Singularity and Importance of Determination of Wood Charring Rate in Fire Investigation

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In this paper experimental studies on charring of wood are reviewed with the objective of providing guidance for interpretation of char patterns in fire investigations. The present paper presents the available data on charring rates and char depth, causation of deep patterns and other. The paper similarly examines research data (on the grounds of ASTM E 119 and ISO 834), where exposure is controlled via the standard time-temperature curve, and data obtained from cone calorimeter or other bench-scale tests where the test conditions are set by specifying a heat flux, normally invariant over time, imposed on the specimen.

Keywords: charring, fire endurance, flashover, wood.

1. Introduction

In many countries, for the development of low-height buildings, wood is often applied in constructions and roof coverings. In the event of a fire in such buildings, cases of burning that usually manifest themselves as charring of wooden details (construction elements) are noticed.

Thus, investigators of fires make every effort in trying to relate such cases with certain important effects of the fire, such as its duration or ways of arising, etc. However, it is worth to mention here that rules of common character pertaining to the foregoing issue, or scientific discussion is rather limited. The situation is so unclear that even well-known specialists propose that in the investigation of fires an important role hasn't been given to the charring rate [1, 2]. NFPA 921 [3] in the standard manual meant for fire investigators states the following: "The investigator is cautioned that no specific time of burning can be determined based solely on the depth of char.". Irrespective of the above-indicated fact, considerable attention is paid to discussions how to measure charring depth and what conclusions could be drawn according to such measurements. Similar logic is followed in recommendations of the Russian scientists [4, 5] as used in our country. Those contain summarized wood charring rates, specifics of measurement of carbonic layer, forecast for charring rate by using theoretical and instrumental methods, however upon failure to evaluate the influence of quite a number of factors that are topical and relevant today.

Objective of the present paper is to show how it is possible to use charring samples for prediction of the onset of a fire, upon reasonable and thorough study of such samples.

The present paper gives the analysis of certain research data (in compliance with ASTM E 119 or ISO 834), by using the standard time-temperature curve, and the results obtained after performance of tests in the cone calorimeter and other measuring devices, by aiming to fix heat flux, imposed on various specimens. A review is stored with researches data of paper authors.

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2. Charring of natural wood specimens by designing ASTM 119 or ISO 834 conditions

For quite a long period of time, designers/constructors of buildings, willing to calculate the loss of the loading holding capacity of wooden beams in the course of time after flare-up during a fire, were interested in the charring rates. By aiming to receive such data, a considerable number of different studies and investigation results, obtained by using a typical fire testing device – a fire-resistant test furnace were published. Usually such tests are performed by forming fire effect conditions (time / temperature curve), as it is provided for in ASTM E 119 [6] or ISO 834 [7]. Parameters of the fire resistance test furnace as indicated in these two-type tests are quite similar.

By using a similar procedure ISO 834, Lawson and others [8], within a 29-minute period, tested Douglas-fir beams and established the following: the average charring rate equaled to 0.635 mm/min. The results obtained were somewhat non-linear, and they submitted the following additional expression to the instantaneous charring rate:

$$\beta_t = \frac{1.04}{t^{0.2}}, \tag{1}$$

where β_t is the instantaneous charring rate (mm/min.) and t is the time (min.). More conveniently, the authors also submitted a similar expression for the average charring rate:

$$\beta = \frac{1.30}{t^{0.2}}, \tag{2}$$

where β is the average charring rate (mm/min.), t is the time (min.).

By using the similar equipment, Rogowski [9] published the test results of the softwood laminated columns. Their charring rate equaled to 0.65 mm/min., when the flame spread in parallel with the surface of the laminated panel, and 0.77 mm/min., when it spread square.

Butler [10] overlooked the results of fire resistance tests carried out by the British researches and drew the following conclusion: when the time of fire action ranges within the interval of 5 min. – 30 min., then the charring rate, equaling to 0.66 mm/min., is typical. In Germany, Lache [11] tested two softwood and three deciduous wood (hardwood) samples and established that the charring rate equaling to the duration of 60 min. ranged within the interval of 0.55 mm/min. – 0.80 mm/min. Swiss scientists Frangi and Fontana [12] tested fir beams in ISO 834 thermal furnace, when the exposure in fire time ranged from 30 min. to 110 min., and fixed the charring rate equaling to 0.7 mm/min., when the thickness of wood of the remaining part exceeded 50 mm, however when the size of the remaining section was less than 50 mm, the charring rate increased in the below indicated procedure:

$$\beta = 2.36 - 0.036\,w, \tag{3}$$

where β is the charring rate (mm/min.), w is the remaining section thickness (mm).

Frangi and Fontana [12] did not fix any effect of the density ρ on the charring rate of wood, when the density of the wood under investigation was within the interval of 340 kg/m^3 – 500 kg/m^3, they also failed to establish any effect of the moisture content (MC) on the charring rate in the presence of moisture values from 8 % to 15 %. Survey performed by White [13] also failed to fix any effect of density on the wood charring rate, when the wood density varies from 400 kg/m^3 to 700 kg/m^3. On the other hand, Lache [11] tested that in general, when the wood MC = 20 %, the charring rate was by 8.3 % lower if compared with the circumstances when MC = 8 %. Lache [11] also mentioned that the charring rates in the radial, tangent and longitudinal directions, practically, were identical.

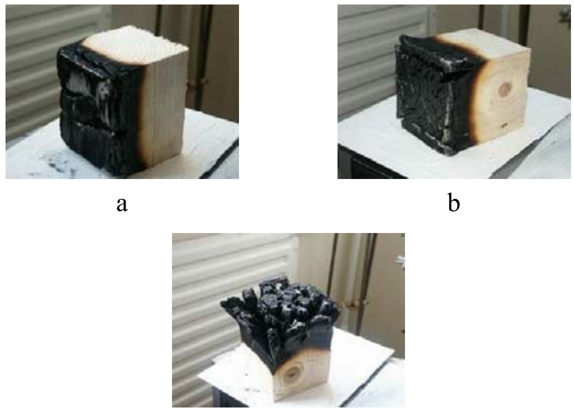
In the course of tests of the similar character, recently performed by paper authors [14], by using ISO 834 conditions, we have established that the charring rate of hardwood (ρ = 680 kg/m^3) of 60 min. duration equals to 0.5 mm/min. – 0.6 mm/min., while that of softwood (ρ = 455 kg/m^3) is 0.8 mm/min. – 0.9 mm/min. Moisture content of the used wood specimens did not exceed 15%.

By using the same testing equipment [14], tests of charring of different wood species, performed by us quite recently, when the specimen are exposed lengthwise of wood, showed that anisothropic media had influence on the wood charring, the foregoing fact may be proved by samples as given in Figure 1. It has been established by tests that the average charring rate of softwood in the direction of its growing equals to 1.2 mm/min.; while that of hardwood is 0.8 mm/min. Moisture content of the used wood specimens did not exceed 15 %. Consequently, it is clear that the values of the charring rate along the direction of wood growing increase. Thus, the results obtained by Lache [11] and us, in fact, are different.

In Australia, in the course of the performed test, Syme [15], in the period of 2 hours, investigated quite a number of different wood species under the conditions of exposure to the fire, similar to ISO 834. However, he failed to establish any specific or peculiar differences of hardwood / softwood (conifers), but determined a certain systemic effect of wood density and produced the following link:

$$d = \frac{413t}{\rho} + 1.6\,, \tag{4}$$

where d is the char depth (mm), t is the time (min.), and ρ is the density (kg/m^3).



a b

c

Fig. 1. Tests of pine wood charring under typical fire conditions: a – perpendicularly of wood after 15 min., b – lengthwise of wood after 15 min., c – lengthwise of wood after 30 min.

Such formula has been obtained only in respect of high-density specimens, when this index varied from 500 kg/m^3 to 900 kg/m^3. Values, obtained from his equation, are close to the data obtained in our case study [14]. Collier [16] performed tests with New Zealand woods and established the charring rates 400 kg/m^3 – 600 kg/m^3 on their specimens, in the presence of 12 % moisture content. In case we use the ratio as applied by Syme [15], consequently, it is possible to presume the following as regards the foregoing interval of density: the charring rate will equal to 0.72 mm/min. – 1.10 mm/min. In the course of tests carried out in Japan [17], upon the presence of circumstances as similar to ISO 834 exposure to fire, the following charring rates were fixed: 0.67 mm/min for Douglas-fir (ρ = 565 kg/m^3) and fir (ρ = 410 kg/m^3), 0.74 mm/min. for the Japanese cedar (ρ = 420 kg/m^3). Njankouo and others [18] have tested the hardwood of tropical forests the density of which reaches 1060 kg/m^3, and have established the undoubted decrease of the charring rate upon increase of the density; however such wood in Europe aren't usually used for the purpose of construction.

White and Nordheim [19], by using a small vertical thermo camera, performed ASTM 119 tests with various sorts of wood. Upon application of the assessment criteria that the charring starts from 288 °C, they have established that a time period equaling to (14.6 – 15.0) minutes was required for charring up of 13 mm depth of the fir or pine in case the specimen were tested in the presence of 50 % RH (relative humidity). In the event of testing specimen under 30 % RH, the charring rate reduced to (12.1 – 14.6) minutes. Accordingly, the time to char through, i.e. 25 mm, equaled to (31 – 34) minutes, in the presence of 50 % RH and (29 – 33) minutes in the presence of 30 % RH. Charring rate of hardwood required 10 % – 20 % more time. In the course of investigation of the time-determined data, they obtained an equation that was similar to equation of Lawson (1):

$$\beta = \frac{b}{t^{0.19}}\,. \tag{5}$$

In his studies, however, the parameter b was not a constant, but rather depended on factors that included density, moisture content and absolute char contraction. The parameter b is calculated by the following formula:

$$b = -0.147 + 0.000564\rho + 1.21u + 0.532f_c, \quad (6)$$

where ρ is the density of the dried wood, kg/m^3; u is the moisture content (fraction of oven-dry mass); f_c is the char reduction factor (dimensionless).

In compliance with the above-described results of the performed tests, it is a usual thing to read very simple recommendations in various publications. For example, the wood chars at the rate of 0.6 mm/min. or 0.5 mm/min. after the initial time period of 30 minutes upon effect of the flame. It should be noted that the value is not exact, however, the experimental results of the tests do not contravene with the below laid-down conclusion: in case a wooden specimen is solid, while the wood density varies from 400 kg/m^3 to 550 kg/m^3, then the charring rate under the conditions of fire-resistant test furnace will range from 0.5 mm/min. to 0.8 mm/min. But this rule shall not be applied in respect of the fires of a very short duration as a certain period of time is necessary for the specimens to heat up and ignite, while later – char. However, it is worth to mention here that the indicated periods greatly differ, while the factors that affect them have not been fully investigated yet. Hadvig [20] specified that in the course of tests, after (4 – 6) minutes the wood specimens only heated up and later ignited in the fire resistant test furnace, and that in the course of the foregoing tests, within the first-6-minute period, only a rather inconsiderable level of charring was noticed. On the other side, Price [21] announced that in the course of his tests the wood specimens heated up and ignited within a 1-minute period, while they fully flared up after a 2-minute period. So the obtained results are diverse.

3. Wood charring rates in regulated heat flux

The collected data obtained by using ASTM E 119 or ISO 834 in the course of the test upon gradual increase of the heat flux. Another important means for organization of the test performance provides for a device spreading heat where the outer heat flux is fixed on the specimen without changing the time. Figure 2 shows results reported by Butler [10], Thomas [22] and Griffiths [23].

The results of Butler were obtained using a bank of infra-red lamps; the other investigators used a gas-fired radiant panel. All of the data involved exposures where no flame was present. The data-fit line shown in Figure 2 is:

$$\beta = 0.028\, q''_{tot}, \quad (7)$$

where β is the charring rate (mm/min.), q''_{tot} is the external heat flux (kW/m^2).

Correlation coefficient of this equation R = 0.9851, while the determination coefficient R^2 = 0.9704.

But the submitted expression (7) is not completely correct as it fails to include the data of the charring rate in the presence of the heat flux values that range from 10 to 20 kW/m^2. After the performance of the regressive analysis of all the Thomas [22] data (Fig. 3), we have obtained a more practical and all-data-reflecting empirical equation in the below-indicated expression:

$$\beta = 0{,}018\, q''^{\,1{,}0343}_{tot}, \quad (8)$$

where β is the charring rate (mm/min.), q''_{tot} is the external heat flux (kW/m^2).

Correlation coefficient of this equation R = 0.9522, while the determination coefficient R^2 = 0.9067.

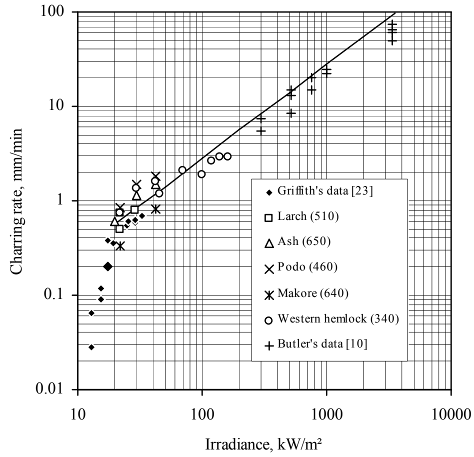


Fig. 2. Results obtained using infra-red lamps or gas-fired radiant panels. The data identified by wood species are from Thomas [22], with the value in parentheses denoting the density (kg/m^3)

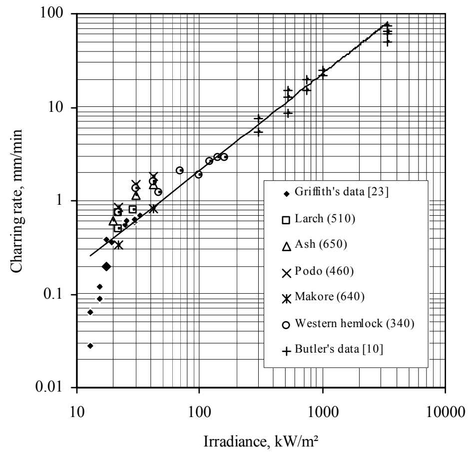


Fig. 3. Regressive analyses all of the data identified by wood species are from Thomas [22], with the value in parentheses denoting the density (kg/m^3)

Upon comparing the equations (7) and (8), we see that not only coefficients are differing, but the indexes of degrees of these equations also vary.

In the recent years, quite a number of different scientists tested various wood species in the cone calorimeter. The majority of them have produced the generalized data without specifying time intervals in the course of which the charring rate and the depth used to be calculated. By taking into account the publications containing information on an appropriate period of time, it is possible to examine the data from Kristofferson [24], Bulien [25] and Tsantaridis [26].

The analysis of data delivered by Babrauskas [27], evidences that the effect of the time period is rather strong; furthermore, dependence on radiation is considerably weaker if compared with the initial power and, in fact, 0.5 power best corresponds it. The predicted equation as obtained from the performed analysis of the data would be as following [27]:

$$\beta = 0.23(q''_{tot})^{0,5}\, t^{-0,3}\,, \tag{9}$$

where β is the charring rate (mm/min.), t is the time (min.), q''_{tot} is the external heat flux (kW/m^2).

It was assumed for the specimens that ignited, that $q''_{tot} = q''_e + 25$, where q''_e – irradiance from cone heater (kW/m^2). Figure 4 shows the agreement between predicted and measured results. Most of the test specimens were roughly of similar density (generally around 480 kg/m^3 – 500 kg/m^3), so an explicit density factor is not derivable from these test data.

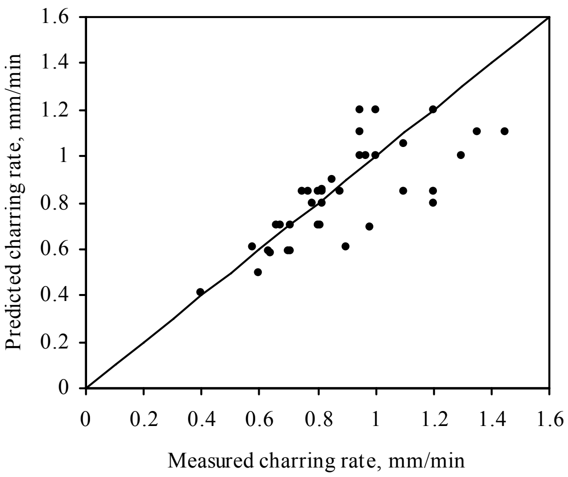


Fig. 4. Comparison of measured and predicted charring rates in the cone calorimeter, according to Babrauskas [27]

Harada [25] investigated the effect of density in the cone calorimeter and indicated that the charring rate β varies in inverse ratio to density ρ, which provides for the following:

$$\beta = 113\frac{\left(q''_{tot}\right)^{0.5}}{\rho t^{0.3}}\,, \tag{10}$$

where β is the charring rate (mm/min.), q''_{tot} is the external heat flux (kW/m^2), ρ is the wood density (kg/m^3), t is the time (min.).

Direction of the heat flux in respect of the specimen is also of great importance as the effect will depend on the effect of the heat flux differences in the testing devices to horizontal / vertical direction of the specimen, however the number of scientific researches on the foregoing issue both under ASTM E 119 and ISO 834 testing conditions is rather inconsiderable.

Babrauskas [27] indicates (Table 1) the average heat fluxes throughout an initial 60-minute period. The author observes that results according ISO are approximately 30 % lower if compared with ASTM E 119 values, however the working temperatures regimes of both methods are rather similar. Furthermore, factual charring rates according ISO 834 do not differ from those as established under ASTM E 119, therefore the author makes the following presumption: measurements of ISO 834 heat flux are less reliable.

However the recent measurements effected by Lukošius [29] do not object to the foregoing fact as thermal furnace of small specimens, corresponding to his ISO 834 conditions, already in a 30-minutes period of time, allows to reach 70 kW/m^2 flux, while the further heat-flux-growing tendency obviously comply with the average data of ASTM E 119 in a 60-minute period of time. In addition to the said, he submits the comparative statistic analysis of the calculated and measured heat flux density that is given in Figure 5. The obtained linear regression equation shows that the measured values of the heat flux are 0.335 kW/m² higher than the calculated ones because in the case of ideal correspondence the linear equation would be expressed as following: $y = x$. All the comparative meanings of the calculated and measured heat flux fall within the reliance limits of the predicted meanings (by linear equation) 95 %.

Table 1. Average heat fluxes for the first 60 minutes of exposure in several test furnaces [27]

Furnace	Method	Avg. heat flux (kW/m^2)
National Gypsum floor furnace	ASTM E 119	99
NRC floor furnace	ASTM E 119	97
UL column furnace	ASTM E 119	79
UCB wall furnace	ASTM E 119	104
Average for 5 wall furnace	ASTM E 119	92
SP floor furnace	ISO 834	69
SP wall furnace	ISO 834	66
FRS wall furnace	ISO 834	76
FRS column furnace	ISO 834	74

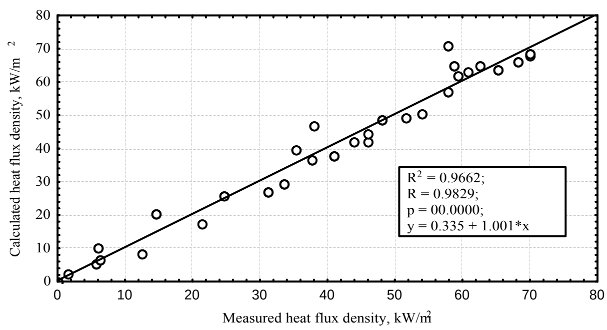


Fig. 5. Comparative statistical analysis of the calculated and measured heat flux density, according to Lukošius [29]

Thus, the differences as indicated in Table 1 in the presence of different test methods may not be strictly evaluated. Furthermore, the author [27] fails to provide the average heat flux of the cone calorimeter; therefore it is rather complicated to compare traditional methods with the widely-popularized new method. Undoubtedly, it is worth to mention here that all the results of the cone calorimeter deal with the tests in presence of 21 % of oxygen in the atmosphere and for this reason such method, definitely, is much more real when the concentration of oxygen in fire resistant test furnaces (both ASTM E 119 and ISO 834) will be considerably lower.

Mikkola [30] states that in the presence of 8 % – 10 % of oxygen, the charring rate will decrease by approximately 20 %. Thus, the author provides for a correction that allows evaluating the amount of oxygen under the test conditions by predicting both the data of cone calorimeter and other experimental furnaces:

$$\beta = 113 k_{\text{ox}} \frac{\left(\bar{q}''_{\text{tot}}\right)^{0.5}}{\rho t^{0.3}}, \tag{11}$$

where β is the charring rate (mm/min.), ρ is the wood density (kg/m^3), t is the time (min.), $\bar{q}''_{\text{tot}}$ is the the test-average total heat flux, $k_{\text{ox}} = 1.0$ for charring in plentiful oxygen (e.g., in the cone calorimeter) and $k_{\text{ox}} = 0.8$ for furnace tests.

If talking about the results of the test in fire resistant furnaces, for example, when $\rho = 455$ kg/m^3, $t = 60$ min., and if it is regarded that the average heat flux is the one as ours furnace (flux of the used furnace 88 kW/m^2), the calculated charring rate obtained is $\beta = 0.55$ mm/min., whereas the one measured by us is 0.8 mm/min. When $\rho = 680$ kg/m^3, then according to (11) reliance, the calculated charring rate will be 0.37 mm/min, while the one calculated by us equals to 0.5 mm/min. Thus, the differences are evident and they prove that the submitted calculation formulation reduces values of the charring rate and fails to fully reflect the results of factual research, however, undoubtedly, differences of the results obtained in the course of two-type experiments may be coordinated within the limits of experimental dispersion.

4. Heat fluxes and the charring rate in case of developed fire

By aiming to finally evaluate the charring rate of wooden constructions it is necessary to assess not only the data as obtained upon applying one or another type of testing devices, but also to make clear what happens in case of fires in the premises. For the above-indicated reason it is of particular importance to discuss whether heat fluxes that are used in the fire resistant test furnaces are typical (standard) heat fluxes in real fires in premises. Fang [31] is an author of one of the most comprehensive and thorough study on the foregoing topic dealing with the issue of heat fluxes in room fires. The duration of his tests is 60 minutes, while the highest temperatures usually were reached upon the expiration of a (10 – 25)-minute period after the ignition. Fang's data evidence the presence of the average heat flux that equals to 91 kW/m^2 $\pm$27 kW/m^2 at the ceiling and 138 kW/m^2 $\pm$26 kW/m^2 at the walls. The author doesn't indicate average heat flux data at the floor, but he indicates maximal heat flux values in all actual points of the premises. Fang [31] tested, that the average heat flux maximum at the floor was less than at the ceiling and is to be expressed by the following ratio: 162/176 = 0.92. In compliance with the delivered numbers, the average heat flux at the floor is 84 kW/m^2 $\pm$25 kW/m^2. Consequently, the average heat fluxes shall be regarded as 84, 138 and 91 kW/m^2 at the floor, walls and ceiling, accordingly. If the average flux of furnace equals to 92 kW/m^2, then there will be no deflection flux at the ceiling and in the case of the fire developed by Fang.

If wooden constructions in case of the fire in the premises are thick and without any joins, cracks or openings, and if there are no any openings and direct air streams near them, then it is possible to predict that the charring rates will be similar to the ones that are established on the beams and columns in the fire resistant test furnaces. Hakkarainen [32] measured the charring of the laminated thick wood elements in the premises upon flare-up of a strong fire in the wooden fireplace. On the ceiling, the charring of 30 mm occurred in a 40-minute period, while on the walls – within a 50-minute period. Within the first 3 minutes no burning process took place, however later, in the first part of the test, the charring rate increased quicker, in the later stage of the test it slowed down. The results allow making the presumption: average charring rates are 0.75 and 0.60 mm/min., accordingly, which fall into the same interval as the major part of the data pertaining to the charring rates of beams and columns in the fire resistant test furnaces (0.5 – 0.8 mm/min.).

5. Discussion

Upon flare-up of the fire in the premises (however not in the presence of most extreme conditions), after development of fire, thick wooden or similar wooden parts without any openings, cracks or joins will char up in a similar way that is to be fixed by performing experiments in the fire resistant furnaces, that is within a 0.5 mm/min. – 0.8 mm/min. period. Thus, if specific previous factors that may affect the conditions of an extreme case are unknown, it is possible to make the following presumption: during the factual fire, the charring rates will not exceed the results as obtained in the course of laboratory researches. Consequently, in a much uncomplicated way, without using any additional laboratory investigations, it is possible to predict the fire-duration. Let's say, the depth of carbon of the wooden construction, measured on site of the fire, complying with the above-indicated conditions, equals to 16 mm, then after evaluation of the possible quickest wood charring rate, i.e. 0.8 mm/min., we may calculate the shortest duration of the fire in the premises which in the present case will equal to 16/0.8 = 20 minutes. However it is worth to notice that the conditions of spreading and ventilation of the majority of real fires may be such that temperatures remain considerably lower than in the case of the developed fire. On the basis of the above given data it is possible to state that the charring rates may be considerably lower than those that are directly related to particularly big fires. Furthermore, wood protection means, as evidenced by investigations, also have influence on the rate of the charring process.

From the submitted analysis it is possible to draw the following conclusion: in ASTM E 119/ISO 834 tests, the researches of the influence of the wood density on the charring rate were rather inconsistent and contradictory. Irrespective of the fact that in quite a number of different countries wood of different species used for construction usually distinguish for a narrow density range, the matter pertaining to the unified method for calculation of the charring rate is rather complicated and problematic and has not been solved up to now.

CONCLUSIONS

1. Investigations of the influence of the wood density in ASTM E 119/ISO 834 standards on the charring rate

were inconsistent and contradictory. Irrespective of the fact that wood species that are used for construction in most of countries distinguish by narrow density range, a mater pertaining to the united method for calculation of the charring rate is problematic and has not been fully settled yet.
2. In the course of real fires in the premises, the average heat fluxes of test furnaces are rather similar, thus, the wood charring rates of wooden constructions as established under the laboratory conditions, and other fire resistant parameters are proper and suitable for performance of various calculation or prediction tasks.
3. In the event of occurrence of the developed fires in the premises, however not under the most severe extreme conditions, thick wooden details without any openings, cracks or joins will char up at the similar rate that is established by performing tests in the fire resistant test furnaces – 0.5 mm/min. – 0.8 mm/min.

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