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IMPACT OF STRENGTH PROPERTIES OF TIMBER LININGS IN FORMER WORKINGS ON THE SINKHOLE FORMATION HAZARD. THE CASE STUDY IS ON THE UPPER SILESIAN COAL BASIN, POLAND

In the Upper Silesian Coal Basin (Poland), numerous former workings have been left unprotected after the liquidation of mines in the 19th and the beginning of the 20th century. The workings have been located at low depths. The paper presents the results of strength tests of wood samples acquired from linings in former workings, and the obtained results have been compared to the results achieved in tests of samples of wood intended to be used in a reconstruction of a historic gallery. The tests consisted in determining the bending strength of wood in compliance with the applicable Polish standard. The results showed that the wood from historic mines was characterised by high variability of bending strength – usually much lower than that of the wood intended for construction. Too low bending strength of timber may result in caving in shallow excavation and lead to sinkhole creation on the surface.

Keywords: old workings timber lining; timber bending strength; sinkhole hazard; wood laboratory tests

1. Introduction

The area of The Upper Silesia, Poland and other European areas where underground mining has been conducted for many years exhibit an abundance of former shallow mine workings [3]. A similar situation also occurs in other countries, such as France and Turkey, where mining operations have been carried out for a long time [1,4]. The workings are often located at a low depth, sometimes reaching as little as a dozen metres, as Strzałkowski and Tomiczek wrote in their paper [19]. Although the low depth of excavation is conducive to ensuring stability [25], the use

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of linings is necessary even at a low depth. As previously described by Strzałkowski [18,20,21], the largest number of sinkholes are formed above former mine galleries.

We can conclude that sinkholes are often formed due to the collapse of shallow galleries that have not been liquidated.

Exploitation workings were liquidated naturally by causing a collapse of roof rocks or backfilling. Voids that were formed in these workings had a lower impact on the formation of sinkholes than the non-liquidated galleries that were left unprotected. Currently used safe steel linings, especially in commonly used rock bolt linings with the application of appropriate injection installations, ensure the stability of excavations for many years, as previously described by Ignat'ev and Ignat'ev [5]. New technologies based on strengthening the rock mass by injection to limit its deformations are also in use. The effectiveness of such treatments has been demonstrated based on numerical modelling and in-situ studies [26]. Until the end of the 1940s, wood, most often pinewood, was usually used as a material for the final lining of workings. The use of timber systematically decreased over the following years according to Stone et al. [15]. Due to biological degradation processes under the influence of the mine atmosphere, the wood was subject to deterioration, which caused a decrease in the strength properties and, consequently, decreased the lining's load-bearing capacity [2]. As a result, the workings may have collapsed, and sinkholes may have been formed at the surface. Currently, timber linings are only used as temporary lining due to their limitations, namely the low strength and durability [8]. On the other hand, some publications may be found showing the present use of timber protection elements in underground constructions, for example, a paper written by Jinrong et al. [6] indicates the use of wood to construct cribs supporting the roof. Of course, the infarction of shallow excavations can be caused not only by the loss of the load-bearing capacity of the former lining but as a result of its biodegradation. The cause may lie in the impact of mining exploitation carried out under a shallow excavation according to Szafulera [22].

In the scope of this article, the considerations were limited to the impact of the loss of the wooden lining resistance to the sinkhole hazard on the surface.

The condition of old wooden support from the 19th century is well illustrated by a photograph taken in adit Marcinków in Sudetes Mountains (Poland). In the photograph, one may note the musty fragments of the lining laying on the floor and the German-type support sets in which the roof bar is bent and broken due to the load exerted by the rock mass. The fracturing of the props may also be noted (Figs. 1 and 2).

The adits in Marcinkowo were penetrated in 2005. The first one was 138 m in length, the second one had collapsed, and its penetration was not possible. The lining was in bad condition. Wood samples were taken, the dendrochronological tests of which allowed us to state that the conifer lining comes from the 17th and 19th centuries. It is probable the wood from the 19th century was used to replace the lining in connection with plans to reopen the mine [23].

Considering the above, the authors have decided that testing the strength properties of timber which was left in underground galleries for a long period of time and comparing them with the properties of wood intended for lining construction is an important issue. To conduct the tests, wood was acquired from headings driven in the 1930s and the 1950s. The wood was acquired both from props and roof bars. The issues presented in the paper are important for social reasons. There are two important reasons to consider. Firstly, the abandoned, shallow workings made with timber lining pose a threat. In the scope of this article, the considerations were limited to the impact of the loss of wooden lining's resistance on sinkhole hazards on the surface.

It may have dangerous consequences, even many years after the workings had stopped being used. Secondly, the abandoned workings may be adapted as tourist attractions [3].

The new wood was intended for construction in a historic working that shall be made available for touristic purposes. There is a rich tradition of reconstructing historic workings in Poland, and it plays a major role in the popularisation of knowledge of mining history [9]. Due to the limited use of timber in modern mining, the modern professional literature does not give much consideration to the problems that are the subject of this paper.

Fig. 1. General view of the adit from the 19th century in Marcinków (Sudetes Mountains – Poland – photograph by A. Pastuszak)

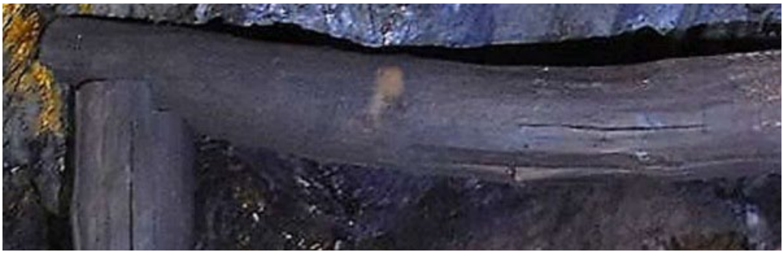

Fig. 2. Damaged prop and roof-bar (enlarged photograph from Fig. 1)

2. Materials and methods

The tests encompassed samples of wood from linings of headings driven in the 1930s and 1950s. The research material was collected following the Polish standard PN-77/D-04227 [12]. Five groups of samples were tested: groups 1 and 2 were obtained from props installed in the gallery, group 3 was acquired from the roof-bars of the same gallery, whilst the remaining groups

(4 & 5) were obtained from props installed in the raise adjacent to the gallery. The gallery was driven in 1950, and the rise was driven in 1937. The diameters of the props and roof-bars were approx 15 cm. The wood was preserved in various conditions, as shown in Fig. 3, exhibiting examples of fragments cut out from the props and roof-bars from groups 2 and 5.

a) b)

Fig. 3. A view of examples of fragments cut out from the props and roof-bars from groups: a) 2, b) 5

Even by visual inspection, it may be concluded that the condition of the wood from the raise was much worse than that of the timber from the gallery. This mostly results from the time of exposure of the lining elements to the corrosive factors, which in the case of the raise was much longer.

A total of 33 laboratory samples were acquired and prepared from all wood groups in line with the Polish standard PN-77/D-04227 [12] and Polish standard PN-77/D-04103 [11]. The samples were subsequently tested in terms of bending strength according to the provisions of the standard referred to above (Fig. 4, Fig. 5). The moisture content of the samples upon testing varied in the range from 8.9% for group 1 up to 9.4% in case of group 2.

a) b)

Fig. 4. A view of examples of laboratory samples acquired from cut out fragments from groups: a) 2, b) 5

Moreover, the samples of new wood intended for the reconstruction of a lining of a historic workings were tested in the same way. Upon the test, the moisture content of the samples was 13.2%. The calculations were made according to the following formulas.

$$f_{kW} = \frac{3 \cdot F_{\max} \cdot l_d}{2 \cdot b \cdot h^2} \tag{1}$$

where:

- f_{kW} — static bending strength of wood subject to test under the current humidity W, MPa
- $F_{\max}$ — maximal load exerted on sample, kN;
- l_d — span of supports, mm;
- b — width of the sample, mm;
- h — height of the sample, mm.

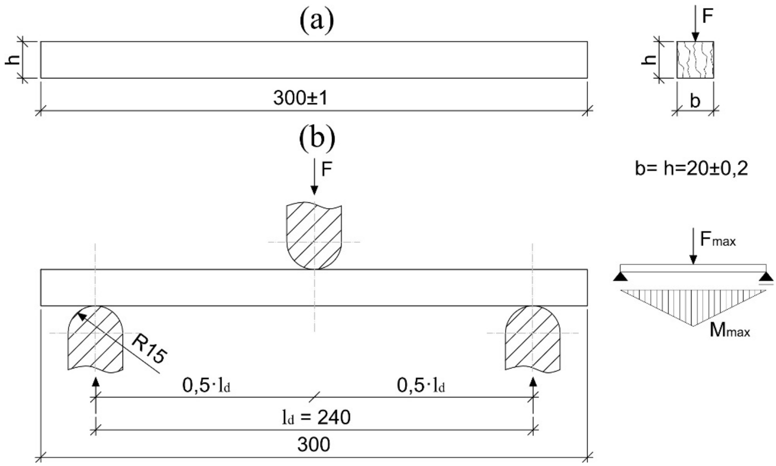

Fig. 5. The determination of static bend strength. a) shape and dimensions of samples, b) bending

To compare the bending strengths of each of the tested wood samples, the samples' strength at the current moisture content was recalculated to the value of 12% moisture content, as provided by the Polish standard PN-77/D-04103 [11], according to the following formula:

$$f_{k12} = f_{mW}\left[1 + \alpha(W - 12)\right] \tag{2}$$

where: α — conversion coefficient, $\alpha = 0.04$.

The numerical values obtained in the testing were subjected to a statistical analysis in line with the Polish standard PN-77/D-04103 [11], while calculating:

1) the arithmetic mean:

$$\overline{x} = \frac{\sum x_i}{n} \tag{3}$$

where: n – sample size;

2) standard deviation of the bending strength:

$$s = \pm\sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}} \tag{4}$$

3) mean square error of the mean:

$$s_r = \pm\frac{s}{\sqrt{n}} \tag{5}$$

4) variability coefficient:

$$v = \frac{s}{\bar{x}} \cdot 100\% \tag{6}$$

5) accuracy indicator for a confidence level of 0.95:

$$p = \frac{2 \cdot s_r}{\bar{x}} \cdot 100\% \tag{7}$$

Based on the test results of samples acquired from each of the wood batches, the characteristic value of the bending strength was estimated. It's assumed that the characteristic value of the strength is the 0.95 quantile of the normal distribution.

The issues connected with the methods of determining strength parameters have been discussed in detail by Kidybiński [7] and by Peng [13].

To determine the ability to transfer bending stresses by the existing timber lining, the analysis method described in [14] was applied. A. Sałustowicz applied a simplification consisting of the assumption that the upper half of the ellipse may be considered a part of a parabola. The load exerted on 1 m of lining consisting of support sets, installed each 1 m, constitutes the weight of the rocks within the pressure arch and amounts to:

$$Q = \frac{2}{3} \cdot \gamma \cdot f \cdot l \tag{8}$$

where:

γ — bulk density, MPa/m;

$f = 0.5\ a - 0.5\ w$

a — vertical axis of the ellipse, m;

w — height of the working, m;

l — width of the working, m.

The maximum bending moment (M_g) in case of a continuous parabolic load amounts to [26]:

$$M_g = \frac{5}{16} \cdot Q \cdot \frac{l}{2} \tag{9}$$

The bending strength indicator amounts to:

$$W = \frac{\pi \cdot d^3}{32} \tag{10}$$

where: d — diameter of the roof-bar, m.

Knowing that:

$$W = \frac{M_g}{R_g} \tag{11}$$

a formula may be achieved expressing the minimal bending strength (R_g), at which the roof-bar will not be destroyed.

$$R_g = \frac{5 \cdot Q \cdot l}{\pi \cdot d^3} \tag{12}$$

3. Results

The results of the calculations according to formulas (1)-(7) have been presented in Table 1.

TABLE 1

A listing of statistical values of determination of the bending strength of samples acquired from the analysed wood batches

Batch	1		2		3		4		5		6	
Moisture content [%]	8.86	12	9.39	12	9.39	12	9.32	12	9.23	12	13.25	12
Number of samples	6	6	14	14	9	9	4	4	4	4	49	49
Minimal strength $f_{k,\,min}$ [MPa]	66.4	58.1	47.2	42.3	35.9	32.0	7.2	6.4	3.8	3.4	63.4	66.5
Maximal strength $f_{k,\,max}$ [MPa]	89.6	78.4	102.8	92.1	45.4	40.5	22.7	20.3	21.1	18.7	105.6	110.9
Mean strength $f_{k,\,śr}$ [MPa]	76.5	66.9	75.2	67.3	40.2	35.8	14.8	13.2	10.5	9.3	80.4	84.4
Standard deviation s_k [MPa]	9.32	8.15	14.88	13.32	3.33	2.96	6.88	6.14	7.68	6.83	10.84	11.38
Mean square error of the mean $s_{r,\,k}$ [MPa]	3.80	3.33	3.98	3.56	1.11	0.99	3.44	3.07	3.84	3.41	1.55	1.63
Variability coefficient v_k [%]	12.17	12.17	19.79	19.79	8.28	8.28	46.45	46.45	73.4	73.4	13.48	13.48
Accuracy indicator for a confidence level of 0.95 p_k [%]	9.94	9.94	10.58	10.58	5.52	5.52	46.45	46.45	73.4	73.4	3.85	3.85
Characteristic strength $f_{\cdot mk}$ [MPa]	61.3	53.6	50.8	45.5	34.8	31.0	3.5	3.2	—	—	62.6	65.8

Batches 1-3 were obtained in the gallery, while batches 4 and 5 were acquired in the raise. In the table, the batch of new wood samples was marked with No. 6. The strength of the wood from the gallery was higher than that of the wood from the raise. Fig. 7 exhibits the strength values converted for the moisture content of 12%.

The statistical analysis was carried out in line with the guidelines comprised in the Polish standard PN-77/D-04103 [11]. It was assumed that the obtained results are characterised by a nor-

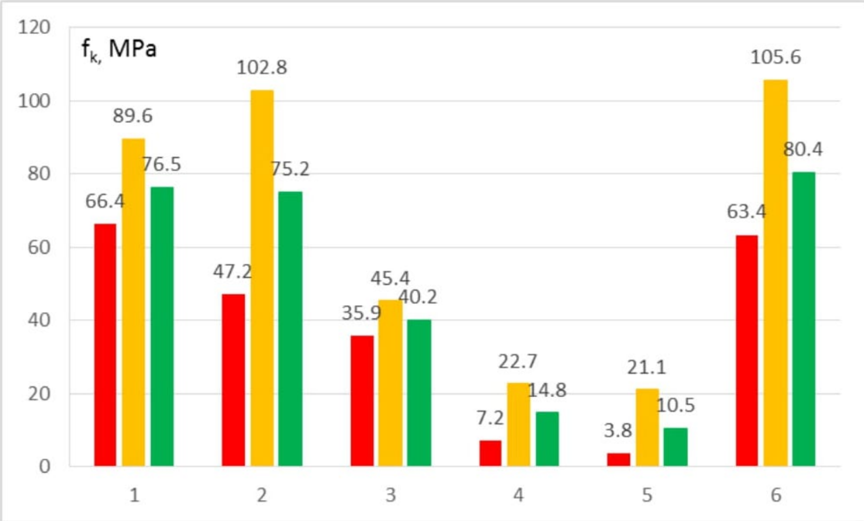

Fig. 6. The bending strength of the tested 6 batches of wood at natural moisture content. Red colour – minimal value; yellow colour – maximal value; green colour – mean value

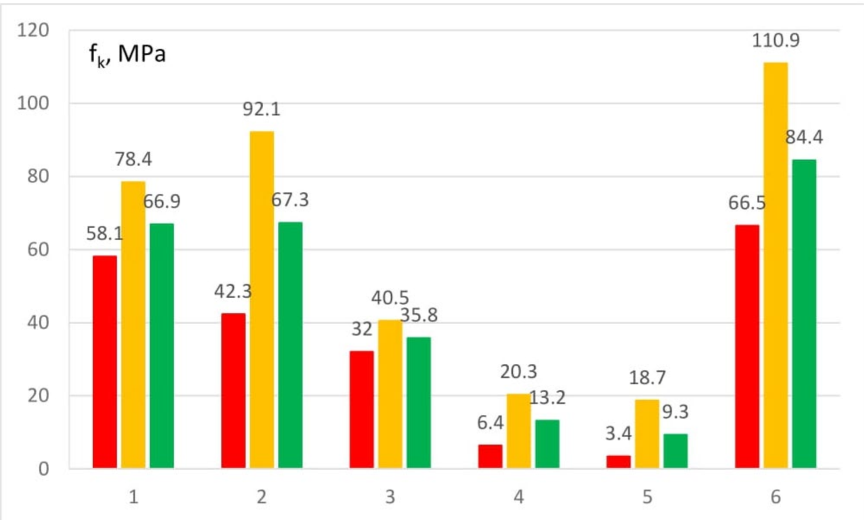

Fig. 7. The bending strength values of the tested 6 batches converted for the moisture content of 12%. Red colour – minimal value; yellow colour – maximal value; green colour – mean value

mal distribution. The standard deviation values ranged from s_k = 2.93 MPa to s_k = 14.88 MPa. The values of the variability coefficient changed from v_k = 8.28% to v_k = 73.4%. The highest values of variability coefficient were reported for the samples collected from batches 4 and 5 (the same working). It was probably caused by unfavourable environmental conditions (waterlogging, poor ventilation) that prevailed in the working throughout its life, which contributed to intensive destruction of props and roof-bars, and hence it brought about high variability of strength parameters of the lining material.

4. Discussion

Based on the results of the conducted tests (Table 1), it may be concluded that the bending strength of wood acquired from old workings was highly variable. Batch No. 1 was characterised by the highest strength varying from 66.4 MPa to 89.6 MPa (mean of 76.5 MPa). The values were comparable to the results obtained for the new wood – batch No. 6. In the case of the new wood, the strength values varied from 63.4 MPa up to 105.6 MPa, which resulted in a mean value of 80.4 MPa. In the case of batch No. 5, on the other hand, the strength of the samples was lower and varied from 3.8 MPa up to 21.1 MPa (with a mean value of 10.5 MPa). The variability was thus considerable. Fig. 6 presents a bar graph of the strength values determined for all the six batches of wood in natural moisture content conditions. As Fig. 7 shows, the variability of the obtained values was also considerable, while the new wood (batch No. 6) was characterised by a strength considerably higher than that of the wood acquired from other batches.

The considerable variability of the bending strengths within each of the batches was related, both to the natural heterogeneity of wood as well as to the biodegradation processes.

The conclusion from the conducted tests is a statement that the atmosphere of a hard coal mine affects timber, causing a general reduction of its strength parameters. The extent of changes in these parameters can be influenced by many factors related to both timber and the atmosphere parameters, and above all its humidity. Formulating more precise conclusions would require further detailed research, which is not possible due to lack of access to the former linings, and in active excavations, a timber lining is rare. Similar research on the strength properties of timber from the old hard coal mine linings has not been conducted yet, or in any case, the results have not been published. The research was conducted on the strength properties of wood obtained from the lining in the excavations of the Salt Mine in Wieliczka [10]. The research results indicate that contrary to expectations, also in this case timber characterises with significantly reduced bending strength than modern timber. Although the timber lining in the Wieliczka Salt Mine still retains its load-bearing capacity, evaporative mineralisation causes a reduction in the strength of the timber.

As concluded in the paper [16], the ignition temperature of wood from the former linings does not differ from the ignition temperature of fresh timber. The former timber lining does not increase the fire hazard of excavations.

To have a more in-depth discussion of the obtained test results, the following is an example of the analysis of the impact of wood bending strength on excavation stability and the possibility of a sinkhole on the surface. For this purpose, the case study provided by Strzałkowski [20] was used.

In the paper, an analysis of a case of sinkhole formation over shallow galleries was conducted. In the analyses, it was assumed that the timber lining lost its bearing capacity and calculations were made in line with the method of A. Sałustowicz's pressure arch theory [14]. This theory is often used in Poland and is included in Polish standards, which justifies its application in this paper.

The profile of the rock mass has been exhibited in Fig. 8, based on a borehole driven in the vicinity of the sinkholes. The overburden was constituted by the following strata: sand with a thickness of 2.0 m, loam with a thickness of 5.5 m, and clayey sand with a thickness of 3.0 m. Below, carboniferous strata are found, consisting of: claystone with a thickness of 1.5 m and coal (seam 342) with a thickness of 3.0 m. The galleries above which the sinkholes were formed were at the depth of 15 m (counting from the floor) in the coal seam – Fig. 9. It was assumed

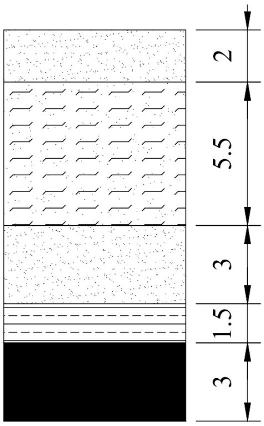

Fig. 8. Lithological profile of the rock mass in the area in concern [20].
Dimensions in metres

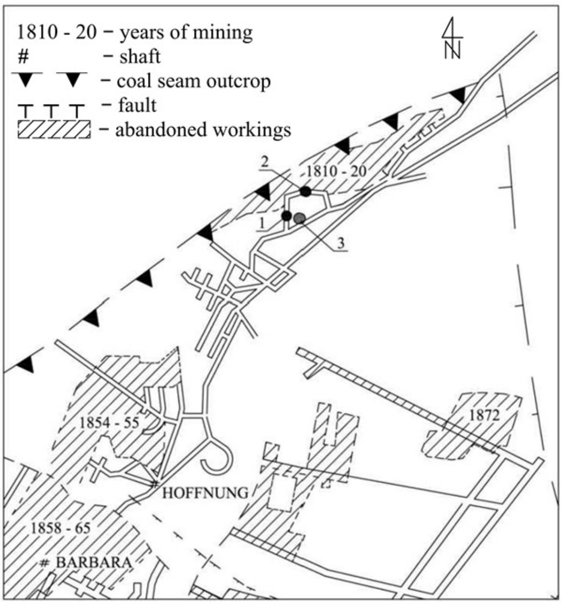

Fig. 9. A fragment of the map of the 342 seam with the locations of sinkholes formed at the surface (1 and 2) and the borehole (3) according to Strzałkowski [20]

that the dimensions of the galleries were 3×3 m. Most likely, the workings have been made in the years 1810-1820. The mine was called Luiza, and its mining area lies within the present-day administrative borders of Mysłowice near Katowice in Upper Silesia.

The following properties of the strata constituting the rock mass have been assumed [20]:

- the overburden strata were generalised by assuming a total thickness of h_n = 10.5 m, a tensile strength of R_r = 0 MPa and a bulk density of γ = 0.020 MPa/m;
- for the claystone, the following values were assumed: tensile strength R_r = 0.15 MPa (due to the small depth, the value is relatively low) and a bulk density of γ = 0.027 MPa/m;
- for the coal, the following values were assumed: tensile strength R_r = 0.40 MPa (due to the small depth) and a bulk density of γ = 0.014 MPa/m.

The calculation results for the data presented above are as follows:

- the horizontal and vertical components of the primary pressure: p_z = –0.2505 MPa, p_x = –0.0358 MPa;
- ratio of ellipse axes of loosened rocks according to A. Sałustowicz: n = 0.9042 (horizontal axis longer than the vertical axis, the possibility of obtaining such a result has been indicated in the paper [23];
- length of ellipse axes: a = 4.04 m, b = 4.47 m.

In the analysed case, a value of R_g = 39.75 MPa was obtained. Thus, the examined wood batches gave the numbers: 3, 4 and 5, which contained samples with a strength which was lower than the above value. This constitutes a potential possibility of destruction of the lining and the collapse of the heading.

4. Conclusion

The loss of support of the wooden lining in old, shallow mining excavations may lead to the collapse of the ceiling and, as a consequence, to a sinkhole on the surface. The loss of supporting capacity of the lining occurs when its load results in the generation of bending stresses in the roof-bar that exceed the bending strength of the lining material. The study includes tests on the bending strength of wood/timber obtained from the lining of former workings. For this reason, the subject matter of the work should be considered important. Wood from 5 batches of the abandoned lining was examined, and the obtained results were compared with those obtained from modern wood. The conducted research and the analysis of its results allow us to present the following conclusions:

1. The obtained strength values were characterised by high variability and were significantly smaller than the strength of fresh wood/timber. This indicates the occurrence of biodegradation of wood depending on the local conditions in the excavations. In the case of wood from batches 1 and 2, the bending strength values did not differ significantly from the values obtained for modern wood, and they were on average approx 80 MPa. The wood from batches 3, 4 and 5 was characterised by much lower values of bending strength, ranging on average from approx 10 MPa to approx 40 MPa.
2. It also indicates the reason for the formation of sinkholes, often after a long time since the excavations were used, and explains why sinkholes occur in some places above shallow excavations and not in others.

3. The obtained research results indicate that some old workings, after a thorough inspection of the condition of lining and appropriate reconstruction works (reinforcement or replacement of some elements), may serve economic or tourist purposes. Other old workings not planned to be used, should be completely liquidated. The loss of stability of a former lining and the transition of the workings into a caving state may occur after a long period of time and in consequence, lead to the formation of a sinkhole on the surface.

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