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APPLICATION OF POLYMER COMPOSITES WITH PLANT REINFORCEMENT USED IN MACHINE AND AIRCRAFT CONSTRUCTION IN CHANGEABLE ENVIRONMENTAL CONDITIONS

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Abstract

Plant reinforced composites are more widely introduced in the automotive or construction industry. Due to good thermal and acoustic insulation, low weight, economical and ecological benefits and limitations resulting mostly from low mechanical strength, they are used primarily as elements, which do not carry heavy loads. Yet, they perform decorative and insulating functions. Expanding the spectrum of usage is connected with analysing properties of these materials in various application conditions. The following article presents results of static tensile tests of composites reinforced with jute, linen and cotton used in changeable environmental conditions. The significance of influence exerted by such factors as water, hydraulic oil, technical lubricant and conditions of moderate climate were evaluated. Taking into account the potential possibilities of using composites with natural reinforcement in aircraft construction, e.g. in helicopters, the influence exerted by direct impact of aviation fuel were tested. It was concluded that different application conditions subject to research do not exert an identical influence on tested composites. Statistically significant influence on the change of tensile strength is exerted while application of cotton composites in water. Composites with jute lose their properties during usage in autumn moderate climate and in hydraulic oil. Conversely, composites reinforced with linen react negatively to the environment of technical lubricant and aviation fuel.

Keywords: *plant fibres, composites, application of composites, tensile strength, environmental conditions*

1. Introduction

Polymer matrix composites with plant reinforcement are more frequently used in machine construction. Their usage is most noticeable in the automotive and construction industry. In aeronautics, in the initial phase of its development, also naturally occurring materials were used. However, with the advancement of aeronautics and material technology, especially those connected with light metal alloys, plant materials ceased to be used. Nevertheless, technological advancement and constant search for the lightest materials make scientists and practitioners interested in the application of composites with the use of natural raw materials. Undoubtedly, such characteristics of plant fibres composites as high coefficient of acoustic and thermal insulation, deadening vibrations and low density of composite slightly higher than that of resin itself [7] are advantages, which are in favour of their usage despite relatively low mechanical strength. Additionally, natural materials introduce another currently significant aspect – the ecological one. Natural fibres are produced from renewable resources, which are relatively cheap. Low energy processing is connected with lower emission of carbon dioxide [4, 20]. Therefore, nowadays composites with natural reinforcement are becoming increasingly popular. Consequently, there is a need to determine various properties of these composites and to test their application possibilities in changeable environmental conditions.

The most significant faults of natural fibres are heterogeneity of structure and chemical composition dependent on conditions of their manufacture including extraction techniques and storage conditions [14]. Moreover, natural fibres are distinguished by low temperature of thermal decomposition and hydrophobicity [13, 18]. Owing to the mentioned characteristics, in order to obtain products of good quality, one spares no effort during the manufacture of composites unlike during the production of composites for instance reinforced with glass fibres. Natural composites are most frequently used to produce elements of car interiors (e.g. BMW, Mercedes, Toyota, Ford) such as: upholstery, door panels, car floor mats, seats and small exterior elements such as: engine cover and casing, wings, wheel arches, bumpers and body side moulding.

In military aviation, for the time being, usage of these composites is limited, yet there are some noticeable application benefits in helicopter construction, civil aviation and constructing unmanned air vehicles. Natural composites can be used as building materials for parts such as: elements of on-board equipment, antenna casings or covers. Nevertheless, the process of application of these solutions is difficult and slow due to security issues as well as strength properties.

New applications require extensive testing of both properties and particular parts of these materials. Accelerated tests in adverse external conditions are frequently conducted. The procedure is to monitor changes of properties during these tests and evaluate changes of final data in relation to the initial state. Conducting tests during the influence of harmful conditions is technically difficult and relatively expensive, which results in adopting the second direction of accelerated research. In the majority of cases, tests of polymer composites as a group of materials rely on standard tests, whose objective is to determine mechanical strength of simple cases of static and cyclic loading. Introducing marking the influence of operational factors into these tests is less frequently adopted. Most often, the influence of hot air on the change of mechanical properties, mainly flexural or tensile strength is tested [3, 11, 12, 15, 16]. As for other application conditions, water absorbency and its influence on specific properties of composites are evaluated [2, 16]. In the whole research, an adverse influence of these factors on maintaining mechanical strength was proved. In the case of dynamic research, the numbers of cycles, which precede failure of the material, are the basis for deciding on the applicability of a composite [10]. For instance, sisal-reinforced polyester matrix composites can be loaded with a force causing stress of 200 MPa with a frequency of 2 Hz. Several thousands of load cycles do not cause their damage [19].

Considering the dynamic development, presented tests and characteristics of natural fibres, it is justified to undertake research aimed at determining the influence of changeable application and environmental conditions on the change of mechanical properties of naturally reinforced composites for application in machine construction. The following paper focuses on tests determining various application conditions on the change of tensile strength of linen, cotton and jute reinforced composites. Results can also be used in predicting the behaviour of composites during a real application of readymade products [6].

2. Materials and research method

Tests were conducted in order to determine the influence of various application factors on the ability of maintaining a specific mechanical property by plant-reinforced composites.

Composites with C.E.S. R70 epoxy resin matrix and H71 hardener were used. The reinforcement used was produced from fabrics made of natural fibres such as cotton, linen and jute. Surface density of reinforcing fabrics was respectively: 130, 320 and 340 g/m^2. Six-layer laminates were manufactured by means of the press method, where pressure was 0.48 MPa. Composites were subject to the following application conditions:

- "water": immersion in water, time of exposure – 48 hours (absorbency tests: after 24 hours, absorbency was approximately 8% w/w on average for linen and jute, after one month – 12 %, for cotton – 12 % after 24 hours and 14% after 30 days),
- "oil": immersion in Nuto H46 hydraulic oil of kinematic viscosity equaling 46 cSt at a temperature of 40°C, the oil is used in hydraulic systems of machines, 48 hours (average oil absorbency for all composites: after 24 hours – 2%, after one month – 2.2%),

- "autumn": direct exposure to the influence of environment in conditions of moderate climate in October in Lublin in 2014, 30 days (changeable weather conditions: rainfall, solar radiation);
- "grease": cover made of AeroShell Grease 7 technical grease, time of exposure – 30 days,
- "fuel": immersion in Avgas 100LL aviation fuel containing tetraethyl lead in the quantity less than 0.1%, time of direct contact was set for 30 days (in initial test, after 20 days when composites were immersed in fuel, there was a stabilization of samples).

After completing the period of application, composites were cleaned and were underwent strength tests. The tensile test was performed by means of the Zwick/Roell Z100 strength device. Tensile stress at break, relative elongation at break and longitudinal elasticity modulus E were established. The multiplicity of samples each time was 15 items. Tensile velocity was 2 mm/min.

A statistical analysis was performed by establishing basic descriptive statistics and conducting the Shapiro-Wilk test. This test is the most sensitive statistical test in this scope. Additionally, correlation with standard distribution was established. W statistics is calculated by means of the following equation 1 [9]:

$$W = \frac{\left[\sum_{i=1}^{k} a_i (x_{n-i+1} - x_1)\right]^2}{\sum_{i=1}^{n} (x_i - \overline{x})^2}, \tag{1}$$

where $(x_{n-i+1} - x_i)$ is calculated for $i = 1, 2, \ldots, k$ at $k = (n+1)/2$ if n is odd, and $k = n/2$ for even n. a_i coefficient is read off from statistical tables at known multiplicity of n_1 and n_2.

Next, after obtaining information about numerous cases of lack of correlation with standard distribution, a nonparametric U Mann-Whitney test for two independent trials was conducted statistically evaluate the significance of influence exerted by application factors on the mechanical properties of composites. The U Mann-Whitney test is based on calculating the U statistics at $n \le 20$ multiplicity of trials. It is expressed by means of the following equations 2 and 3, from which the lowest value is selected [5]:

$$U(n_1) = n_1 n_2 + \frac{n_1(n_1+1)}{2} - \sum_{i=1}^{n_1} R_{1i}, \tag{2}$$

$$U(n_2) = n_1 n_2 + \frac{n_2(n_2+1)}{2} - \sum_{i=1}^{n_2} R_{2i}, \tag{3}$$

where $\sum_{i=1}^{n_1} R_{1i}$ and $\sum_{i=1}^{n_2} R_{2i}$ are a sum of ranks tied to individual results in both groups of n_1 and n_2 multiplicity. U statistics should accord with the 4 and 5 equations:

$$n_1 n_2 = U_1 + U_2, \tag{4}$$

$$\sum_{i=1}^{n_1} R_{1i} + \sum_{i=1}^{n_2} R_{2i} = \frac{(n_1+n_2)(n_1+n_2+1)}{2}. \tag{5}$$

In order to fulfil the hypothesis concerning the significance of variance, U statistics must be lower that the U_{kr} critical value read off from the table relevant to the adopted α confidence level (usually $\alpha < 0.05$) as well as n_1 and n_2 multiplicity of groups [17].

In the case of bigger multiplicity of groups, z statistics according to the Z test and the following equation 6 is calculated:

$$Z = \frac{U - \frac{n_1 n_2}{2}}{\sqrt{\frac{n_1 n_2 (n_1 + n_2 + 1)}{12}}}. \tag{6}$$

If the z value is close to the z_{kr} critical value, an equation with the so-called continuity correction or correction including tied ranks is used if such occur [17]. Similarly, at U and z statistics, z_{kr} value is read off from statistical tables. Additionally, z values must be lower than z_{kr} critical values to fulfil the hypothesis concerning the significance of variance.

3. Test results and discussion

Composites were subject to strength tests before their application in unfavourable application conditions. These composites were called "Basis" since test results obtained for these composites were a starting point for interpreting the influence of application factors. The greatest tensile strength among non-applied composites was observed in the case of cotton-reinforced composites, whereas the lowest – jute-reinforced composites. Simultaneously, in some application conditions, this order is changed (Fig. 1). Fig. 1 presents results of stress measurements at the static tensile test as histograms with a distribution of results in a given group and accompanying box and whiskers diagram showing such statistical information as median, minimum, maximum, lower and upper quartile as well as outliers. The biggest standard deviation and standard error were observed among cotton-reinforced composites. Generally speaking, all composites show a high variation coefficient and high standard deviation. It is a consequence of great structural heterogeneity of composites, which results from diverse properties between single fibres of the same type. Moreover, heterogeneity of composites is influenced by the occurrence of faults in the form of air bubbles, which get inside composites during the technological process of their manufacture.

Characteristics of the tensile process change only slightly in the case of water, grease and aviation fuel influence (Fig. 2). Generally speaking, relative elongation during the tensile test performed on epoxy cotton and linen-reinforced composites ranges from 9% to 11% independent on the application method. On the other hand, jute-reinforced composites are distinguished by approximately 6% elongation after application in grease and fuel. In other cases, their average relative elongation equals approximately 4%. Young's modulus of all composites is small. In none of the application cases does it exceed 6 GPa for cotton composites and 4.5 GPa for linen ones. Conversely, 5 GPa is the upper limit for jute-reinforced composites.

Heterogeneity of composites and in consequence considerable variance of results also influence their distribution. Irregularities visible on histograms are emphasized by the dissymmetry of distribution. In some cases, skewness significantly diverges from the zero value. Results of the Shapiro-Wilk test indicate that half of the tested groups accords with the standard distribution (Tab. 1). Standard distribution for W statistics with p probability fitting within the confidence range $\alpha < 0.05$ was marked in the red in the table. Cotton-reinforced composites were marked with B. L and J is respectively symbols for linen and jute reinforcement.

Tab. 1. Results of the Shapiro-Wilk test (description of symbols within the text)

S-W	Basis			Water			Oil			Autumn			Grease			Fuel		
	B	L	J	B	L	J	B	L	J	B	L	J	B	L	J	B	L	J
W	0.794	0.914	0.971	0.902	0.945	0.868	0.776	0.916	0.800	0.825	0.911	0.912	0.729	0.943	0.689	0.905	0.853	0.685
p	0.003	0.157	0.870	0.103	0.449	0.031	0.002	0.167	0.004	0.008	0.140	0.145	0.001	0.422	0.000	0.112	0.019	0.001

Various conditions of application show a different influence on naturally reinforced composites. On the basis of average tensile stress values of composites after application, in relation to average values of tensile stress of composites which had not been subject to the influence of environment,

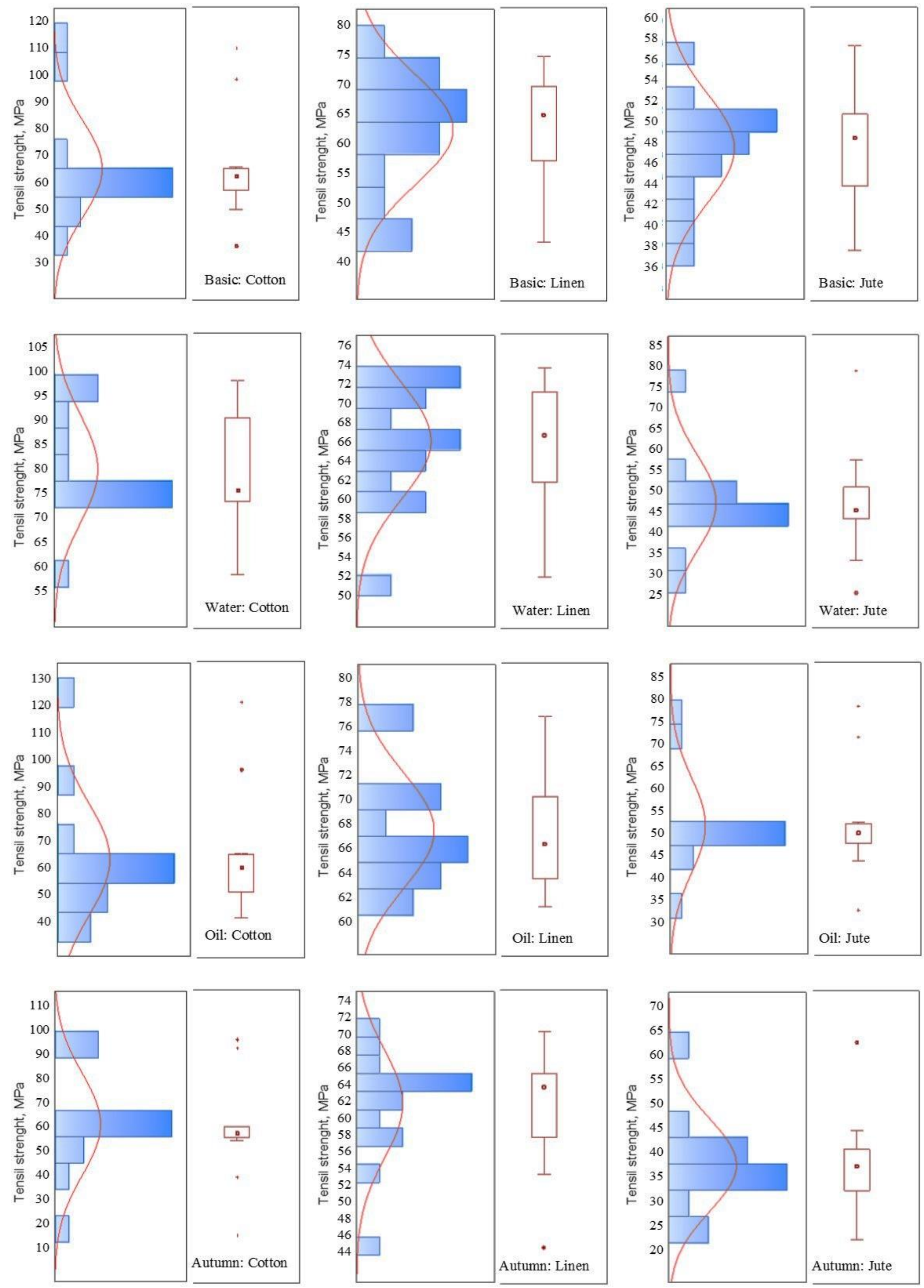

Fig. 1 Tensile strength of cotton, linen and jute reinforced composites subject to application in various conditions (description provided in the text)

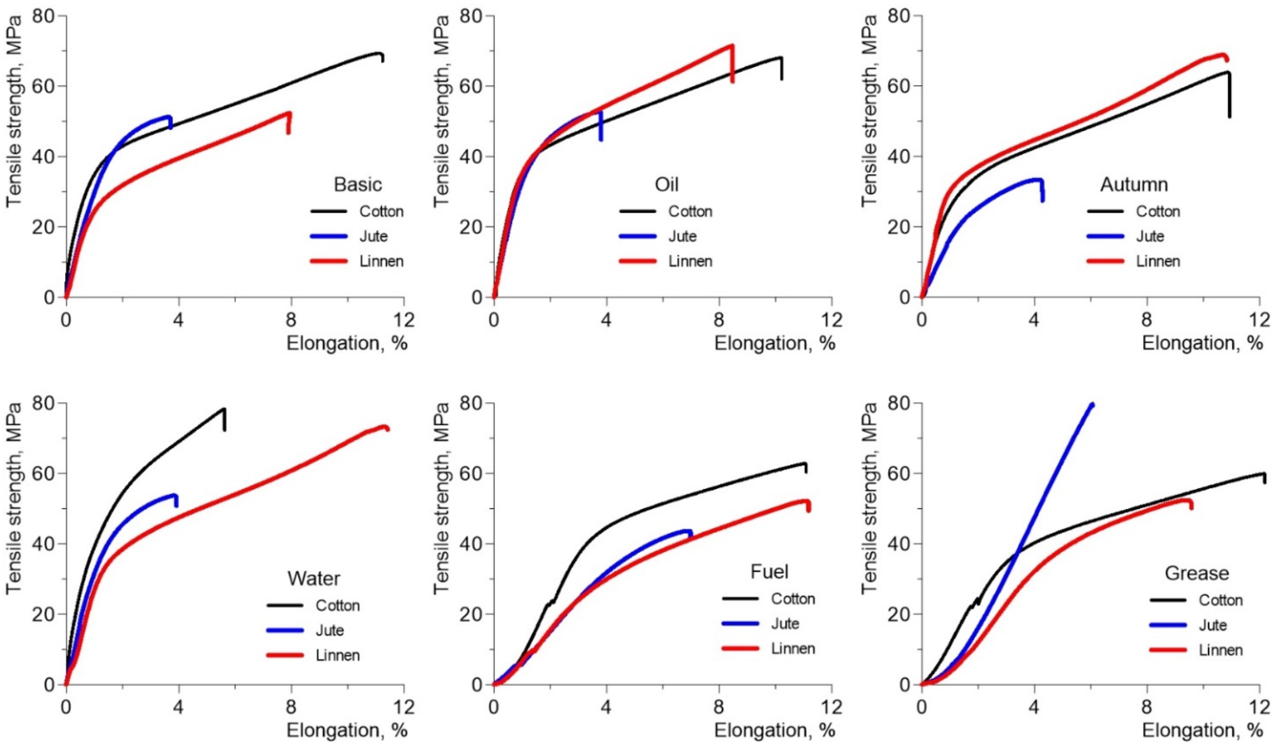

Fig. 2. Sample tensile test results of natural composites

s percentage differences were established. The line on the level zero (Fig. 3) is a line corresponding to the average tensile strength of non-applied composites.

Positively written markers stand for the increase in this strength. The lowest influence of changes in the static tensile test of the researched composites was exerted by their exposure to hydraulic oil. Conversely, the highest influence was exerted by weather conditions, grease and fuel. Simultaneously, the forty-eight-hour influence of water results in an increase in tensile strength. Other factors of application, except for oil, have rather negative effects. The above discussion of results is partly confirmed by the variance analysis, which includes standard deviation of the obtained results.

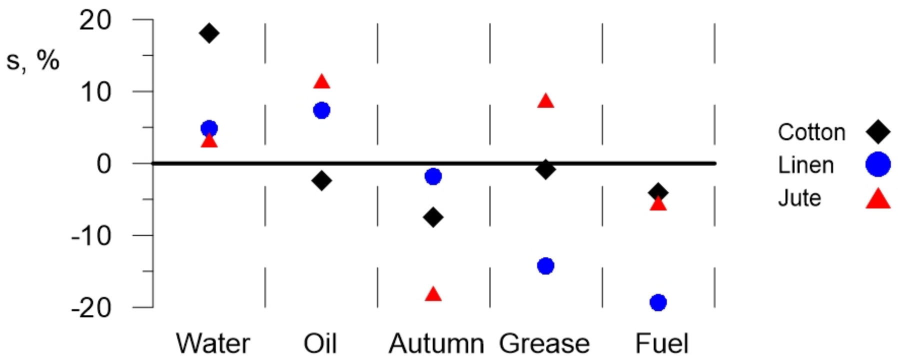

Fig. 3. Percentage change of tensile strength s in relation to non-applied composites

The conducted analysis of variance with the use of the U Mann-Whitney test points to the significance of the water influence on tensile strength only in relation to cotton-reinforced composites provided the $\alpha < 0.05$ confidence range is adopted. A significant decrease in the flexural strength appears also after the application of linen-reinforced composites in the environment of technical grease and aviation fuel. Aviation fuel has also an adverse influence on mechanical properties of jute-reinforced composites. The *p* probability exceeds the assumed level of significance, yet it is only by 0.001. Jute is sensitive to the influence of hydraulic oil and conditions of moderate climate. The discussed results are presented in Tab. 2, where the statistic significance of changes of the static tensile strength among naturally reinforced composites is marked with red. The U_{kr} = 64 value of statistics is read off from statistical tables at two groups of $n_1 = n_2 = 15$ multiplicity.

Tab. 2. Significance evaluation of groups subject to the influence of different environmental conditions in relation to the non-applied group according to the U Mann-Whitney test

Reinforcement	Sum of ranks of the basis group	Name of the second group	Sum of ranks of the second group	U	p
Cotton	160	Water	305	40	0.003
	253	Oil	212	92	0.407
	275	Autumn	190	70	0.081
	264	Grease	201	81	0.199
	262	Fuel	203	83	0.229
Linen	208	Water	257	88	0.320
	202	Oil	263	82	0.213
	254	Autumn	211	91	0.384
	302	Grease	163	43	0.004
	314	Fuel	151	31	0.001
Jute	225	Water	240	105	0.772
	177	Oil	288	57	0.023
	314	Autumn	151	31	0.001
	245	Grease	220	100	0.619
	280	Fuel	185	65	0.051

4. Conclusion

Plant fibres reinforced composites manufactured by means of the press method show a high variance of results. In many cases, it is not consistent with standard distribution. Undoubtedly, to a large extent, it is a consequence of structural heterogeneity, which results from the very structure of fibres. It was concluded that various application conditions included in the testing agenda do not exert a uniform influence on the tested composites. Statistically significant influence on the change of tensile strength is exerted by application of cotton composites in water. Jute-reinforced composites lose their properties during usage in conditions of moderate climate in autumn and hydraulic oil. Nevertheless, linen-reinforced composites react negatively to the environment of technical grease and aviation fuel.

To sum up, application conditions described in the paper do not certainly and unequivocally exclude naturally reinforced composites from the potential usage for construction elements of machines and aircraft. Therefore, it is justified to continue research in order to conduct a detailed verification of properties among composites following their application. Test results will allow for determining critical states of tensile stress in various application conditions of composites.

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