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Daniel Pieniak, PhD, Asst. Prof.
The Main School of Fire Service
e-mail: dpieniak@sgsp.edu.pl
ORCID: 0000-0001-7807-3515

Agata Walczak, PhD
The Main School of Fire Service
e-mail: awalczak@sgsp.edu.pl
ORCID: 0000-0002-0303-1748

Wiktor Wąsik, MSc
The Main School of Fire Service
e-mail: wwasik@sgsp.edu.pl
ORCID: 0000-0002-0934-3961

Sławomir Siwiec, Eng.
graduate student at the Faculty of Security Engineering and Civil Protection, The Main School of Fire Service
e-mail: 13719@student.sgsp.edu.pl

Piotr Piątek, MSc
The Main School of Fire Service
e-mail: ppiatek@sgsp.edu.pl
ORCID: 0000-0001-8594-2889

Ireneusz Naworol, PhD
The Main School of Fire Service
e-mail: anaworol@sgsp.edu.pl

TESTS OF THE MECHANICAL STRENGTH OF SELECTED CLIMBING ROPES USED BY THE STATE FIRE SERVICE WITH RESPECT TO DAMAGE OCCURRING DURING RESCUE OPERATIONS

Abstract

The paper deals with the issue of mechanical strength of climbing ropes. These ropes are exposed to the influence of exploitation factors both during training and in rescue operations. Among others, they may sustain mechanical, thermal and chemical damage. The study attempted to provide an evaluation of the effect this damage has on the mechanical strength and extensibility of ropes. The tests were carried out in laboratory conditions, and the courses of force in the function of deformation and impact of force on deformation were recorded. An unfavourable influence of some types of damage on the strength and extensibility of ropes was demonstrated. Mechanical and thermal stresses mainly cause damage to the rope sheath. Their effect on endurance is similar. The remaining strength of the rope is slightly above the minimum allowable tensile strength. On the other hand, the chemical treatment did not cause a noticeable decrease in the rope's strength.

Keywords: climbing ropes, strength, operational damage

BADANIA WYTRZYMAŁOŚCI MECHANICZNEJ WYBRANYCH LIN ALPINISTYCZNYCH WYKORZYSTYWANYCH W PSP ZE WZGLĘDU NA USZKODZENIA POWSTAJĄCE W DZIAŁANIACH RATOWNICZYCH

Abstrakt

W pracy podjęto problematykę wytrzymałości mechanicznej lin alpinistycznych. Line te narażone są na oddziaływanie czynników eksploatacyjnych w warunkach ćwiczeń i działań ratowniczych. Mogą powstawać m.in. uszkodzenia mechaniczne, termiczne i chemiczne. W pracy oceniono wpływ uszkodzeń na wytrzymałość mechaniczną i rozciągliwość lin. Badania wykonano w warunkach laboratoryjnych, rejestrowano przebiegi siły w funkcji odkształcenia oraz pracę siły na odkształceniu. Wykazano niekorzystny wpływ niektórych typów uszkodzeń na wytrzymałość i rozciągliwość lin. Narażenia mechaniczne i termiczne uszkadzają głównie oplot liny. Ich wpływ na wytrzymałość jest podobny. Pozostała wytrzymałość liny w niewielkim stopniu przewyższa minimalną dopuszczalną wytrzymałość na rozciąganie. Natomiast działanie środkiem chemicznym nie spowodowało zauważalnego spadku wytrzymałości liny.

Słowa kluczowe: liny alpinistyczne, wytrzymałość, uszkodzenia eksploatacyjne

Introduction

Climbing lines are made of natural and synthetic materials [1]. Ropes made of cotton fibres, flax, hemp, coconut, banana leaves and sisal are well known. Nowadays, ropes based on natural fibres have been almost completely substituted by ropes made of plastic. They are made of polypropylene, polyester, polyethylene, polyamide and a plastic of the polyamide group bearing the trade name Kevlar [2]. The issue of rope strength deterioration has been addressed by diverse researchers. In the work [3] it has been noted that the number of dynamic loads that can arise during usage, e.g. during uncontrolled lowering on the rope or falling off, translates into a change in the rope's elastic properties. Moreover, Leuthäusser [3] has proven that cyclical dynamic loads become transposed on accumulation of local damage according to the earlier hypothesis of Palmgren-Miner [4]. Such operational work tends to reduce the elastic elongation of some climbing ropes by 30% [3]. In another research the impact of chemical damage has been investigated. Study [5] attempted an assessment of extinguishing foam on strength properties of climbing ropes. The lines have been subjected to exposure in extinguishing foam for a period of 60 days. A moderate reduction in mechanical strength (from 38 kN to 33.3 kN) was demonstrated for only one of the four types of ropes tested. In the paper [6] an analysis was carried out of the impact of accidental partial cutting of the climbing rope by a handsaw. It was measured how much of the rope's diameter is cut by the saw blade, as well as the strength loss of the rope after it has been cut (in percentage terms). The researchers showed that the type of blade was a more important factor than the type of rope, as far as the degree of notching and the percentage loss of strength by the rope were concerned, and a high correlation between these variables was recorded [6].

This study attempts to find whether the occurrence of mechanical, thermal and chemical damage affects mechanical properties that determine the load capacity of the climbing rope. The answer to this question is of a utilitarian significance, because the undertaken research problem translates into the level of danger for firefighters-rescuers during rescue operations. It should be emphasised that as regards climbing ropes, diagnostics tend to be performed only in a qualitative way by visual inspection. In practical terms the assessment is left to the personal judgement of the user, leaving considerable margins of uncertainty as to the actual condition of the rope [7]. Therefore, the authors of this paper presented the results of conducted research in quantitative terms. Taking into account the above considerations, the aim of the work was to experimentally determine the influence of selected operational failures on mechanical properties of static climbing ropes used in the State Fire Service (SFS) operations.

Object and method of research

The subject of the tests was a static climbing rope Tendon 4work L105TW47S200R. Table 1 shows the rope properties declared by the manufacturer. The Tendor static line is intended for mountaineering activities. It is a rope with a low stretch level, which makes it appropriate to use in the State Fire Service, among others when working at a height and when saving people.

Table 1. Features of the Tendon 4work L105TW47S200R line

Diameter	10.5 mm
Weight of 1 metre	69 g
Colour	black
Material	Polyamide (PA)
Type	A
Minimum number of falling offs	20
Mass of external braid	36%
Braid feed	-3 mm
Elongation 50/150 kg	2%
Shrinking	1.9%
Tensile strength	30 kN
Strength with knots	Min. 15 kN
Standards	CE 1019, EN 1891

Source: own study on the basis of manufacturer's data [8]

For needs of the tests, 12 rope sections, each approximately 2500 mm long, were prepared (Fig. 1a). A loop knot with a mesh diameter of 12 cm was tied at their ends (Fig. 1b). According to [9] this type of a knot causes a decrease in the strength of undamaged rope by 50%. The specimens were divided into four groups (Figure 1a), and artificial damage was applied to three groups. Artificial damage simulated in this study may also occur during normal operation. Mechanical damage or abrasion may take place during the cyclic movement of the loaded rope over the edge or along a rough surface. This phenomenon can occur while working in caves, climbing a rope in the mountains, or saving people. Thermal damage can be caused by friction (which increases the temperature), radiating heat sources (e.g. when drying ropes near the furnace), open fire or sparks, or contact with hot surfaces. On the other hand, chemical damage may take place due to the exposure of the ropes to chemical substances, which is possible during transport, rescue operations, as well as cleaning and storing of the ropes. Both aggressive liquids and vapours may affect the ropes. They included thermal damage (fig. 2a) – in mid-length of the samples a heat treatment was carried out using a gas burner (natural gas) so that the tongue of the flame touched the line braid for 10 seconds, causing damage to the rope braid; mechanical damage (fig. Mechanical (fig. 2b) – the rope was abraded in its mid-section with a sharp edge of a rough stone for 1 minute (oscillating movement) causing the braid to break to the visible core; Chemical (fig. 3c) – the middle section of the rope sample having a length of approx. 20 cm was immersed in the cleaning agent "Puracid" with an acid reaction ph = 0.5.

a) b)

Fig. 1. Samples of climbing rope Tendon 4work L105TW47S200R

Source: own study

a) b) c)

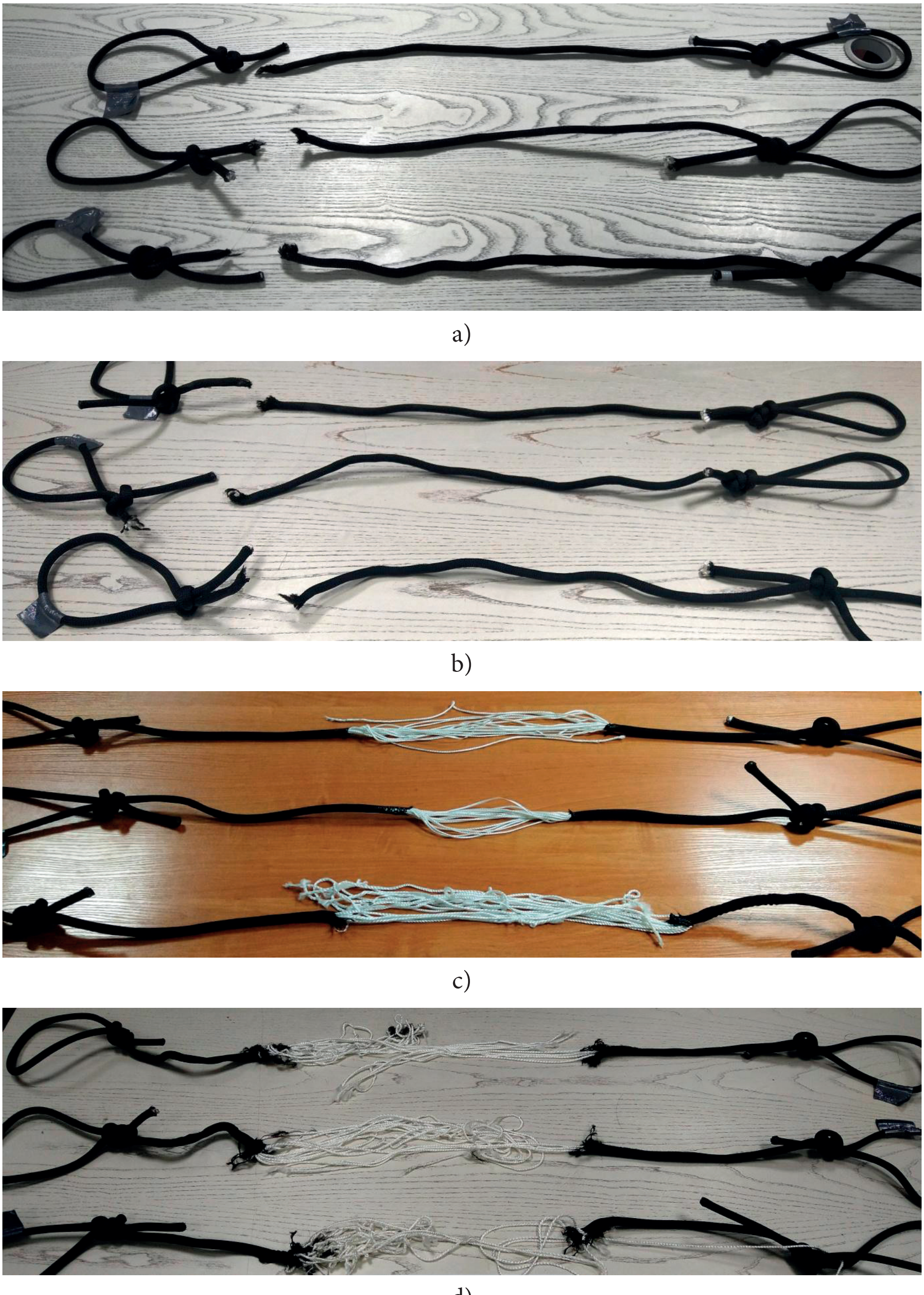
Fig. 2. Rope samples during strength testing: a) thermally damaged rope sample, b) mechanically damaged rope sample, c) mounting of chemically damaged rope (damage not visible during macroscopic examination) in the grips of the testing machine

Source: own study

Tensile tests were carried out on a Zwick/Roell Z100 testing machine. The method of gripping the specimens is shown in Figure 2c. A load cell with a nominal range of 100 kN was used in the tests. The test speed was 200 mm/min. The testing was continued until the specimens failed.

Results of tests

First of all, the deterioration of the rope samples was analysed in a qualitative way. Figure 3 presents photographs showing damaged samples. We can see differences caused by the dissimilarity of the destruction mechanism of rope structures depending on the sustained damage. As regards samples with no sustained damage (fig. 3a) and those with thermal conditioning (fig. 3b), cracking of the line was found to be similar. The rope braid and core would become broken concurrently. In the case of mechanically and thermally damaged samples, the damage acquired



a)

b)

c)

d)

Fig. 3. Forms of failure of climbing rope samples: a) undamaged rope, b) chemically damaged rope, c) thermally damaged rope, d) mechanically damaged rope (friction)

a different form (Fig. 3c and 3d). First, the continuity of the braid fibres was broken and then successive core fibres broke in stages. This means that the core fibres did not break simultaneously (Fig. 4). When the load reached the strength of the rope, the remaining bundle of core fibres broke.

The behaviour of the ropes under load was also analysed in a quantitative way. This was done based on parameters in line with mechanical quantities. Graphs and tables show the values of these quantities in a way that allows comparison according to the type of damage.

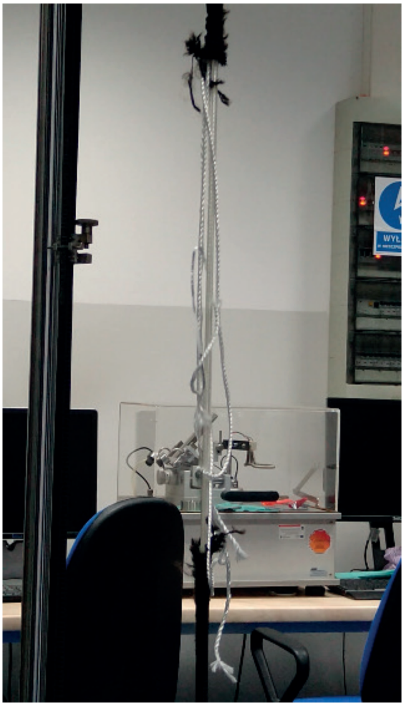


Fig. 4. The course of rope core destruction with mechanical (frictional) damage of a staged character. Visible broken single fibres of the core during load increase

Figure 5 presents the results of static elongation tests of ropes. The elongation of the rope under a load of 80 kg was established. The standard for dynamic ropes EN 892 [10] anticipates deformation that does not exceed 10%. The graphs are therefore related to this strain range, even though the comparison is indicative for static ropes. Differences in the behaviour of the ropes have been shown. It was observed that chemically and mechanically damaged ropes achieved a deformation of 10% well below the assumed load, i.e. approximately 30 kg and 20 kg respectively. In comparison, the undamaged rope achieved a deformation of 10% under a load of ca. 65 kg, while the heat damaged rope at approx. 55 kg.

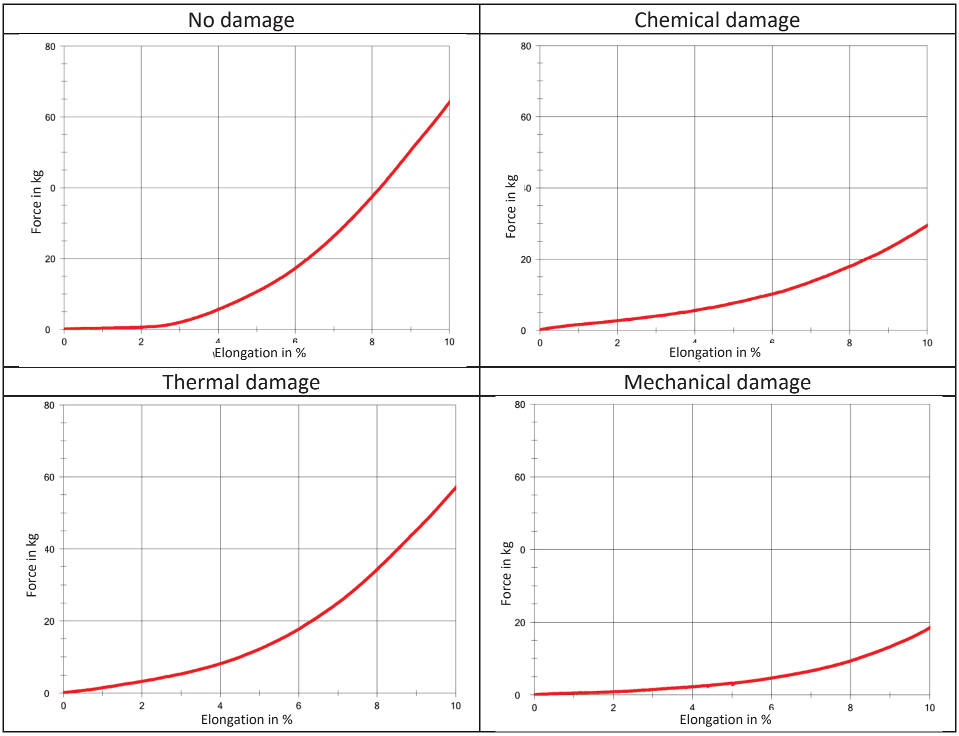


Fig. 5. Force in kilograms at a 10% elongation

Figure 6 shows the force vs. elongation curves of the rope. These are the load courses of sample ropes up to the moment of their failure (rupture). In the case of type A static ropes, the technical standard EN 1891 [11] assumed the tensile strength of ropes with knots. At this point, it is worth clarifying that this is not a concept expressed in terms of stress, as it is accepted in the fundamentals of strength of materials [12]. It is expressed as a force whose minimum value should be 15 kN for ropes within a diameter range of 8.5 – 16 mm. In this work, this parameter is indicated as F_{max} (table 2). For the undamaged and chemically damaged rope samples, the minimum strength condition was met, as well as for the average strength of all the samples in the series (Table 2). But for some thermally and mechanically damaged specimens, the condition has not been met, and the average values in Table 2 are exactly 15 kN. Table 2 also shows the values of elongation at maximum force (dL at F_{max}). The average values were found to vary. The highest average elongation was shown for chemically conditioned and the lowest for heat-treated samples. It is likely that this is related to the damage to the polymeric structure of the rope materials, which had already been demonstrated for polyamides [13].

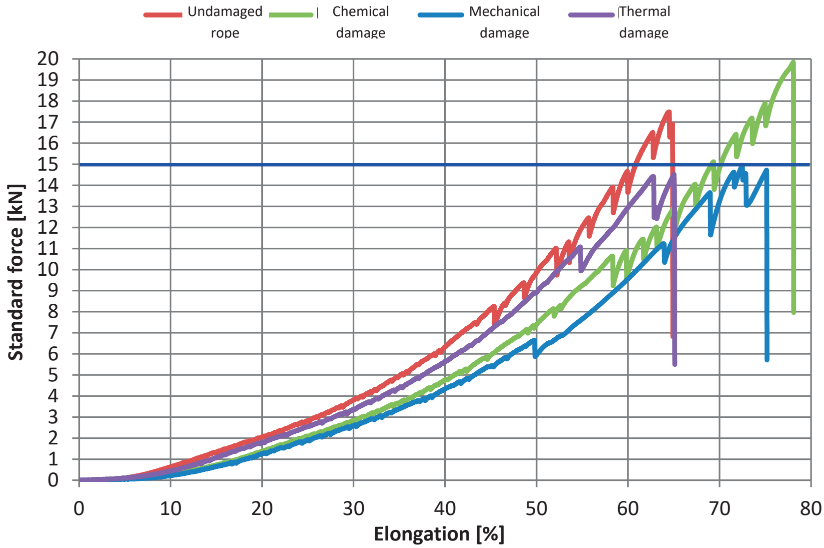


Fig. 6. Comparison of selected force-extension characteristics in relation to the required minimum strength of ropes with knots according to EN 1891

Table 2. Descriptive statistics for tensile strength test results

Series	E_{mod}	F_{max}	dL at F_{max}	F_{destr}	dL at failure	W to F_{max}	W until failure	$t_{testing}$
n = 3	MPa	N	mm	N	mm	J	J	s
No damage (control group)								
x	133	16700	522.2	6230	528.8	2770.45	2867.88	440.07
s	29.3	1160	21.2	354	26.2	134.67	68.25	65.85
n	22.06	6.93	4.07	5.67	4.96	4.86	2.38	14.96
Chemical damage								
x	114	18300	559.6	7070	559.8	3185.15	3188.72	492.81
s	14.6	1930	39.9	787	39.9	464.54	464.35	59.05
ν	12.85	10.58	7.13	11.14	7.12	14.58	14.56	11.98
Thermal damage								
x	142	15000	504.0	5600	508.2	2568.61	2628.44	417.19
s	10.8	1000	18.5	478	16.3	175.20	160.13	16.73
ν	7.61	6.69	3.66	8.54	3.21	6.82	6.09	4.01
Mechanical damage								
x	121	15000	537.6	4890	552.6	2545.92	2748.62	491.17
s	6.82	773	22.5	524	19.3	54.17	17.39	48.52
ν	5.64	5.17	4.19	10.73	3.50	2.13	0.63	9.88

E_{mod} – modulus of elasticity, F_{max} – maximum force, F_{destr} - force at failure, dL - elongation, W – work, t - time

The force at failure (F_{destr}) also varied. It was higher for undamaged and chemically conditioned specimens and lower for thermally and mechanically damaged specimens. As in the case of Fmax, elongation (dL at failure) was also specified for F_{destr}. The energy absorbing capacity of the rope was expressed by the impact of force on deformation, in the first case up to the maximum force (W to F_{max}). F_{max} is the force above which the process of intensive failure of the rope specimen occurs. The impact of force on the deformation until failure was determined by the parameter (W to failure). The values of both quantities are shown in Table 2. Both parameters are energy quantities, which refer to the energy absorbing capacity and are determined by the area under the load-deformation diagram of the specimen [14]. In a sense, this quantity expresses the amount of energy required to obtain a given state of deformation or the work involved in destroying the sample [15]. In the case of ropes, it is the ability to absorb the forcing energy, e.g. in a situation of falling off and the energy of the fall being captured by the rope. The highest value of these quantities was obtained for chemically conditioned ropes, which is related to the increased stretch and strength of the ropes after conditioning. This is a condition unexpected by the researchers. Heat damage is unfortunately the most unfavourable for this magnitude.

The modulus of elasticity is a measure which, in the case of tested ropes characterised by the non-preservation of a material continuum, can only be assessed indicatively. But this quantity characterises stiffness, which in the case of ropes is related to extensibility. It can be interpreted in such a way that the higher the modulus of elasticity (E_{mod}), the lower the rope's susceptibility to stretching (extensibility). The higher the extensibility, the higher the capacity of the rope to absorb and dissipate forces, and the lower the redistribution of forces towards the rescuer [16]. The highest values of E_{mod} were observed in thermally damaged samples, which may confirm the above assumption of changes taking place in the plastic structure after flame exposure. It has already been shown that thermal treatment of cured polyamide can cause changes leading to an increase in the proportion of the crystalline phase in relation to the amorphous phase in the plastic [17]. This transformation translates into an increase in the hardness and stiffness of the material but also in its brittleness, which may be reflected in the low strength (F_{max}) and deformability (dL at F_{max}) of these samples.

Discussion

Firefighters-rescue personnel use mountaineering ropes in specific rescue situations, for example to protect the victim from falling, to evacuate people, animals and property by pulling, lowering and descending with belaying to the victim and for self-rescue, but depending on the needs that arise from the specific nature of the protected area, it is possible to extend those operations [18]. A firefighter should have the capacity for using rope techniques intended to allow them to reach below ground level by executing ascent, descent or belay and to reach above ground level by belaying from above [18]. In the specialised area, high-altitude rescue is carried out by high-altitude rescue groups demonstrating their operational readiness A or B or AS or BS depending on equipment capabilities, number of rescuers and their training. Tasks for readiness level S include all A and B readiness tasks as well as the use of rope techniques and specialised equipment from a helicopter [18]. Unfortunately, the preparation and execution of such rescue tasks involves damage that can be sustained by the equipment. The damage concerns in particular the climbing ropes, on which the effectiveness of the rescue action depends to a large extent. Damage to ropes can increase the level of danger to rescuers and the rescued. Mechanical frictional damage can occur at the interface between mating parts, where friction takes place. There can be cases of static and kinematic friction. The structure of a rope consists of a braid and a core. This type of structure is referred to in specialist literature as "kernmantle" [19]. Friction inside the rope is a consequence of the rope structure; Leech [20] has identified various instances of internal friction in braided ropes of polymeric fibres, classified as friction between components or within components of ropes. In the case of climbing ropes, external friction can occur when contact is made with rocks [21], rope carabiner and other edges of, among others, elements of building and industrial structures. These instances of loading can occur during rescue operations and determine frictional damage, which is described as principal ones by researchers [22, 23]. To the greatest extent, friction wear concerns the rope braid, which forms the outer layer of the rope [21] and secures the rope core that assures its loading capacity. For this reason, this case was considered in the present work, and the deterioration of the mechanical properties of the rope samples was demonstrated in our own research. Naturally, such damage can affect the durability of ropes, and the way in which the rope is used also matters. Study [16] reported that descending, lowering and so-called "top rope" climbing reduce the life of the rope by 3-4 times. Unfortunately, some of the above mentioned climbing techniques concurrently constitute the basis of rescue operations. An extreme form of rope wear causes sections damaged by the synergistic action of friction and heat. This phenomenon occurs when there is frictional cooperation between ropes, mainly kinematic one, in the range of relatively high relative velocities, e.g. in the case of a rapid descent or in the case of extreme braking of a fall [16]. That is, in the process of kinematic friction the mechanical energy is accompanied by thermal energy. This condition may even lead to softening and deformation of some braid fibres [24]. It is possible that thermal damage to ropes, due to the specificity of operations executed by the State Fire Service, may be caused by yet other factors, such as contact with hot elements or flame. As stated by [25], the main sources of thermal hazard in firefighter's work are hot surfaces and hot gases. The intensity of their action depends primarily on the density of the heat flux, the composition of the gas or smoke and on temperature [25]. In this paper, damage to the specimens was caused by thermal shock. During the exposure to flame, changes in the material properties, mainly, but not only, in the braid, appear to be the most significant. This includes the softening of the polymer material, i.e. polyamide, of which the rope is made. After cooling, the material regains its rigidity and the plastic hardens once again. But it is possible that the structure of the material damaged in such a way could be changed. It is possible that a process of secondary crystallisation of the plastic takes place or other phase transformations depending on the temperature level [26]. The crystallisation process leads to the formation of non-equilibrium systems characterised by partial crystallinity. A crystalline polymer, apart from a certain amount of solid phase, contains an amorphous polymer with a liquid nature [27]. It is possible that the proportion of the crystalline phase increased after re-curing. With respect to polymers, crystals have been shown to be stiffer and harder than amorphous regions, and thus crystallinity and stiffness change under thermal exposure [28]. In our own research, the increase in the crystalline phase in thermally damaged samples was indicated by the highest mean value of the modulus of elasticity obtained (Table 2); this mechanical parameter is responsible for the stiffness of the rope. The differences between particular groups are not very high, yet noticeable. It should also be noted that the values of the modulus of elasticity represent the average state of the damaged material structure and the strength depends on the damage causing the greatest local weakening [29]. Furthermore, the artificially introduced damage covered a small section of the length of the analysed rope samples. Chemical damage was another case considered. It was found in other works [30] that acids cause relatively fast chemical corrosion of polyamides. Numerous industrial and cleaning products contain acids in diluted form. Many of these chemicals are solvents, including organic solvents. It is also important whether they are polar solvents, such as for example acetone. Polar solvents can have a degrading effect on polar polymers that can include the polyamide of which the test rope is made. However, the chemical used to condition the rope samples did not cause changes in the rope structures visible during macroscopic evaluation, nor did it cause adverse changes in strength properties. But an increase in strength and a decrease in modulus of elasticity were discovered in relation to the control group, which is partly consistent with the results of the work [5]. Considering the above analyses, it has to be stated that the three considered defects seem to affect the service properties of the tested mountaineering to varying degrees.

Conclusions:

Based on a study of available literature sources, own research and analyses of the results, the following conclusions may be drawn:

1. Mechanical and thermal damage to the rope, which mainly destroys the braid, cause a decrease in the static tensile strength by approximately 10%.
2. The chemical agent "puracid" does not cause a decrease in the rope strength; in the study an improvement of the rope strength parameters was registered as compared to the rope strength without damage.
3. In the case of thermal and mechanical damage, the average remaining strength of the ropes is in accordance with the requirement imposed by the standard but oscillates close to the limit state (minimum permissible strength).
4. Further rope tests should take into account the influence of various operating conditions on the properties of the ropes. It is important to maintain technical and operational properties, which may change due to aging and fatigue processes.

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