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RESEARCH ON THE ELECTRICAL CAPACITANCE AND ELECTRICAL CONDUCTIVITY OF CHAR RESULTING FROM NATURAL AND TREATED WOOD

Romualdas MAČIULAITIS[a], Andrejus JEFIMOVAS[a], Donatas LIPINSKAS[b]

[a]*Vilnius Gediminas Technical University, Saulėtekio av. 11, LT-10223 Vilnius, Lithuania*
[b]*Fire Research Centre, Švitrigailos str. 18, LT-03223 Vilnius, Lithuania*

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Abstract. Wood is a material widely used for construction purposes and having quite a number of advantages. However, one of the major drawbacks of wood are its flammability. In case of fire in wooden buildings or constructions made of timber structures, the most noticeable feature of combustion is charring these structures. This property is important for identifying the cause of a fire. Therefore, it is necessary to relate charring timber structures with certain significant effects of fire such as its duration or temperature. It is also particularly important to identify whether timber has been treated with fire retardant solutions before the fire break-out. The values of electrical capacitance and conductivity for the media obtained from char resulting from natural wood and that treated with fire retardant solutions and dispersed in distilled water depending on heating time have been determined. Moreover, it has been stated that the electric conductivity of char resulting from natural wood is 100 times lower, and the electrical capacitance of such char is 1000 lower than those resulting from treated wood. The regression analysis of the obtained data has been performed. The empirical equations have been derived. The results of the conducted research have been summarised. Priority has been given to the application of the method evaluating electrical conductivity.

Keywords: wood, wood characteristics, charring, electrical capacitance, electrical conductivity, fire retarders.

Introduction

Wood is a unique anisotropic porous substance of plant origin where the volume of pores takes 50–75% of the wood volume. Due to strength, it can bear high loads, and therefore has plenty of advantages in comparison with other building materials. At the same time, it is light enough, has low thermal conductivity and can be easily processed. However, a few drawbacks can be mentioned: wood absorbs much water, decays and deforms if dried or under the influence of humidity. Flammability is one of the major drawbacks of the discussed material. As a rule, the combustibility of timber structures is decreased by treating them with fire retardant solutions. A large number of works have been dedicated to research the efficiency and durability of fire retardant solutions (Hagen *et al*. 2009; Grigonis *et al*. 2012; Liodakis *et al*. 2013; Czégény *et al.* 2013; Arao *et al.* 2014).

In terms of mass, completely dry wood (about 99%) consists of organic substances in addition to which, wood contains some mineral substances in the form of saline solutions in water that feeds trees from soil, takes part in photosynthesis and turns to ash after wood has been burnt. Regardless of tree species, carbon (49–50%), oxygen (43–44%), hydrogen (about 6%) and nitrogen (0.1–0.3%) prevail in completely dry wood. Complex organic substances are formed from such elements as cellulose, hemicellulose (natural polymers and oligomers), lignin, pectins and the so-called extractive (soluble in water and organic solvents) substances, including inorganic salts of potassium, sodium, calcium, manganese, oxides of silicon, aluminium, phosphor, etc. (Preston *et al*. 1998; Pandey 1999; Jakimavičius 2003).

The structural composition of wood depends on botanic origin, growing conditions, species, the age of a tree and other factors (Hagen *et al*. 2009; Nagrodzka, Maloziec 2011). The prevailing proportion of its components is as follows: 50% of cellulose, 25% of hemicellulose and 25% of lignin. Other chemical compounds present in the composition of wood are of a various chemical structure and different degree of thermal resistance as well as are soluble in water and electrically conductive (Drysdale 1998; Jakimavičius 2003).

Referring to the research data obtained by various authors, the thermal decomposition of wood components

Corresponding author: Andrejus Jefimovas
E-mail: *andrejus.jefimovas@dok.vgtu.lt*

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takes place at different temperatures. Hemicellulose decomposes at 200–325 ºC, cellulose – at 220–375 ºC, lignin at 250–500 ºC (Bolling *et al*. 2009; Mahltig *et al*. 2009; Goodrich *et al*. 2010; Taghiyari 2011). The results of thermographic research carried out by other authors suggest that, within the decomposition of materials, combustion is affected by both substance (tree) species (Bednarek *et al.* 2009) and the rate of a rise in temperature (Hagen *et al*. 2009; Fulianga *et al*. 2012; Blijderveen *et al*. 2013) as well as by the environment (oxidizing, reducing gas) in which the substance is studied (Jiang *et al*. 2010; Fu *et al.* 2011).

The thermal decomposition of wood can take place in case of a free and partial supply of atmospheric oxygen. It can also appear under a shortage of oxygen in the atmosphere. Wood combustion is a specific process because of a char layer resulting on the surface of wood. During combustion, this layer makes a tight shell that impedes heat entrance into deeper undecomposed layers of the material and blocks the free release of volatile (gas and vapour) products into the atmosphere in the course of thermal decomposition. Such behaviour at high temperatures restricts fire spreading for a certain period of time. However, it is important that the thermal decomposition of the material continues taking place under the charred layer of wood that may be very dangerous, as oxygen makes 43–44% of the chemical composition of wood (Drysdale 1998). The products of thermal decomposition can condition the start of smouldering. In the course of time, the formation of gases during smouldering can cause pressure to increase so high that the char layer breaks resulting in flaming up (Jaskolowski 2001).

During the decomposition of natural polymers present in the composition of wood char, resins, water and gases are formed (Drysdale 1998; Turner *et al*. 2010).

The combustibility of wood is useful only in case it is used as fuel; however, it is very harmful when buildings and structures made of timber are burning during fire. The combustibility of timber is decreased by treating it with fire retarders. Combustibility values of wood treated with a fire retardant solution depend on the chemical composition of the solution used, its consumption, treatment method as well as the structure and characteristics of the timber itself (Liodakis *et al.* 2002; Agueda *et al*. 2008; Pereyra, Giudice 2009).

Fire is a complex phenomenon: its course and effects depend on a number of interrelated factors. In case of fire in wooden buildings and constructions made of timber structures, charring timber products seems to be the most noticeable result of combustion. This feature is important for identifying the cause of fire, and therefore necessitates relating the charring of timber products and structures with particular significant effects of fire such as its duration and temperature (Lipinskas, Mačiulaitis 2005). Fire retarders change inflammation temperature and the charring rate of wood. Thus, investigation into fire finds the determination whether timber has been treated with fire retardant solution before combustion a critically important issue. No results of such scientific research have been found in literature.

The aim of the work is to determine changes in the electrical capacitance and electrical conductivity of char resulting from the combustion of various species of natural wood and that treated with fire retarders and dispersed in water. The paper also suggests the best electrical parameter that suits the evaluation of identification effect for wood treatment with fire retarders.

1. Tested materials and testing methods

1.1. Tested materials and their characteristics

For experimental purposes, pine and fir wood were used. Before testing, wood was conditioned according to the requirements of LST EN 13238:2010 (2010). The content of moisture in the specimens was determined using moister meter HPM 2000 and found to be ≤15%. For treating purposes, fire retardant solutions BAK-1 and Flamasepas-2 were applied.

1.2. Special one-side heating equipment

To identify the charring peculiarities of the wood of different species when heating for different periods of time and reaching respectively different temperatures, a special chamber for one-side heating of structures was employed (Lukošius 2004; Lipinskas, Mačiulaitis 2005). This equipment ensures the simulated one-side heating of the tested specimen up to 950 °C, which is prevailing in most fires. The used equipment consists of a one-side heating device, a heat controller as well as instrumentation and equipment for recording measurements. The principle of the experiment was to heat the specimen on one side based on the dependency of temperature on time specified in and regulated by LST EN 1363-1:2000 (2000).

The height and width of wood specimens was 210 mm and 150 mm respectively, and thickness varied from 47 mm to 59 mm. Both natural wood and that treated with fire retardant solutions BAK-1 and Flamasepas-2 were determined. Impregnation was carried out by means of brush coating. Different consumptions of fire retarders making 250 ml/m^2 (half of consumption prescribed by manufacturers) and 500 ml/m^2 (consumption prescribed by manufacturers) respectively were used. At the consumption of 500 ml/m^2, the number of coating applications totalled three, whereas at the consumption of 250 ml/m^2 it made two. Between the applications, wood was covered with a polyethylene film and kept for 12 hours to get the solution soaked.

Using the above described equipment, wood specimens were exposed to heating for a specific pre-set period of time τ, (5, 10, 20, 30 and 45 minutes). During this period, the average heating temperatures and heat flux shown in Table 1 were reached. Afterwards, the specimens were removed from the chamber extinguishing with a fire blanket or household water spray.

The char formed during the conducted tests was used for further research. For that purpose, the layer of

Table 1. The dependency of the maximum reached temperature and heat flux in the heating chamber on time

Heating time, min.	Maximum reached heating temperature, °C	Heat flux, kW/m^2
5	580	35
10	680	55
20	780	70
30	840	85
45	900	90

the resulting char of up to 5 mm thick was scraped off with a knife.

1.3. Method for measuring the electrical capacitance of char

The equipment used for research (Fig. 1) consists of an electrical capacitance metering device – LCR meter E7-13 connected to stainless steel electrodes with 1 mm thickness, 12 mm in width and 30 mm in height (working height 20 mm) using copper wires. The distance between the electrodes is 24 mm and the operating frequency of the device is 1000 Hz.

The electrical capacitance of a medium (compound) composed of distilled water and dispersed (ground) char particles (diameter of ground particles did not exceed 250 µm) was poured into a glass vessel with 36 mm in diameter and a depth of 58 mm. The compound was composed of 50 g of distilled water and 0.1 g of dispersed test substance.

The composition of the media used for testing purposes was as follows:

- Medium 1: distilled water and dispersed char of natural fir (extinguished with a fire blanket);
- Medium 2: distilled water and dispersed char of natural pine (extinguished with a fire blanket);
- Medium 3: distilled water and dispersed char of pine (extinguished with a fire blanket) treated with BAK-1 (consumption – 500 ml/m^2);
- Medium 4: distilled water and dispersed char of pine (extinguished with a fire blanket) treated with BAK-1 (consumption – 250 ml/m^2);
- Medium 5: distilled water and dispersed char of pine (extinguished with water) treated with BAK-1 (consumption – 500 ml/m^2);
- Medium 6: distilled water and dispersed char of pine (extinguished with a fire blanket) treated with Flamasepas-2 (consumption – 500 ml/m^2);
- Medium 7: distilled water and dispersed char of pine (extinguished with a fire blanket) treated with Flamasepas-2 (consumption – 250 ml/m^2);
- Medium 8: distilled water and dispersed char of pine (extinguished with water) treated with Flamasepas-2 (consumption – 500 ml/m^2);
- Medium 9: distilled water and dispersed char of fir (extinguished with a fire blanket) treated with BAK-1 (consumption – 500 ml/m^2);
- Medium 10: distilled water and dispersed char of fir (extinguished with a fire blanket) treated with BAK-1 (consumption – 250 ml/m^2);
- Medium 11: distilled water and dispersed char of fir (extinguished with water) treated with BAK-1 (consumption – 500 ml/m^2);
- Medium 12: distilled water and dispersed char of fir (extinguished with a fire blanket) treated with Flamasepas-2 (consumption – 500 ml/m^2);
- Medium 13: distilled water and dispersed char of fir (extinguished with a fire blanket) treated with Flamasepas-2 (consumption – 250 ml/m^2);
- Medium 14: distilled water and dispersed char of fir (extinguished with water) treated with Flamasepas-2 (consumption – 500 ml/m^2).

1.4. Method for measuring the electrical conductivity of char

The electrical conductivity of the tested specimens was measured using multi-purpose metre Hanna HI4521 (Fig. 2).

The medium to be used for measuring electrical conductivity was prepared in the same manner.

Fig. 1. Equipment for measuring electrical capacitance

Fig. 2. Equipment for measuring the electrical conductivity of char

2. Research results and discussion

Figure 3 shows the dependency of electrical capacitance measurements obtained from media 1 and 2 (Y) on heating time (X_1). Changes in the electrical capacitance of these media are insignificant and vary from $2.9 \cdot 10^{-11}$ F/cm to $6.4 \cdot 10^{-11}$ F/cm. Data distribution is wide and an obvious direction of the change has not been determined. Therefore, the regression analysis of the received data regarding natural fir and pine wood was performed using the linear model, and Eqn (1) was obtained to predict the electrical capacitance of wood against heating time. Research results were processed using the methods of mathematical statistics (Sakalauskas 1998).

Electrical capacitance, nF/cm:

$$Y = 0.03310 + 0.00042X_1, \quad (1)$$

where correlation coefficient R = 0.6126 and standard error Se = 0.0080 nF/cm.

Figure 4 presents the average electrical capacitance measurements obtained from media 3, 4 and 5 and composed of char resulting from pine wood heated for a different period of time, treated with different consumption of fire retardant solution BAK-1 extinguished using different methods and dispersed in distilled water.

Figure 4 demonstrates that, after 5 minutes of heating, the maximum average electrical capacitance for medium 3 – $7.1 \cdot 10^{-8}$ F/cm was recorded, whereas for the identical compound extinguished with water (medium 5), it made $2.8 \cdot 10^{-8}$ F/cm. However, the average electrical capacitance for the compound from pine treated with 250 ml/m^2 and extinguished with a fire blanket (medium 4) was $1.8 \cdot 10^{-8}$ F/cm. Thus, after heating for a minimum period of time and correspondingly reaching minimum temperature, both consumption amount and the extinguishing method have a great influence on the average electrical capacitance.

After 10 minutes of heating, the maximum average electrical capacitance was recorded for medium 3, as after 5 minutes of heating, it was equal $3.9 \cdot 10^{-8}$ F/cm, and for the identical compound extinguished with water (medium 5), it made $8.0 \cdot 10^{-9}$ F/cm and for medium 4 – $1.1 \cdot 10^{-8}$ F/cm (Fig. 4).

Also, after 20 minutes of heating, the maximum average electrical capacitance was recorded for medium 3 and was equal to $1.3 \cdot 10^{-8}$ F/cm. However, for the identical compound from pine treated with 250 ml/m^2 and extinguished with a fire blanket (medium 4), it equalled $5.0 \cdot 10^{-9}$ F/cm, whereas for the compound from pine treated with 500 ml/m^2 and extinguished with water (medium 5) – $3.0 \cdot 10^{-9}$ F/cm (Fig. 4).

When pine wood treated with BAK-1 was heated for 30 and 45 minutes, irrespective of the consumption of the fire retarder and extinguishing method (media 3, 4 and 5), the difference in electrical capacitance values was insignificant and the values varied from $2.0 \cdot 10^{-9}$ F/cm to $3.0 \cdot 10^{-9}$ F/cm (Fig. 4).

After heating for the maximum period of time and correspondingly reaching maximum temperature, the influence of consumption amount and the extinguishing method on the average electrical capacitance was significantly smaller. However, electrical capacitance in case of the heated natural pine char dispersed in water (media 1 and 2) compared to that of treated with fire retardant solution BAK-1 (media 3, 4 and 5), was by 100–1000 times lower irrespective of fire retardant consumption or the extinguishing method.

Figure 5 presents the average electrical capacitance measurements obtained from media 6, 7 and 8 composed of char resulting from pine wood heated for a different period of time, treated with different consumption of fire retardant solution Flamasepas-2, extinguished using different methods and dispersed in distilled water.

Figure 5 shows that, after 5 minutes of heating, the maximum average electrical capacitance was recorded for medium 6, which made $4.5 \cdot 10^{-8}$ F/cm, whereas for the identical compound extinguished with water (medium 8) – $1.8 \cdot 10^{-8}$ F/cm. However, the average electrical capacitance for medium 7 was equal to $1.3 \cdot 10^{-8}$ F/cm. Thus, after heating for a minimum period of time and correspondingly reaching minimum temperature, both the consumption amount of Flamasepas-2 and the extinguishing method have a great influence on the average electrical capacitance.

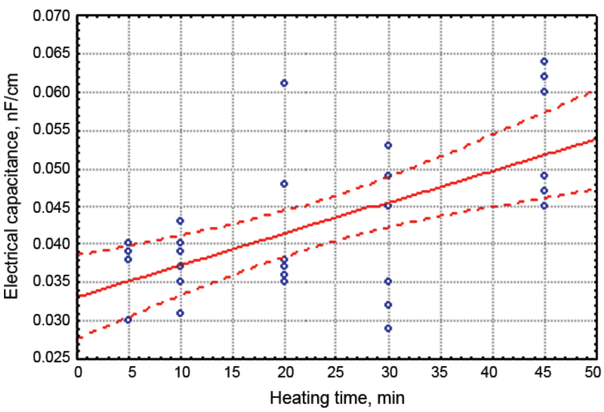

Fig. 3. The dependency of actual electrical capacitance on heating time for media 1 and 2

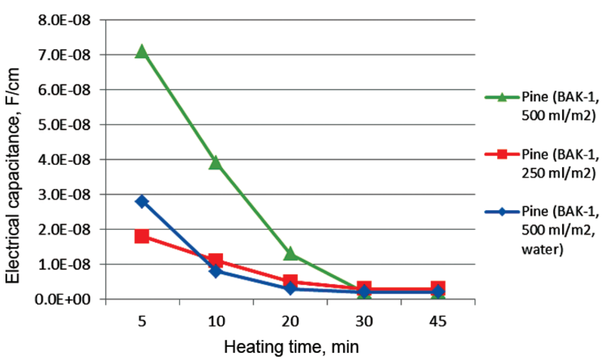

Fig. 4. The dependency of the average electrical capacitance on heating time for media 3, 4 and 5

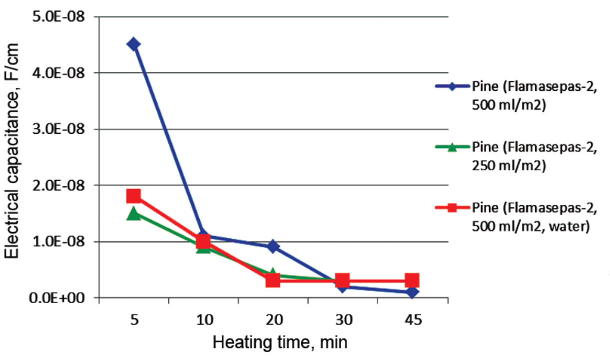

Fig. 5. The dependency of the average electrical capacitance on heating time for media 6, 7 and 8

After 10 minutes of heating, the maximum average electrical capacitance was recorded for medium 6 as after 5 minutes of heating and equalled $1.1 \cdot 10^{-8}$ F/cm. For the identical compound extinguished with water (medium 8), it made $1.0 \cdot 10^{-8}$ F/cm and for medium 7 – $9.0 \cdot 10^{-9}$ F/cm (Fig. 5).

After 20 minutes of heating, the maximum average electrical capacitance for medium 6 was $9.0 \cdot 10^{-9}$ F/cm. However, for the identical compound composed of pine wood treated with 250 ml/m^2 and extinguished with a fire blanket (medium 7), it was equal to $4.0 \cdot 10^{-9}$ F/cm, and for medium 8, it made $3.0 \cdot 10^{-9}$ F/cm (Fig. 5).

When pine wood treated with Flamasepas-2 was heated for 30 and 45 minutes, irrespective of fire retarder consumption and the extinguishing method (media 6, 7 and 8), the difference in the values of electrical capacitance was insignificant and the values varied from $1.0 \cdot 10^{-9}$ F/cm to $3.0 \cdot 10^{-9}$ F/cm (Fig. 5).

After heating for the maximum period of time and correspondingly reaching maximum temperature, the influence of consumption amount and the extinguishing method on the average electrical capacitance minimised. However, electrical capacitance, in case of heated natural pine char dispersed in water (media 1 and 2) compared to that of treated with fire retardant solution Flamasepas-2 (media 6, 7 and 8), was by 100–1000 times lower irrespective of fire retardant consumption or the extinguishing method.

The same tendencies were also determined in cases when fir wood was used for research purposes.

Research results in Figure 6 indicate that, after 5 minutes of heating, the observed average maximum electrical capacitance was recorded for char resulting from fir wood treated with 500 ml/m^2, extinguished with a fire blanket and dispersed in the water compound (medium 9) of $4.2 \cdot 10^{-8}$ F/cm. For the identical compound extinguished with water (medium 11), it made $1.2 \cdot 10^{-8}$ F/cm. However, the average electrical capacitance for media 10 was equal to $1.5 \cdot 10^{-8}$ F/cm. In this case, again, after heating for a minimum period of time and correspondingly reaching minimum temperature, both consumption amount and the extinguishing method had an influence on the average electrical capacitance. At the same time, the wood itself influenced the average values of electrical capacitance (Figs 4 and 6).

After 10 minutes of heating, the maximum average electrical capacitance was recorded for medium 9, which made $2.2 \cdot 10^{-8}$ F/cm while for the identical compound extinguished with water (medium 11) – $8.0 \cdot 10^{-9}$ F/cm. The average maximum electric capacitance for medium 10 equalled $7.0 \cdot 10^{-9}$ F/cm (Fig. 6).

After 20 minutes of heating, the maximum average electrical capacitance for medium 9 was recorded and equalled $1.2 \cdot 10^{-8}$ F/cm. However, for the identical compound composed of pine wood treated with 250 ml/m^2 and extinguished with a fire blanket (medium 10), it was equal to $4.0 \cdot 10^{-9}$ F/cm, whereas for medium 11 – $4.0 \cdot 10^{-9}$ F/cm (Fig. 6).

When fir wood treated with BAK-1 was heated for 30 and 45 minutes, the difference in the values of electrical capacitance was insignificant depending on fire retarder consumption and the extinguishing method, and the values varied from $1.0 \cdot 10^{-9}$ F/cm to $4.0 \cdot 10^{-9}$ F/cm. The wood itself had a slight influence on the average values of electrical capacitance (Figs 4 and 6).

The research results in Figure 7 disclose that, after 5 minutes of heating, the observed average maximum electrical capacitance was recorded for medium 12 and made $4.2 \cdot 10^{-8}$ F/cm, which coincided with the case when wood had been treated with the BAK-1 solution of identical concentration (medium 9, Fig. 6). Nevertheless, the average electrical capacitance of the compound with fir wood treated with Flamasepas-2 solution having the concentration of 500 ml/m^2 and extinguished with water (medium 14) was equal to $2.2 \cdot 10^{-8}$ F/cm, and the average electrical capacitance of the compound with fir wood treated with the concentration of 250 ml/m^2 and extinguished with a fire blanket (medium 13) equalled $1.3 \cdot 10^{-8}$ F/cm.

After 10 minutes of heating, the maximum average electrical capacitance was recorded for medium 12 and was equal to $1.8 \cdot 10^{-8}$ F/cm, whereas for the identical compound extinguished with water (medium 14), it made $9.0 \cdot 10^{-9}$ F/cm and for medium 13 – $7.0 \cdot 10^{-9}$ F/cm (Fig. 7).

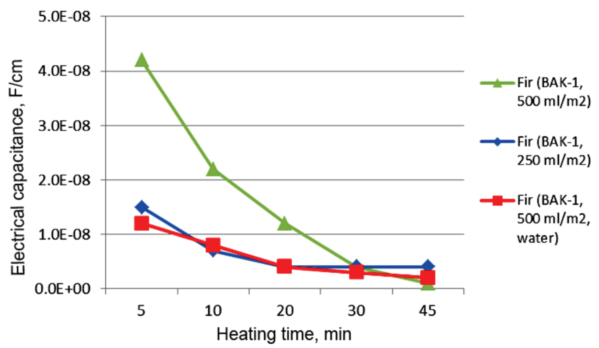

Fig. 6. The dependency of the average electrical capacitance on heating time for media 9, 10 and 11

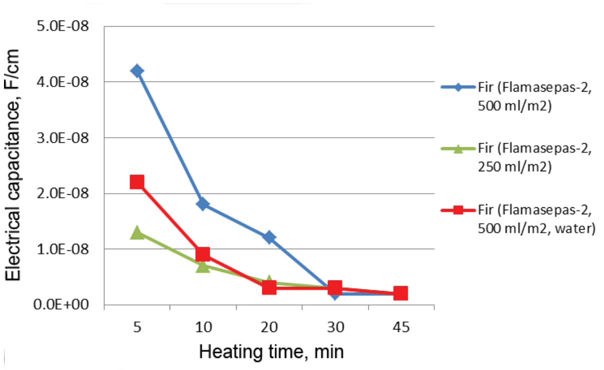

Fig. 7. The dependency of the average electrical capacitance on heating time for media 12, 13 and 14

After 20 minutes of heating, the maximum average electrical capacitance was again recorded for medium 12 and was equal to $1.2 \cdot 10^{-8}$ F/cm. However, for the identical compound composed of fir wood treated with 250 ml/m^2 and extinguished with a fire blanket (medium 13) it made $4.0 \cdot 10^{-9}$ F/cm and for medium 14 totalled $3.0 \cdot 10^{-9}$ F/cm (Fig. 7). Such results were either identical or very close to those when fir wood was treated with the BAK-1 solution (Fig. 6).

When fir wood treated with Flamasepas-2 is heated for 30 and 45 minutes, irrespective of fire retarder consumption and the extinguishing method, the difference in the values of electrical capacitance is insignificant and the values vary from $2.0 \cdot 10^{-9}$ F/cm to $3.0 \cdot 10^{-9}$ F/cm.

However, electrical capacitance in case of heated natural wood char dispersed in water (media 1 and 2) compared to that of treated with fire retardant solution (media 4 through 14) was by 100–1000 times lower irrespective of the type and consumption of the fire retarder or the extinguishing method. This is valid for different kinds of wood (pine and fir).

Figure 8 presents the dependency of the measurements of electrical conductivity (Y) obtained from media 1 and 2 on heating time (X_1) (described in Section 1.3). Changes in the electrical conductivity of these media are insignificant and make from $5.0 \cdot 10^{-6}$ S/cm to $2.7 \cdot 10^{-5}$ S/cm. Data distribution is wide and the direction of an obvious change has not been determined. Therefore, the regression analysis of the obtained data on natural fir and pine wood was performed using the linear model, and Eqn (2) was obtained to predict the electrical conductivity of wood against heating time.

Electrical conductivity, mS/cm:

$$Y = 0.00937 + 0.00020 X_1. \quad (2)$$

In Eqn (2), correlation coefficient R = 0.5082 and standard error Se = 0.0050 mS/cm.

Figure 9 presents the measurements of the average electrical conductivity obtained from media 3, 4 and 5, composed of char resulting from pine wood heated for a different period of time, treated with different consumption of fire retardant solution BAK-1, extinguished using different methods and dispersed in distilled water.

Figure 9 displays that, after 5 minutes of heating, the maximum average electrical conductivity was recorded for medium 3, which made $1.5 \cdot 10^{-3}$ S/cm and for the identical compound extinguished with water (medium 5) – $7.5 \cdot 10^{-4}$ S/cm; however, the average electrical conductivity for the compound from pine treated with 250 ml/m^2 and extinguished with a fire blanket (medium 4) was equal to $8.0 \cdot 10^{-4}$ S/cm.

After 10 minutes of heating, the maximum average electrical conductivity for medium 3 as after 5 minutes of heating was recorded and equalled $1.0 \cdot 10^{-3}$ S/cm. Electrical conductivity for media 4 and 5 was identical and equalled $7.0 \cdot 10^{-4}$ S/cm (Fig. 9).

After 20 minutes of heating, the maximum average electrical conductivity was again recorded for medium 3 and was equal to $7.0 \cdot 10^{-4}$ S/cm. However, for the identical compound composed of pine wood treated with 250 ml/m^2 and extinguished with a fire blanket (medium 4), it made $4.0 \cdot 10^{-4}$ S/cm, and for the compound composed from pine wood treated with 500 ml/m^2 and extinguished with water (medium 5), it totalled $3.0 \cdot 10^{-4}$ S/cm (Fig. 9).

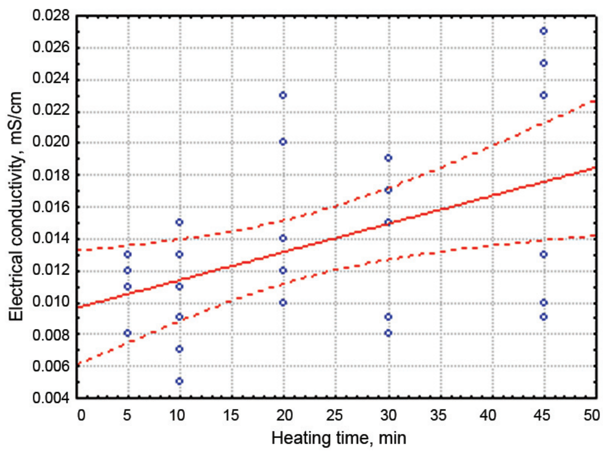

Fig. 8. The dependency of actual electrical conductivity on heating time for media 1 and 2

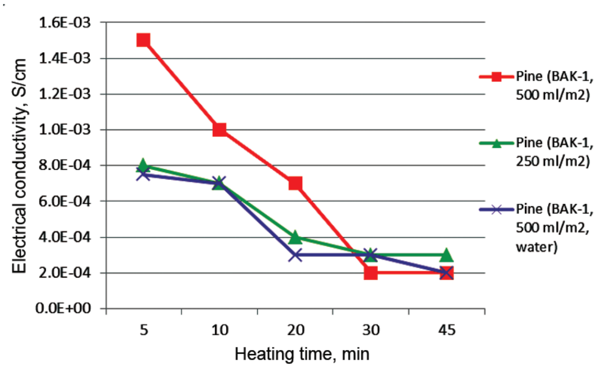

Fig. 9. The dependency of the average electrical conductivity on heating time for media 3, 4 and 5

When pine wood treated with BAK-1 was heated for 30 and 45 minutes, irrespective of fire retarder consumption and the extinguishing method (media 3, 4 and 5), the difference in the values of electrical conductivity was insignificant and the values varied from $2.0 \cdot 10^{-4}$ S/cm to $3.0 \cdot 10^{-4}$ S/cm. However, electrical conductivity, in case of heated natural pine wood char dispersed in water (media 1 and 2) compared to that of treated with fire retardant solution BAK-1 (media 3, 4 and 5), was by 10–100 times lower irrespective of fire retarder consumption or the extinguishing method (Figs 8 and 9).

Figure 10 presents the measurements of the average electrical conductivity obtained from media 6, 7 and 8, composed of char resulting from pine wood heated for a different period of time, treated with different consumption of fire retardant solution Flamasepas-2, extinguished using different methods and dispersed in distilled water.

Figure 10 shows that, after 5 minutes of heating, the observed value of the maximum average electrical conductivity for medium 6 was recorded and made $1.3 \cdot 10^{-3}$ S/cm while for the identical compound extinguished with water (medium 8) reached $9.1 \cdot 10^{-4}$ S/cm; however, the average electrical conductivity for medium 7 was equal to $7.0 \cdot 10^{-4}$ S/cm.

After 10 minutes of heating, the maximum average electrical conductivity was recorded for medium 8 and equalled $8.0 \cdot 10^{-4}$ S/cm. For the identical compound extinguished with a fire blanket (medium 6) it was equal to $3.0 \cdot 10^{-4}$ S/cm and for medium 7 – $5.0 \cdot 10^{-4}$ S/cm (Fig. 10).

After 20 minutes of heating, the maximum average electrical conductivity for medium 7 was recorded and equalled $5.0 \cdot 10^{-4}$ S/cm. For medium 8, it was equal to $4.0 \cdot 10^{-4}$ S/cm and for medium 6 – $3.0 \cdot 10^{-4}$ S/cm (Fig. 10).

When pine wood treated with Flamasepas-2 was heated for 30 and 45 minutes with slight dependency on fire retarder consumption and the extinguishing method (media 6, 7 and 8), the difference in the values of electrical conductivity was insignificant and the values varied from $1.0 \cdot 10^{-4}$ S/cm to $4.0 \cdot 10^{-4}$ S/cm. However, electrical conductivity, in case of heated natural pine wood char dispersed in water (media 1 and 2) compared to that of treated with fire retardant solution Flamasepas-2 (media 6, 7 and 8), was by 10–100 times lower irrespective of fire retarder consumption or the extinguishing method (Figs 8 and 10).

The research results presented in Figure 11 suggest that, after 5 minutes of heating, the observed maximal average electrical conductivity of char resulting from fir wood treated with 500 ml/m^2, extinguished with a fire blanket and dispersed in water (medium 9) was recorded and made $1.3 \cdot 10^{-3}$ S/cm, which for the identical compound extinguished with water (medium 11) reached $7.6 \cdot 10^{-4}$ S/cm; however, the average electrical conductivity for medium 10 was equal to $7.0 \cdot 10^{-4}$ S/cm.

After 10 minutes of heating, the average maximal and identical electrical conductivity for media 9 and 11 was recorded and equalled $7.0 \cdot 10^{-4}$ S/cm, and that for medium 10 – $4.0 \cdot 10^{-4}$ S/cm.

After 20 minutes of heating, the maximum average electrical conductivity for medium 9 was recorded and equalled $4.0 \cdot 10^{-4}$ S/cm. However, for the identical compound from fir wood extinguished with water (medium 11), it made $3.0 \cdot 10^{-4}$ S/cm, and for medium 10, it totalled $2.0 \cdot 10^{-4}$ S/cm.

When fir wood treated with BAK-1 was heated for 30 and 45 minutes, the difference in the values of electrical conductivity was insignificant with slight dependency on fire retarder consumption and the extinguishing method, and the values varied from $2.0 \cdot 10^{-4}$ to $4.0 \cdot 10^{-4}$ S/cm. However, electrical conductivity, in case of heated natural fir wood char dispersed in water (media 1 and 2) compared to that of treated with fire retardant solution BAK-1 (media 9, 10 and 11), was again by 10–100 times lower irrespective of fire retarder consumption or the extinguishing method (Figs 8 and 11).

The research results presented in Figure 12 indicate that, after 5 minutes of heating, the observed maximum average electrical conductivity for medium 12 was recorded and made $1.2 \cdot 10^{-3}$ S/cm. The average electrical conductivity of fir wood treated with Flamasepas-2 solution of 500 ml/m^2 extinguished with water (medium 14) was equal to $8.3 \cdot 10^{-4}$ S/cm, and the average electrical conductivity of fir wood treated with 250 ml/m^2 and extinguished with a fire blanket (medium 13) equalled $6.0 \cdot 10^{-4}$ S/cm.

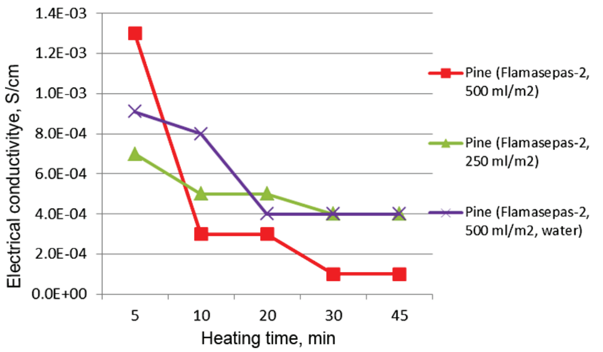

Fig. 10. The dependency of the average electrical conductivity on heating time for media 6, 7 and 8

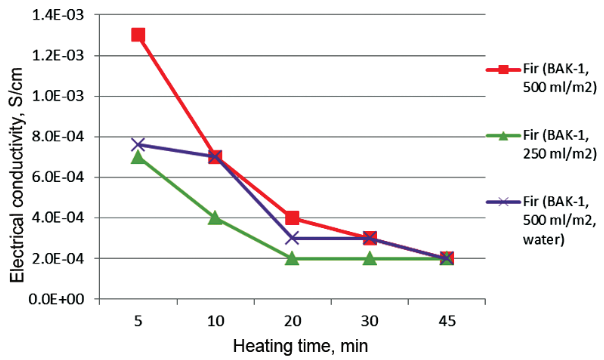

Fig. 11. The dependency of the average electrical conductivity on heating time for media 9, 10 and 11

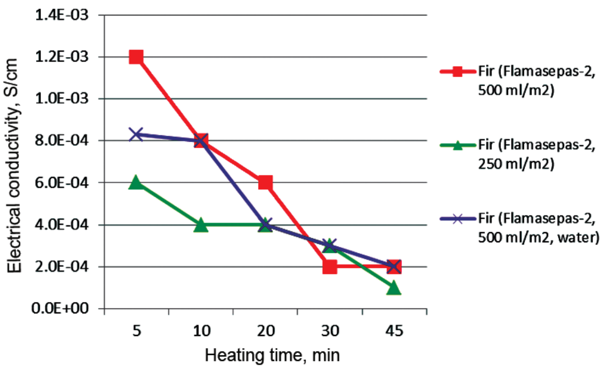

Fig. 12. The dependency of the average electrical conductivity on heating time for media 12, 13 and 14

After 10 minutes of heating, the maximum average and identical electrical conductivity for media 12 and 14 was recorded and equalled $8.0 \cdot 10^{-4}$ S/cm, whereas for medium 13, it made $4.0 \cdot 10^{-4}$ S/cm (Fig. 12).

After 20 minutes of heating, the maximum average electrical conductivity for medium 12 and was recorded and equalled $6.0 \cdot 10^{-4}$ S/cm. However, for the identical compound from fir wood treated with 250 ml/m^2 and extinguished with a fire blanket (medium 13) and for medium 14, electrical conductivity was identical and made $4.0 \cdot 10^{-4}$ S/cm (Fig. 12).

When fir wood treated with Flamasepas-2 was heated for 30 and 45 minutes, the difference in the values of electrical conductivity was insignificant irrespective of fire retarder consumption and the extinguishing method, and the values varied from $1.0 \cdot 10^{-4}$ S/cm to $3.0 \cdot 10^{-4}$ S/cm. However, electrical conductivity, in case of heated natural fir wood char dispersed in water (media 1 and 2) compared to that of treated with fire retardant solution Flamasepas-2 (media 12, 13 and 14), was again by 10–100 times lower irrespective of fire retarder consumption or the extinguishing method (Figs 8 and 12).

The electrical capacitance values of media 1 and 2 have been obtained through experiments, calculated using Eqn (1) and are presented in Figure 13 for comparison purposes.

The electrical conductivity values of media 1 and 2 have been obtained through experiments, calculated using Eqn (2) and are presented in Figure 14 for comparison purposes.

The obtained results confirm the possible use of a linear algorithm for dependency description unlike the electrical capacitance and electrical conductivity of char resulting from treated pine and fir wood and dispersed in water.

Using the model of piecewise linear regression with a breakpoint, the Eqns from (3) to (6) were obtained for predicting the electrical capacitance and electrical conductivity of treated wood with the help of all obtained actual results of experimental research.

Electrical capacitance, nF/cm:

$$Y = (8.467165 - 0.155827\, X_1)^* \,(Y \leq 10.60) + (34.61525 - 1.10617\, X_1)^{**} \,(Y > 10.60); \quad (3)$$

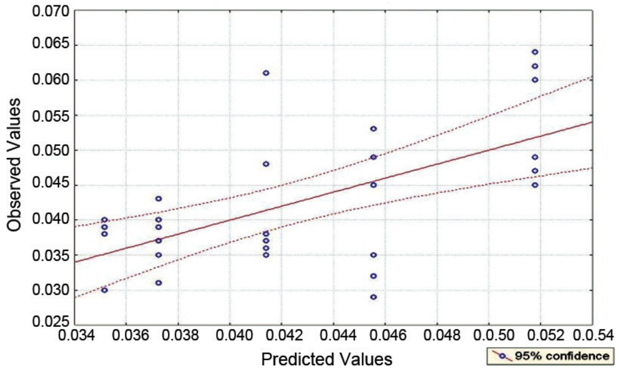

Fig. 13. The observed and predicted electrical capacitance values of natural wood

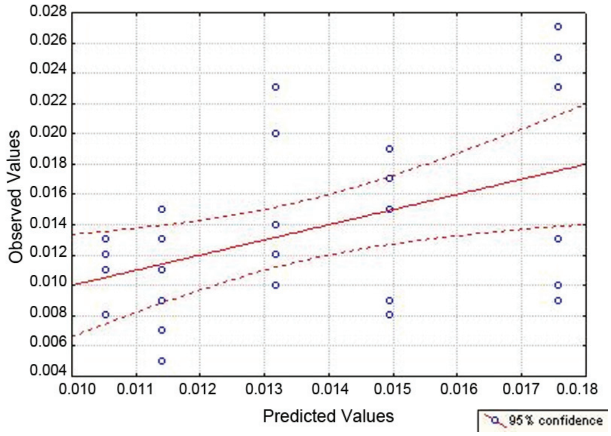

Fig. 14. The observed and predicted values of electrical conductivity for natural wood

Electrical conductivity, mS/cm:

$$Y = (0.454180 - 0.005474X_1)^* \,(Y \leq 0.501667) + (1.006419 - 0.015334X_1)^{**} \,(Y > 0.501667); \quad (4)$$

Electrical capacitance, nF/cm:

$$Y = (39.14294 + 0.140241X_1 - 0.048092X_2)^* (Y \leq 10.60) + (68.78462 - 0.194231X_1 - 0.066058X_2)^{**} (Y > 10.60); \quad (5)$$

Electrical conductivity, mS/cm:

$$Y = (0.658082 - 0.003616X_1 - 0.000315X_2)^* (Y \leq 0.501667) + (2.299387 + 0.010049X_1 - 0.002370X_2)^{**} (Y > 0.501667), \quad (6)$$

* – the equation is applied when electrical capacitance or electrical conductivity is ≤ than the observed specific value;

** – the equation is applied when electrical capacitance or electrical conductivity is > than the observed specific value;

X_1 – heating time, min; X_2 – heating temperature, °C.

Having performed the regression analysis of experimental data on treated wood, the highest value of correlation coefficient R = 0.8691 was obtained predicting electrical conductivity based on heating time and temperature (Eqn (6)), electrical conductivity only based on heating time while R = 0.8493 (Eqn (4)). Whereas for predicting electrical capacitance based on heating time, the value of R = 0.7539 (Eqn (3)), for predicting electrical capacitance based on heating time and temperature, R = 0.7672 (Eqn (5)). The values of electrical capacitance and electrical conductivity calculated using Equations from (3) through (6) and observed during the conducted experiments are provided in Tables 2 and 3.

Data in Table 2 indicate that the difference between the electrical capacitance values of treated wood observed and calculated using Equations 3 and 5 is insignificant except for heating for 5 minutes.

Data in Table 3 reflect that the difference between the electrical conductivity values of treated wood observed and calculated using Equations 4 and 6 is insignificant except for heating for 5 minutes.

Conclusions

Changes in the electrical capacitance and electrical conductivity of the media composed of distilled water and dispersed char resulting from natural fir and pine wood heated for different periods of time at different temperatures are insignificant and not tendentious, and data correlation is average if the linear model is used in a reasoned manner.

The electrical capacitance and electrical conductivity of the media composed of distilled water and dispersed char resulting from softwood treated with fire retardant solution BAK-1 or Flamasepas-2 heated for different periods of time at different temperatures reduces faster up to 20 min of heating; afterwards, it either slowly decreases or the observed changes are minor. For a description of such a change, the model of a piecewise linear regression with the breakpoint seems to be the best solution.

For media composed of distilled water and dispersed char resulting from natural softwood heated for different periods of time at different temperatures, electrical capacitance is by 100–1000 times lower and electrical conductivity is by 10–100 times lower compared to those for media from softwood treated with fire retardant solution BAK-1 or Flamasepas-2 of different consumption and using different methods for wood extinguishing.

Referring to obtained Eqns from (1) to (6), it is possible to predict the electrical capacitance or electrical conductivity of both untreated and treated softwood irrespective of the type of a fire retarder, its consumption, heating time and the extinguishing method. Priority is given to the evaluation method of electrical conductivity, as in Eqn (6), the correlation coefficient is the highest and equal to 0.8691.

Table 2. The observed and predicted electrical capacitance values of treated wood in the individual specimen

Heating time, min	Electrical capacitance, nF/cm			
	Observed value		Value calculated using Eqn (3)	Value calculated using Eqn (5)
	Fir (Flamasepas-2, 500 ml/m^2)	Fir (BAK-1, 500 ml/m^2)		
5	40.0	34.0	29.1	29.5
10	24.0	22.0	23.6	21.9
20	13.0	12.0	12.5	13.4
30	2.2	3.7	3.8	3.0
45	2.0	1.3	1.5	2.2

Table 3. The observed and predicted electrical conductivity values of treated wood in the individual specimen

Heating time, min	Electrical conductivity, mS/cm			
	Observed value		Value calculated using Eqn (4)	Value calculated using Eqn (6)
	Fir (Flamasepas-2, 500 ml/m^2)	Pine (BAK-1, 500 ml/m^2)		
5	1.2	1.3	0.93	0.98
10	0.8	0.7	0.85	0.79
20	0.7	0.7	0.70	0.65
30	0.3	0.3	0.29	0.29
45	0.2	0.2	0.21	0.21

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Romualdas MAČIULAITIS. Prof., Dr Habil. of Technological Sciences at the Department of Building Materials, Vilnius Gediminas Technical University (VGTU). Research interests: development of building materials and analysis of their characteristics.

Andrejus JEFIMOVAS. PhD student at the Department of Building Materials, Vilnius Gediminas Technical University (VGTU). Research interests: research of timber charring.

Donatas LIPINSKAS. Dr, the Head of Fire Research Centre of the Fire and Rescue Department under the Ministry of the Interior of the Republic of Lithuania. Research interests: fire protection, fire research.