mm by 600 mm sheets were cut out of the fabric. Next, the fabric was arranged in layers with fibre strands parallel to one another. The arranged reinforcement phase was saturated, maintaining the parameters presented in Table 2. In each case, the height of the produced laminate was 4 ±0.6 mm.

TABLE 2. **Parameters of process for manufacturing laminates by RTM method**

TABELA 2. **Parametry procesu wytwarzania laminatów - metoda RTM**

Parameter		Value
Saturation temperature	[°C]	23
Saturation time	[s]	900
Curing temperature	[°C]	23
Curing time	[s]	259 200

The composition and markings of the composites produced are shown in Table 3. The shape and dimensions of the specimens were selected for each test in accordance with the requirements set out in the standards [18-21]. Specimens were cut out (from cold laminate sheets) by hand where possible with wood-carving knives or a guillotine, which achieved an even cut line without visible splinters.

TABLE 3. **Composition and marking of laminates manufactured with polyester matrix and various reinforcement fabrics (glass, carbon, jute)**

TABELA 3. **Skład i oznaczenie wytwarzanych laminatów o osnowie poliestrowej i różnym materiale tkaniny umocnienia (szklana, węglowa, jutowa)**

Item	Marking	Polyester resin	Glass fabric	Carbon fabric	Jute fabric	Density [g/cm^3]
1	GFRP	mass fraction of 60%	mass fraction of 40%	–	–	1.84±0.05
2	CFRP	mass fraction of 60%	–	mass fraction of 40%	–	1.57±0.03
3	JFRP	mass fraction of 60%	–	–	mass fraction of 40%	1.42±0.08

TESTING METHODOLOGY

The mechanical properties depend on the strain and stress on the structural members, which are primarily influenced by: the type and condition of the material, the shape and dimensions of the member, as well as the type and magnitude of the loading forces. The mechanical properties of the produced laminates were assessed using:

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- The hydrostatic method to determine the density of the produced composites (Table 3) according to standard PN-EN ISO 1183-1:2013-06 [18].
- The static tensile test, according to PN-EN ISO 527-1:2016 [19], for thin-beam-shaped specimens. The static tensile test is based on the single-axis strain of suitably prepared specimens and measurement of the tensile forces. This kind of testing is one of the main sources of information about the mechanical properties of plastics, and is also used to evaluate other properties of plastics. The Shimadzu testing machine (Fig. 3) was used in this work. The test involves measuring the maximum stress corresponding to the greatest tensile force obtained during the static single-axis tensile test, related to the initial cross-sectional area of the specimen. The specimen is fixed in the jaws of the tensile testing machine, the machine is started and continues until the specimen breaks. The data obtained was then read on the display screen.

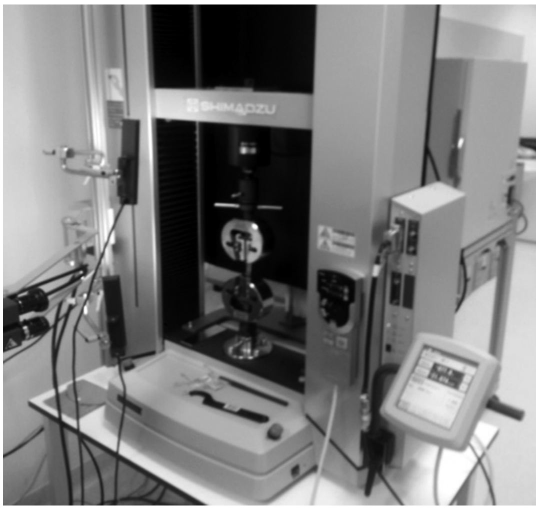

Fig. 3. Shimadzu testing machine used in the work

Rys. 3. Widok maszyny wytrzymałościowej Shimadzu użytej w badaniach

- Bending strength, according to PN-EN ISO 178:2011 [20]. The bending test is a commonly used strength test. It is particularly suitable for determining the mechanical properties of brittle construction materials, the characteristics of which are not fully reflected in the tensile test. The bending test consists of changing the original curvature of the longitudinal axis of a beam under the action of a system of forces perpendicular to the axis, acting in a plane containing the beam axis. Bending moment (M_g) and transverse force (T) act on the cross-section of the bent beam. In the cross-section, the bending moment is balanced by a system of normal stresses, while the transverse force is balanced by the resultant tangential stresses acting in the plane of the cross-section. The load comes from a force (P) in the middle of the beam and forces ($P/2$) against its supports at the beam ends (Fig. 3). In this case the greatest bending moment is (1):

$$M_g = \frac{P \cdot l_o}{4} \tag{1}$$

The greatest normal stress due to moment M_g is:

$$\sigma_g = \frac{P \cdot l_o}{4 \cdot W_g} \tag{2}$$

The deflection of the beam at the point where force (P) is applied is given by formula (3):

$$f = \frac{P \cdot l_o^3}{48 \cdot E \cdot J_y} \tag{3}$$

The bending strength is calculated with formula (4):

$$R_g = \frac{P_{\text{crit}} \cdot l_o}{4 \cdot W_g} \tag{4}$$

where: P_{crit} - critical force needed to destroy the specimen. In uncertain cases, the greatest force is the one that loads the specimen [N]; J - moment of inertia of the cross-section; W_g - moment of resistance to bending [mm^3]; l_o - as in the diagram [mm].

Impact strength testing is performed using the Charpy method on an unnotched specimen, according to standard PN-EN ISO 179-1:2010 [21]. Impact tests are dynamic tests which determine the ability of a material to withstand severe impact-type loads. They provide information on those mechanical properties which cannot be detected by static tests.

ANALYSIS OF TEST RESULTS

The rules for the classification and construction of sea yachts in part II Hull - describe the requirements for the construction to be made from polyester-glass laminates. These regulations describe which mechanical properties a material should possess, e.g. for a laminate containing 40% reinforcement the bending strength should be a minimum of 174 MPa [22]. The tested composites fulfil this condition.

The testing of selected mechanical properties has indicated that the type of reinforcement phase used significantly influences the properties of the composite (Table 4).

The lowest density was observed in the composites reinforced with natural jute fibres. It was 10% lower than that of the carbon-fibre-reinforced composites and 29% lower than that of the glass fibre composite materials.

In the static tensile tests, the highest strength was observed in the carbon-fibre-reinforced laminate, and the lowest strength was found in the natural-fibre-reinforced composite. When it came to the bending strength, the highest strength was observed in the glass-fibre-reinforced composite, namely 9% greater than in the CFRP composite and 23% more than the JFRP.

TABLE 4. **Summary of test results for selected mechanical properties of produced laminates, as marked in accordance with Table 3**

TABELA 4. **Zestawienie wyników badań wybranych właściwości mechanicznych wytworzonych laminatów oznaczonych zgodnie z tabelą 3**

Item	Material	Density ρ	Tensile strength R_m	Impact strength a	Bending strength R_g
		[g/cm^3]	[MPa]	[J/cm^2]	[MPa]
1	GFRP	1.84±0.05	43±6	22±2	539±24
2	CFRP	1.57±0.03	148±12	14±1	491±27
3	JFRP	1.42±0.08	32±3	16±2	413±19

In the Charpy testing the GRFP laminate displayed the highest impact strength (Table 4). The impact strengths of the CFRP and JFRP laminates were lower by 36 and 21%, respectively.

Having analysed the obtained results, it can be concluded that GFRP composites are characterized as having the best mechanical properties (bending strength and impact strength).

The prevailing destruction mechanism in laminates that are subjected to bending forces should be decohesion resulting from the tensile stress or shear stress of the matrix or the boundary layer, and breakage of the fibres in the stretched part of the specimen where these phenomena occur, before matrix destruction initiation. Therefore greater deformability of the fibre (Table 4) improves the strength properties of the composite.

Figure 4a-c shows the tested mechanical properties of the produced composites in relationship to their density.

Having analysed the obtained results, it can be concluded that the specific strengths obtained for the glass and natural fibres were similar, therefore the glass can be replaced with cheap jute fibres. Among the tested composites, the best mechanical properties (R_m and R_g) were observed in the carbon-fibre-reinforced composites. The composites with natural fibres performed only slightly worse than the glass-fibre-reinforced composites when taking into account the mechanical properties relative to their density. The natural fibre-reinforced laminates exhibit mechanical properties at a satisfactory level. All the analysed types of fibres have the appropriate characteristics and properties that allow them to be used in the design of composite products intended for different applications, e.g. for the hulls of small vessels.

The materials used for the hulls of small vessels, in addition to their strength properties, should be characterized by a low mass, resistance to damage as a result of collisions and resistance to atmospheric factors. In future work, the authors will investigate the influence of atmospheric and operational factors on the properties of composites utilizing natural fibres.

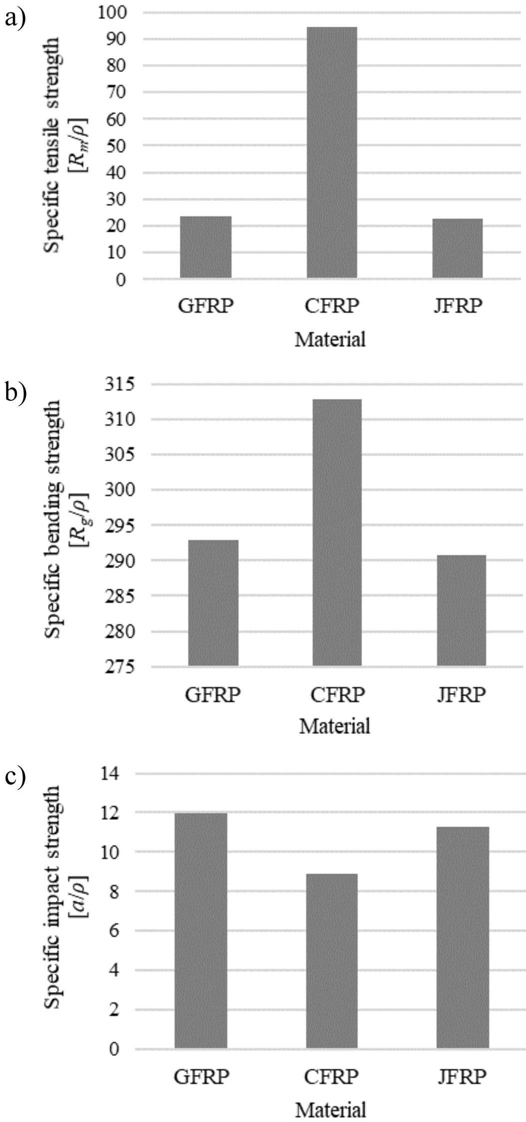

Fig. 4. Summary of tested mechanical properties of produced composites: specific strength: a) specific tensile strength, b) specific bending strength, c) specific impact strength

Rys. 4. Zestawienie badanych właściwości mechanicznych wytworzonych kompozytów: a) wytrzymałość właściwa na rozciąganie, b) wytrzymałość właściwa na zginanie, c) udarność właściwa

CONCLUSION

a) All the analysed types of fibres have the appropriate characteristics and properties that allow them to be used in the design of composite products intended for different conditions, such as the hulls of small vessels.
b) As expected, the best mechanical properties (R_m and R_g) were observed in the carbon-fibre-reinforced composites. The result was that the jute fibre composite cannot replace such materials in terms of their mechanical properties. The natural fibre-reinforced laminates exhibited mechanical properties at a satisfactory level.

c) The specific strengths obtained for the glass and natural fibres were similar, hence the jute fibres are an interesting alternative to synthetic fibres. The advantages of natural fibres are: favourable manufacturing cost, a green source of raw materials, and - in contrast to composites containing glass or carbon fibres - the possibility to obtain energy from waste.
d) To widen the applications of these fibres to solve the above mentioned environmental problems, further studies must be undertaken in future.

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