The application of thermal analysis in testing the combustibility of timber used in supporting of mine roadways

E Strzałkowska

Silesian University of Technology, Faculty of Mining and Geology, 2 Akademicka Street, 44-100 Gliwice, Poland
E-mail: ewa.strzalkowska@polsl.pl

Abstract The paper presents the results of thermal analyses of three samples of wood acquired from props and roof-bars constituting timber lining constructed in the beginning of the 20th century and found in active roadways of one of the USCB coal mines. The results were compared with the results of thermal analyses of samples of timber intended for construction. A derivatograph – a device allowing for the maintenance of identical measurement conditions, was used in the study, which is significant in testing the thermal stability of materials of organic origin. The conducted tests allowed to determine the ignition temperature of both types of timber. The study exhibited that the combustibility of the timber acquired from the old timber lining is comparable to the combustibility of fresh timber, which is significant in terms of the operational safety both in active and historic collieries.

1. Introduction

Until the mid-20th century, timber was commonly used to construct the final linings of mine workings, both in case of roadways and exploitation headings [1]. Until that time, the workings were located at low depths, which was related to lower loads exerted on the linings of such workings. Many centuries of using timber linings exhibit that such linings fulfilled their purpose well in the conditions of low and stable loads caused by the rock-mass (static pressure). Such linings offered many advantages including a low price as well as simple and quick construction. Its combustibility, however, is one of its basic flaws.

Currently, when the workings are driven at depths often exceeding 1,000 m and high deforming loads are exerted on the linings, hard coal mines almost exclusively apply steel yielding linings. Thus, in current geological and mining conditions, mine timber is not fit to be a material used in final linings. This, of course, results from the low load bearing and yielding capacities of such lining. At the same time, one should note that shallow workings with timber linings serving e.g. ventilation purposes, are still operating in some of the older coal mines. Such linings are also often maintained in historic mining objects (such as the Salt Mine in Wieliczka or in Bochnia, the Gold Mine in Złoty Stok, or the historic Silver Mine in Tarnowskie Góry – figure 1). A wide range of underground historic objects, including ones with reconstructed timber linings, has been presented in the work [2]. It is difficult to imagine a reconstruction of historic workings in a lining other than made of timber, excluding the locations, however, where the worse local geological and mining conditions require a lining characterized by a higher load bearing capacity due to safety reasons.
Linings in mine headings, both active and historic, should – of course – fulfil all safety requirements [1, 2, 4, 5]. The problem of safety in view of the fulfilment of strength requirements by the materials and structures has been widely discussed. It is not different in case of timber linings. In the paper [6], the author focused on the impact of wood mineralization on its strength parameters, concluding that the impact is decisively negative. The presence of mineral compounds and resins in wood also significantly impacts its combustibility. The research has shown that the ignition delay increases along with the increase of the bulk density of timber, while it decreases in case of a high content of resins and fats in the timber [5]. The presence of these components may thus highly modify the properties of wood and its usability [7]. In the paper [8] various types and kinds of wood were tested and it has been exhibited that combustibility decreases along with the increase of its density, while several types and kinds of wood exhibited combustion properties different to those indicated by the density classification. In the authors’ opinion, it is the result of the chemical composition and structure of wood (type and content of non-structural compounds). Undoubtedly, the moisture content has a decisive impact on the combustibility of mine timber. It is evident that the lower the content of moisture in the wood, the higher its combustibility. This parameter depends on the conditions in which the timber is stored and it has a significant impact on the remaining properties of timber. In underground mine atmosphere conditions, the humidity is high, which has a significant impact on the reduction of the fire hazard level pertaining to timber used for a long time.

Other valuable studies have concerned timber lining combustibility depending on: the diameter of props, the level of saturation with fire protection agents or the mechanical damages [5]. Elements that are particularly susceptible to combustion are the elements with mechanical damages such as breaking, fractures or splitting [9]. The elements with the highest diameters and without any damages caused by the surrounding rocks have been found to be the most resistant [10].

A review of technical literature has, however, provided limited data concerning the minimal temperatures required for the wood to ignite, while the results obtained by various researchers throughout the years indicate certain discrepancies [5, 11, 12]. Undoubtedly, this is mostly due to the fact that the ignition temperature is a heat flux function [13]. While studying the professional literature,
one may also be under the impression that the problem of the impact of time of use of wood in mine conditions on its combustibility was not a subject of researchers’ interest. Wood combustibility is defined by several parameters, e.g.: the ignition temperature, the amount and rate of heat emission and the amount and composition of the emitted gases. At this point, it should be underlined that the combustibility of timber lining has a significant impact on the operational safety of workings both in the active and historic mines. To understand the behavior of wood during a fire, it is necessary to learn its decomposition process in detail. This process is affected by numerous parameters. The derivatographic analysis is the most commonly used method for testing the thermal decomposition of both low and high molecular weight organic compounds [14]. The method provides information not only regarding the composition of wood, but may also be useful in determining its thermostability.

Considering the observations referred to above, it should be considered substantiated to study the combustibility of mine timber used for many years and compare it to the combustibility of wood intended for construction. This problem has been adopted as the subject of this paper.

2. Research methods
The object of the study were wood samples acquired from props and roof-bars of a timber lining in a heading and the rise gallery in one of the USCB mines. A view of the gallery with the timber lining has been shown in (figure 2).
The study encompassed three powdered samples of the old mine timber (figure 3) and three samples of wood intended for construction. To eliminate the impact of the bulk density, the same kind of wood was used in the comparative study. The wood samples were stored in similar conditions. The sample measurements were conducted under dry air conditions.

The thermographic tests were conducted using a Paulik-Paulik-Erdey derivatograph in air atmosphere using the standard heating rate of 10°C/min. The samples were heated to 1,000°C in corundum crucibles while assuming the following parameters: analytical sample of 40 mg, sensitivity of DTA – 1/5, DTG – 1/10, TG – 50 mg. Al₂O₃ was used as the inert substance.

**Figure 3.** A view of a fragment of a wooden prop (phot. G. Dyduch).

3. **Discussion**

The results of the conducted study have been presented in figures 4–6. The resulting curves enabled the determination of characteristic temperatures, such as: \( T_i \) ignition temperature, maximum degassing temperature \( T_{\text{max}} \) and the burnout temperature \( T_k \). The ignition temperature was determined as the temperature in which the rapid emission of heat occurs. It has been obtained by extrapolation of the peak arm of the DTA curve and the base line. The maximum degassing temperature was determined as the maximum peak temperature at the DTG curve, where the rate of mass loss was the highest in a unit of time. The \( T_k \) burnout temperature was determined as the temperature in which the mass of the sample remains unchanged. Table 1 presents the characteristic temperatures and mass losses registered by the resulting thermoanalytic curves, related to the physical and chemical transformations occurring in wood.
Figure 4. DTA curves for wood combustion.

Figure 5. TG curves for wood combustion.
Figure 6. DTG curves for wood combustion.

Table 1. Characteristic temperatures and mass losses related to the transformations occurring in wood samples.

| Sample No.         | W (%) | $T_i$ (°C) | $T_{max}$ (°C) | $T_k$ (°C) | $\Delta t$ (min) |
|--------------------|-------|------------|----------------|------------|------------------|
| Old wood           |       |            |                |            |                  |
| (approx. 80 years in use) | |     |               |            |                  |
| $1s$               | 7.5   | 250        | 270            | 430        | 18               |
| $2s$               | 8.5   | 240        | 260            | 440        | 20               |
| $5s$               | 8     | 245        | 265            | 455        | 21               |
| Fresh wood         |       |            |                |            |                  |
| (intended for construction) | |     |               |            |                  |
| $1n$               | 5     | 245        | 280            | 460        | 21.5             |
| $3n$               | 9     | 250        | 275            | 440        | 19               |
| $4n$               | 8     | 255        | 280            | 430        | 17.5             |

$T_i$ – ignition temperature  
$T_{max}$ – maximal degassing temperature  
$T_k$ – temperature of completion of the combustion process  
$\Delta t$ – time of combustion  
$W$ – moisture content

The shape of the thermoanalytic curves representing the samples of the old wood is close to the shape of the curves representing the wood intended for construction (figures 4–6).

In all DTA curves, the presence of one weak endothermic effect was observed, after which two exothermic effects usually occur (with the exception of the $1s$ sample, where 3 exothermic reactions have been observed) (figure 4). The endothermic effect with the maximum at a temperature of approx.
100°C is related to the energy required to evaporate the adsorbed water. In case of the old wood, the moisture content was within the range of 7.5–8.5%, while in case of the fresh wood the range was wider – from 5 to 9% (table 1). After dehydrating the samples, the proper process of wood combustion begins in the temperature range of 200–500°C. The process consists in the physicochemical change of the wood's microstructure. The change of the shape of the curves in that range is initially related to the degassing and subsequently the combustion of the resulting decomposition products. When the temperature of approx. 200°C is reached, an exothermic reaction begins due to energy release. The ignition temperature of the old wood falls within the range of 240°C to 250°C, while in case of the wood intended for constructions, the range is from 245°C to 255°C. The highest reactivity was exhibited by the 2s old wood sample. A higher ignition temperature (despite the lowest content of moisture) was exhibited by the In sample of wood intended for construction (table 1). This may probably be explained by the presence of strongly bound water in the sample, which is supported by the slightly higher maximum evaporation temperature (figure 6).

Because the thermal resistance of the individual components of wood is different, the shape of the first exothermic effect at the DTA curve (figure 4) is dependent on the percentages of the main wood components, that is: hemicellulose, cellulose and lignin [10, 15–17]. Hemicellulose is the first component subjected to depolymerisation. Subsequently, cellulose is decomposed. The decomposition of these two components proceeds in a relatively narrow, partially overlapping, range of temperatures [18]. The maximum of cellulose depolymerisation occurs at a temperature of approx. 300°C – which coincides with the beginning of decomposition of lignin in the sample.

In the DTA curve of the Is sample 3 exothermic effects were observed: the maximal effect in the combustion temperature of 300°C and two lower effects in temperatures of 340 and 380°C. The first peak may be attributed to the combustion of cellulose and hemicellulose. Subsequently, the residue cellulose is combusted and the combustion lignin is initiated, resulting in a smaller exothermic peak at a temperature of 380°C. Following that phase, the degradation and oxidation of lignin proceeds.

Lignin is the most thermally stable component of wood. The higher decomposition temperature of lignin may be explained by the higher content of carbon and the aromatic character thereof. As compared to cellulose, the lignin decomposition process proceeds at a slower rate and in a broader range of temperatures, which is exhibited by the shape of the DTG curves (figure 6). This is caused by the fact that the oxygen contained in the functional groups of lignin is characterized by a different thermal stability [19]. In case of the 2s sample (old wood), the extreme value of the second exothermic effect is shifted towards higher temperatures, which may indicate a higher stability of lignin decomposition semiproducts (figure 4) [15].

Simultaneously with the exothermic reaction, the TG and DTG curves exhibit a significant loss of wood mass (figure 5–6). The rapid loss reaches its maximum at the temperature range from 260 to 270°C for the old wood and from 275 to 280°C for the wood intended for construction (figure 6).

In temperatures over 500°C, no significant changes of the mass are observed in the TG curve, which exhibits the completion of the combustion process (figure 5). A slight loss of mass above this temperature was observed for the In sample, which may testify of the presence of levoglucosan formed from cellulose over the temperature of 350°C. This component decomposes into combustible gases which react with oxygen, and are subject to combustion while emitting CO₂, CO and H₂O [10, 20].

Undoubtedly, the rate of combustion of a material is the most significant parameter determining the fire hazard. While comparing the obtained thermoanalytic curves (figures 4–6, table 1), one may note that the mean times of combustion for the old wood and the wood intended for construction are comparable and reach approx. 19 minutes.

4. Conclusions
Within the paper, thermal analyses of fresh wood intended for construction of linings and of wood acquired from a lining constructed approximately 80 years ago, have been conducted. The main purpose of the study was the determination whether the prolonged use of timber results in an increased fire hazard in a mine working. The conducted study was of an initial character and the results – due to the small
number of samples – are partial. Based on the results, the following conclusions may, however, be drawn:

1. According to the TG and DTG curves the main stage of weigh loss of most samples occurs from about 240°C to about 440°C during which the samples lose almost 90% of the total weight.
2. The conducted study has also confirmed that the temperature of ignition and combustion time are not only affected by the hygroscopic water content, but also the content of water forming bonds between cellulose molecules.
3. The temperature of ignition and the time of wood combustion are indicators of the fire hazard in workings with timber lining. In case of the acquired samples, it may be noted that both the ignition temperature and the combustion time was comparable for both types of wood.
4. The comparative thermal analysis of wood samples has unequivocally exhibited that even after several dozens of years, the use of timber lining does not constitute a higher hazard due to its combustibility as compared to the lining constructed of fresh timber.

5. References

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