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Effect of Fire Retardant Painting Product on Smoke Optical Density of Burning Natural Wood Samples

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Abstract**—**Natural wood is used in many applications in Jordan such as furniture, partitions constructions, and cupboards. Experimental work for smoke produced by the combustion of certain wood samples was studied. Smoke generated from burning of natural wood, is considered as a major cause of death in furniture fires. The critical parameter for life safety in fires is the available time for escape, so the visual obscuration due to smoke release during fire is taken into consideration. The effect of smoke, produced by burning of wood, depends on the amount of smoke released in case of fire. The amount of smoke production, apparently, affects the time available for the occupants to escape. To achieve the protection of life of building occupants during fire growth, fire retardant painting products are tested. The tested samples of natural wood include Beech, Ash, Beech Pine, and white Beech Pine. A smoke density chamber manufactured by fire testing technology has been used to perform measurement of smoke properties. The procedure of test was carried out according to the ISO-5659. A nonflammable vertical radiant heat flux of 25 kW/m^2 is exposed to the wood samples in a horizontal orientation. The main objective of the current study is to carry out the experimental tests for samples of natural woods to evaluate the capability to escape in case of fire and the fire safety requirements. Specific optical density, transmittance, thermal conductivity, and mass loss are main measured parameters. Also, comparisons between samples with paint and with no paint are carried out between the selected samples of woods.

Keywords**—**Optical density, specific optical density, transmittance, visibility.

I. INTRODUCTION

NATURAL woods are widely used in buildings in Jordan, particularly kitchens, furniture and doors. Wooden materials often play an important role in the compartment fire, especially in occupancies involved by natural wood such as residential and office occupancy. Most interior finishings of buildings in Jordan use natural wood. When woods are burnt, high quantity of smoke plumes are generated. One of the major causes for death and property loses in wooden fire accidents is generation of carbon monoxide through the thermal degradation of cellulose and partial oxidation of carbon. Smoke is the airborne solid and liquid particulates in gases evolved when a material undergoes pyrolysis or combustion [1], [2].

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Statistics illustrate that smoke inhalation and asphyxiation, rather than burn injury, leads to a majority of the fire fatalities. To protect the life of occupants and property construction from fire burning wood accidents, fire retardant material (FRM) as a form of paint is used by several researches. Products of smoke threaten life directly, either by damaging the body by toxic gases or by reducing visibility and causing disorientation from the light scattering effects of products' gases and particles.

The large amounts of smoke generated by fire is considered as a major hazard, particularly in the early stages of fire growth, which is associated with visibility problems and exposure to toxic environments. The reduction in visibility due to smoke concentration leads to a critical situation for am occupant's life protection and fire safety provisions. It affects the heart rate and blood circulation. This situation may be hazardous in case of toxic gases and high temperature products, particularly if people are not quickly able to find the means of escape. Since measuring visibility is not possible directly, opacity quantity, stopping the passage of light rays, is measured. Theoretical models for determining the optical density in smoke using Computational Fluid Dynamics (CFD) simulations were compared with the experimental data of Haukur and Bror [3]. Several experimental works were carried out and collected to find a correlation between visibility and optical density (OD) [4]. The study found that at an OD of 5.0 m^{-1}, a person can only see 0.6 meters in front of him. Also, they concluded that visibility limit is at a smoke OD value of 0.08 per meter, corresponding to a 10 meter visibility minimum.

Reference [5] reported the optical measurements for smoke generated from burning sheets of building materials (polymers) with a two-white laser beams (Helium Neon Laser) simultaneously for checking whether forward scattering exists or not. Helium-Neon laser is found to be an effective mean for eliminating the forward scattering effects. Both gave the same amount of attenuation and the same OD with small deviation due to the non-homogeneity of the smoke and soot deposited on the glass holes.

Reference [6] measured the smoke density of wood based materials like general purpose plywood, Marine Plywood (BWP grade), Medium Density Fibre Board (MDF), Bamboo Mat Board (BMB), and Pre-laminated Particle Board (PPB) using chamber methods (ASTM D 2843-70). They found that the general purpose plywood has the lowest smoke density (40.59) and marine plywood has the highest smoke density (62.81). Reference [7] carried out a measurement in non-flaming condition on smoke produced by solid materials, wood and PMMA, which exposed to 25 kW/m^2 heat flux. They performed measurement of transmittance and OD of smoke on visible wavelength spectrum between 350 nm and 1125 nm. The main conclusions of their study were the transmittance of the smoke is 20,000 times lower for wood than for PMMA and concentration of smoke is 20 times higher for wood than for PMMA after 20 minutes of smoke emission. Reference [8] compared specific OD of smoke for expanded polystyrene (EPS) with and without cover components used in external thermal insulation composite systems (ETICS). The samples were exposed to a constant heat flux 50 kW/m^2. The results showed, during flame combustion, samples evolved high amount of smoke. Samples from EPS released more smoke like samples with ETICS cover. Smoke density chamber method for evaluation the potential smoke generation of building materials was developed in 1966 by the Fire Research Section at the National Bureau of Standards (NBS) [9].

The current study aims to use bench-scale testing device, smoke density chamber (SDC), which is considered as one of the standardized experimental methods to measure smoke properties such as OD and transmittance of certain samples of wood materials painted with FRM as the basis for prediction of fire behavior. The effect of painting on the smoke characteristics is also experimented due to the limited quantitative data of smoke production for natural wood painted with FRM with non-flaming mode. Also the obtained properties under bench-scale tests will be added to the knowledge data to develop building codes and to enable researches to make accurate modeling. Moreover, a building designer should be able to use the resulted data to select a material with a moderate smoke load. Four types of natural wood samples were chosen for the current research.

II. Experimental Approach

A quantitative measurement of the specific OD and transmittance of the smoke is carried out in the fire safety engineering laboratory at Prince Hussein bin Abdullah II Academy of Civil Protection using a smoke density chamber (SDC) apparatus, as shown in Fig. 1, which is manufactured by Fire Testing Technology Limited (FTT). The SDC includes a sealed test enclosure, an electrical furnace, gas burner, and photo multiplier (PM) system with a collimated light beam passing through the chamber. The electrical furnace emits a constant heat flux with a capacity 25 kW/m^2 on the exposed sample surface which is horizontally oriented. The sample to be tested measured ($76\,\text{mm} \times 76\,\text{mm}$) must be wrapped in aluminum foil and placed in the sample holder. The sample holder was designed to expose a surface area ($65\,\text{mm} \times 65\,\text{mm}$), as shown in Fig. 2. All the samples were tested in the horizontal direction. The smoke produced was allowed to accumulate inside the enclosure and its opacity was measured by PM system. The apparatus calibration and the procedure of testing have been performed according to the procedure described in ISO 5659 under non-flaming condition [10]. The sample was burned inside the enclosure and the light transmission was recorded each five seconds.

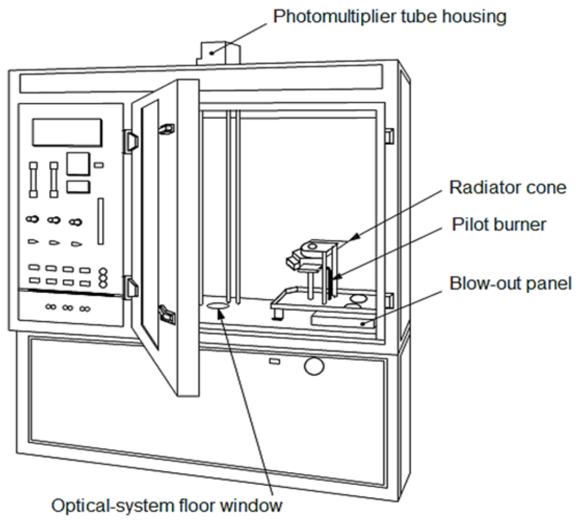

Fig. 1 Typical arrangement of test apparatus [11]

Fig. 2 Specimen and holder with final preparation

III. Theoretical Background

Measurements were made in terms of loss of light transmittance through a collected volume of smoke and effluent of a test sample produced in a fixed volume chamber under standardized conditions. Monitoring the attenuation of a beam of light passing through the smoke is expressed as percentage of overall transmittance (T), as given in (1) [14], [15]

$$T = \frac{I}{I_o} 100 \quad (1)$$

where I and I_o are the transmitted light intensity in presence and absence of smoke, respectively. The smoke concentration is measured by degree of the opacity of smoke and usually expressed by quantitative quantity called OD (De), its unit is decibel (db), which introduced in the following form [14], [15]:

$$D_e = 10 \log_{10} \frac{I_o}{I} \quad (2)$$

The OD is always given for a specific path length. The OD per meter (D_L), db /m is:

$$D_L = \frac{10}{L} \log_{10} \frac{I_o}{I} \quad (3)$$

The following correlation between the OD, DL, and visibility in meter (S) through the smoke are recommended, as in [11]:

$$S = \frac{1}{D_L} \tag{4}$$

To convert percentage of transmittance obtained on PM system to specific OD (D_s), Beer's laws is applied in:

$$D_s = G \log_{10}\left(\frac{100\%}{T}\right) \tag{5}$$

where G is geometrical factor for chamber (132) which would be directly proportional to the chamber volume in which the smoke is accumulating (0.5 m^3) and indirectly proportional to the optical path length of light (0.941 m) and exposed sample surface area producing smoke (65 mm × 65 mm).

IV. Results and Discussion

Natural wood is a heterogeneous, hygroscopic, cellular, and anisotropic material. It consists of cells, and the cell walls are composed of micro-fibrils of mainly cellulose (40%-50%), hemicellulose (15%-25%) impregnated with lignin (15%-30%). The summation of these three constituents makes up 95% by weight of dry wood, which varies from species to species [12]. Wood in general is classified as either softwood or hardwood. The wood from conifers is called softwood, and the wood from dicotyledons is called hardwood. In chemical terms, the difference between hardwood and softwood is related to the composition of the constituent lignin. Hardwood lignin is primarily derived from sinapyI alcohol and coniferyI alcohol, while soft wood lignin is mainly derived from conifer II alcohol. Four types of natural wood were taken into consideration in this works. Beech and Ash wood were taken as a hardwood, and Beech Pine and White Pine Beech wood (white wood) were taken as softwood. These types of wood based on statistical information of the Jordan market, which represent approximately 40% of total wood market.

There is a wide variation in the composition and structure between woods of different samples. The various factors which are known to be significant in determining the rate of smoke generated are listed in Table I. The rate of smoke generated can depends as much on the physical properties of a material as on its chemical composition. Therefore, it is reasonable to identify these parameters, which influence the obtained experimental results. Table I represents the main chemical and physical parameters of selected wood sample in normal condition. The tabulated thermal conductivity values are listed. It is measured experimentally using thermal conductivity apparatus model TCA300 DTX manufactured by TAURUS, also the density of the samples were computed.

The rate of smoke generated depends on the wood properties as much as the paint chemical composition. The paint chemical composition specifications are listed in Table II. It presents a composition of ingredients of FRM, paint, which is manufactured by Envirograf and product number 42 is used. The chemical characterization of paint is water based clear top coat comprising an aqueous solution of acrylic polymer with non-hazardous fire retardant and intumescent coating [13], [14]. Several experiments were done to study the quantitative of smoke concentration as a function of time variation under identical experimental condition. The results show the percent of transmittance and the amount of specific OD (D_s) with time for both painted and unpainted samples. A FTT SDC is used for the determination of smoke generated by wood samples in a horizontal orientation mounted within an adiabatic chamber of fixed volume and the collimated light beam and photomultiplier tube are oriented vertically in the chamber to reduce smoke stratification effects. It measures the percent light of transmittance and the specific optical density (SOD) of smoke generated by testing of samples (wood samples) to quantitative the smoke concentration with and with no paint. The smoke produced during experiments is caused by the combustion of burning samples by the received heat flux.

TABLE I
Properties of Selected Samples

Wood samples	Density ($\frac{g}{cm^3}$)	Thermal conductivity ($\frac{W}{m.k}$)	Lignin (%) [12]	Cellulose (%) [12]
Beech	0.7473	0.13970	22	46
Ash	0.6392	0.10510	24	41
Beech Pin / Swedish timber	0.3732	0.10470	29	45
White Pine Beech	0.4213	0.42128	27	45

TABLE II
Chemical Specification of FRM Use (Paint) [13]

Chemical name	Product name	CASE NO.	Chemical characterization
Ethylene Glycol	HWAP Primer clear	107-21-1	Aqueous(emulsion) polymer system
Benzyl alcohol	HW02E Clear	107-98-2	Aqueous dispersion of a polymer with non-hazardous fire retardant and intumescent additives.
1-Methoxy -2-propanol Mono- propylene glycol methyl ether		100-51-6	
Benzyl alcohol	HW ENVIRO Clear	100-51-6	Water based clear top coat comprising an aqueous solution of acrylic polymer.
Mono- propylene glycol methyl ether		107-98-2	
2,2,4- Trimethyl-1,3-pentanediol Monoisobutyrate		25265-77-4	

The temporal variations of transmittance curves for various tested samples under the same conditions of heat flux of 25 W/m^2 are presented in Figs. 3 and 4. Fig. 3 shows the variations of transmittance for unpainted samples. Fig. 4 shows the variations in the case of painted samples. As shown in the figures, at the beginning of the test, the temporal transmittance variations are insignificant and decrease slowly during the first 60 seconds, while radioactive heat flux is constant. During the test, the increase in the concentration of smoke particles produced decreases the transmitted light to the spectrometer. By the time, as the temperature of the samples rises up, the concentration of the smoke particles increases. After that the temporal transmittance variations is significant due to the progressive increase in the volume of smoke generated by the wood. It varies from sample to sample depending on the mass burning rate and the volumetric flow rate of smoke formation into the chamber. In this case, the transmittance decreases strongly with time leading to low oxygen concentrations and high levels of un-burnt fuel in the smoke generated. With the present non-flaming conditions, it may be suspected that main content of smoke is a condensed phase in the form of small droplets suspended in air. A chemical analysis must be carried out to check the presence of these constituents. At the end of the test, the transmittance reaches its lower values due to the increase in the rate of accumulation of smoke particles in an enclosed chamber. It decreases very slightly with time until the sample has been completely consumed or blows down. Where, the entrainment of air in the hot smoke leads to a progressively decreasing in the concentration of oxygen and the yield of particulate smoke is significantly less. This pattern becomes more and more pronounced with the increase of smoke concentration by time.

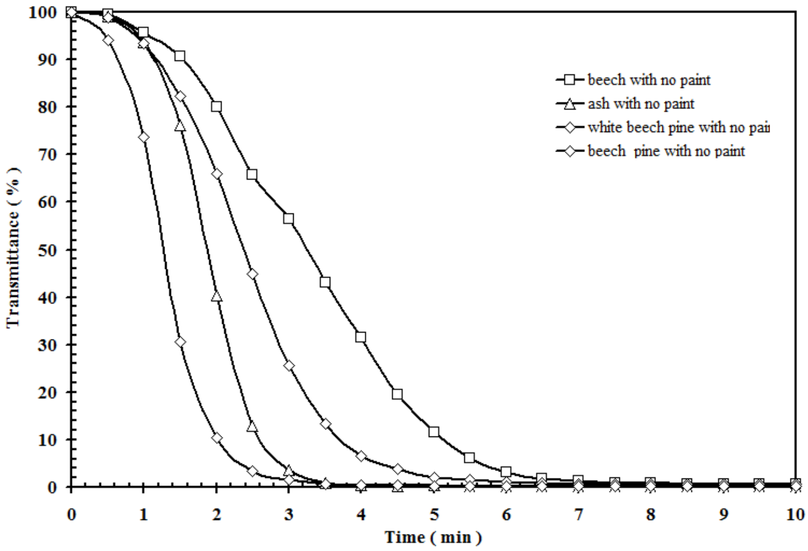

Fig. 3 Temporal evolution of transmittance for wood specimen smoke with no paint measured with SDC

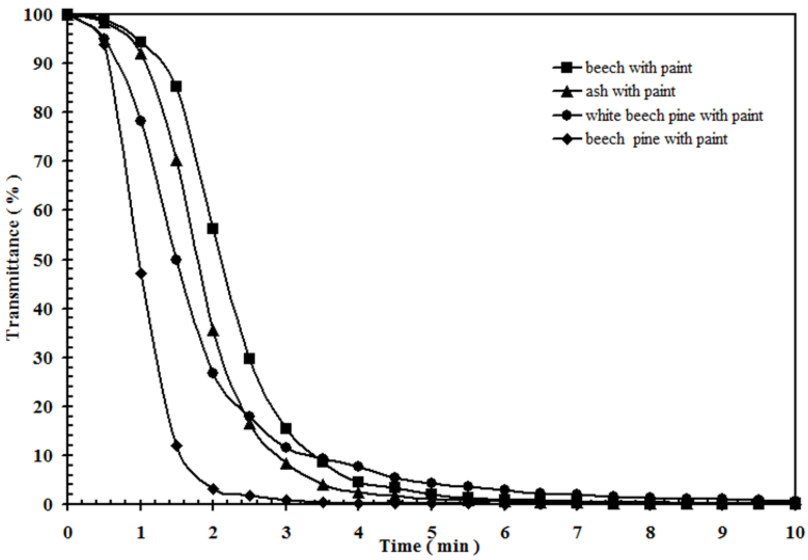

Fig. 4 Comparison of temporal evolution of the overall transmittance for the painted wood samples

Fig. 5 displays the effect of FRM, intumescent paint, on the transmittance of smoke for the selected samples before and after painting under the same conditions of constant heat flux of 25 W/m^2 without flaming condition. As seen in the results, the general trends of transmittance variation with time are similar in both cases for all samples of wood. The decrease in transmittance gradients with time is significant. Its variations between the samples are clear and significant. The lower values occurred in the unpainted Beech sample. The decrease in temporal transmittance variation is slow initially, by the time it becomes more significant. To show the effect of painting on transmittance, Beech curve is selected with paint and with no paint, at the first 60 seconds of exposing heat flux on the samples, the variation of transmittance is not clearly identified which means the smoke release through this period is very small and the material is still undergoing warm up and produces little smoke. After that, the transmittance variation is clearly identified where the transmittance evolution is almost linear until reaching 10% transmittance, such that after 150 seconds the transmittance of painted Beech is around 29%, while it is around 65% with no paint. The figure shows the gap between the curves of paint and with no paint of each sample is slightly different and depends on the species of wood; but in general, there is a delaying of painted curves compared with no paint for all samples of wood. The smallest gap between painted and unpainted ones occurs in the Ash sample.

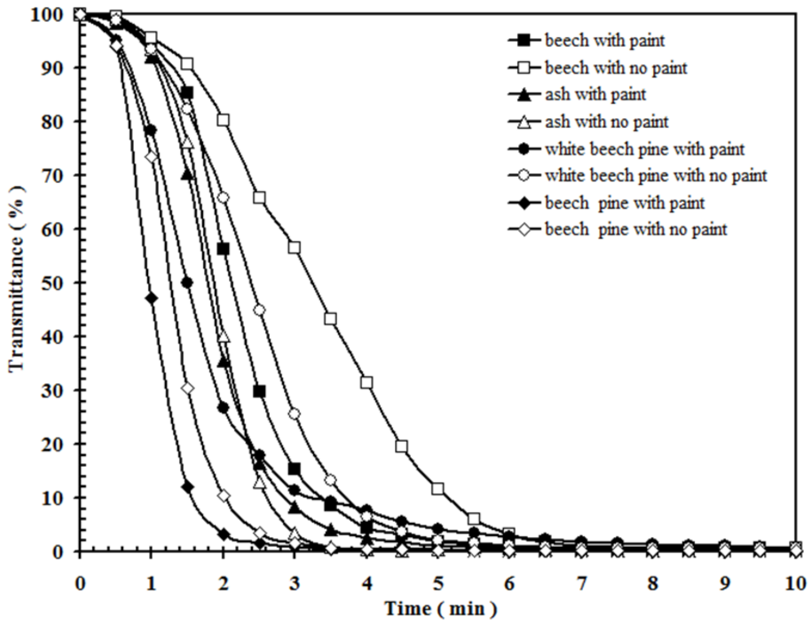

Fig. 5 Comparison of temporal evolution of the overall transmittance for the wood with and without paint

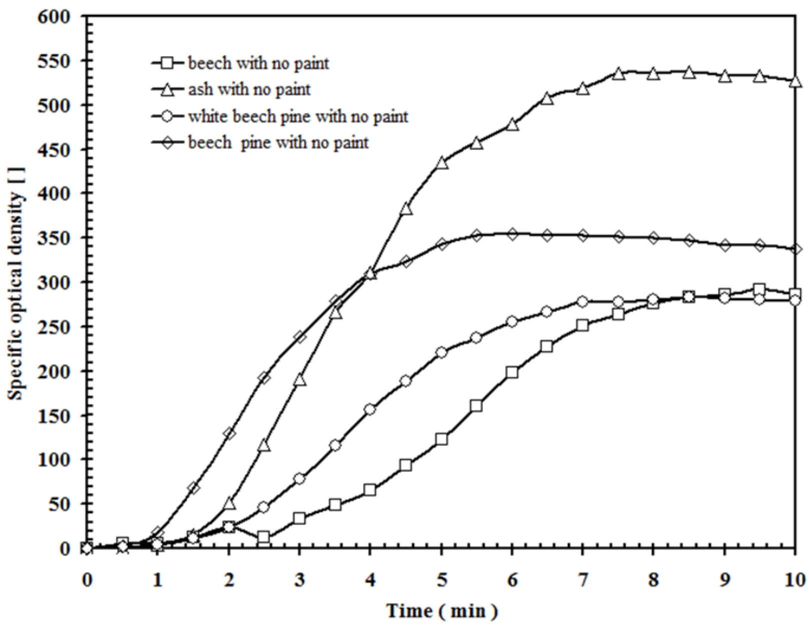

Fig. 6 Comparison of temporal evolution of the SOD for the unpainted wood samples

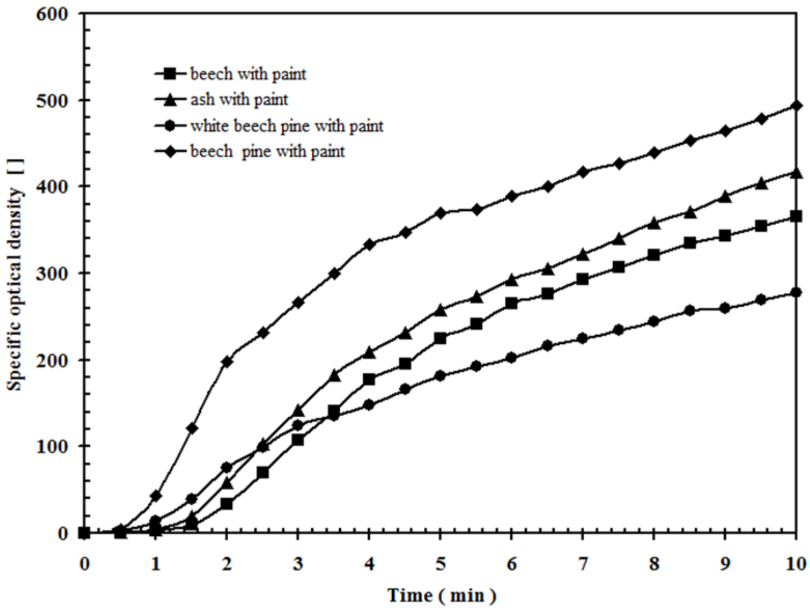

Fig. 7 Comparison of temporal evolution of the SOD for the painted wood samples

SOD differs from one type of wood to another depending on a set of chemical, physical and environmental parameters. It depends on the amount and size of particles produced and if it is painted or not. The concept of SOD enables the researchers to study the smoke behavior of materials in terms of the exposed surface area, volume of the enclosure and the optical path length of light. The smoke density value is very important for designing the fire detection system [15]. It enables the researcher to predict smoke density that can be developed by the same product in other fire area situations and other enclosure volumes. The temporal variation of SOD curves for various tested sample under identical condition of heat flux 25 W/m^2 in non-flaming condition are presented in Figs. 6 and 7. The results show the time variations in case of unpainted samples, Fig. 6. The accumulated SOD values are obvious increases with time. Its increase starts slowly during the first 60 seconds, and then increases rapidly to reach its higher values. It is due to the moisture contents and the time needed for wood, oxygen and heat to combine. These figures illustrate the increasing of OD with time due to the increase in temperature and heat that is required to breakdown the chemical bonds between the sample's atoms, which lead to the increase in the burning rate and amount of smoke produced from the sample. According to Fig. 7, high values of OD were found after painting the sample with fire resistance paint. The values of OD increase slowly during the first 60 seconds, and then increases rapidly to obtain a certain value. Fig. 6 indicates that the Beech and white Beech with no paint have low SOD in comparison with other samples studied; whereas, Fig. 7 indicates that white Beech with paint have low SOD, in comparison with other samples of wood. Large amount of smoke will be emitted after painting due to the use of polymers component which have a large number of carbon atoms. This is explained by the increase of the smoke concentration in the box which induces a decrease of the visibility and the transmitted light, and thus, an increase of SOD.

Fig. 8 shows the effect of FRM, intumescent paint, on SOD of smoke for the selected samples before and after painting, for the same conditions under constant heat flux of 25 W/m^2. As seen by the results, the general trends of SOD variations with time are similar in both cases for all samples. Initially, SOD increases slowly, and then becomes more and more significant. To show the effect of painting on SOD, Beech curve is selected with paint and with no paint for comparison. At the first 60 seconds of exposing heat flux on the samples, the variation of transmittance is not clearly identified, which means that the smoke release in this period of time is not enough for the material to undergoing warms up and produce smoke. After that, the SOD variations are clearly identified. After 300 seconds, the SOD of painted Beech is around 225 corresponds to a transmittance of 2%, while it is around 123 corresponds to a transmittance of 12% with no paint. Usually, the transmittance is much higher for wood samples and also corresponds to a much smaller whether the sample is painted or not. The figure shows the gap between the curves of painted and unpainted samples is slightly different and depends on the species of wood, but the average SOD for painted samples is always greater than the unpainted samples. For the four tested materials it is found that, smoke liberated from burning paint increases SOD and decreases transmittance percentage.

Measurements of the yield of smoke generated from different wood samples were made using small-scale test procedures. The yield can be quantified by measuring the OD of the smoke under specified conditions. OD correlates directly with visibility. The generation of smoke in fires is associated with a reduction in visibility, which leads to a critical situation for escaping people [3]. Visibility is considered as the main parameter which affects the time allowed for escape, since the generation of smoke within a confined space is assumed to be directly proportional to the amount of oxygen. In general, the higher the smoke production, the lower time available for escape. It is very hazardous if occupants are not quickly able to find their way to a safe place [3]. In this part of the discussion, Ash samples are taken for analysis of visibility parameters. Visibility can be estimated by recording the maximum distance that an observer can see an object on the horizontal among the space at any given time. This estimation can however be difficult to provide accurately due to the variation in the skill and eyesight of the observer. The relationship between the visibility and the transmittance for painted and unpainted Ash samples are shown in Fig. 9. The results shown demonstrate that the relationship between the variations of visibility with transmittance is exponentially trend lines. Measurements of transmittance were used to estimate the visibility of painted and unpainted samples. There is a slight difference between the measured values of both samples. For the transmittance of 70%, the corresponding maximum visibility distance for the painted sample is around 7 m, while it is around 6 m for the unpainted sample.

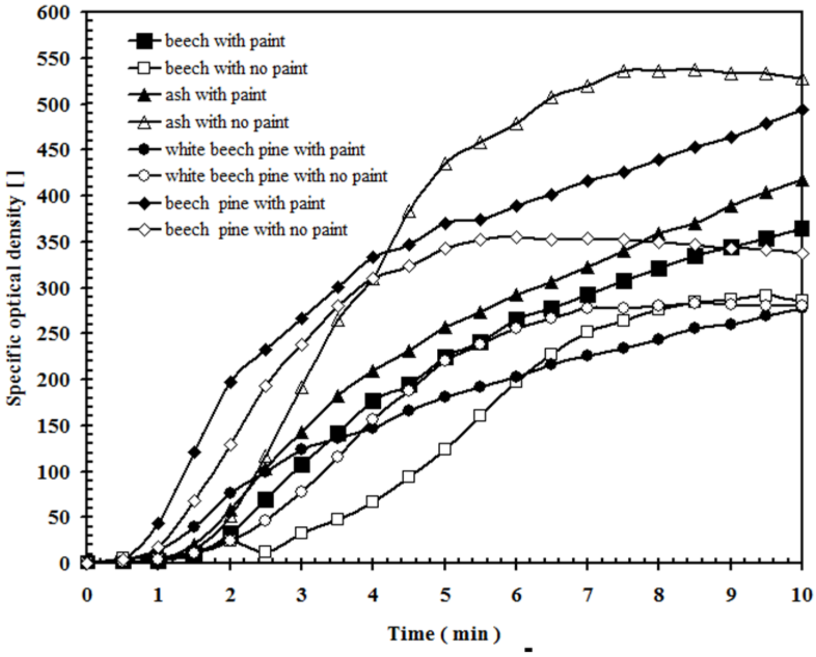

Fig. 8 Comparison of temporal evolution of the SOD for the wood samples with and without paint

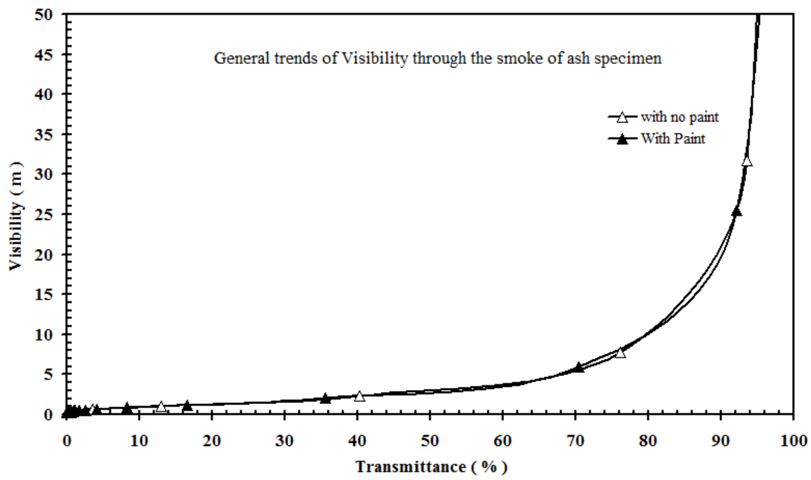

Fig. 9 Comparison of visibility and transmittance for Ash smoke with paint and with no paint

Fig. 10 shows the relationship between visibility and transmittance for painted and unpainted Ash samples. Both visibility and transmittance are important factors in fire safety management, where estimation of visibility is particularly important since it will manage the means of escape for occupants. The degree of visibility is very important to occupants to allow them to find the provided signs, for identification of the locations of exits and paths of travel to an exit in the case of fire. It affects the evacuation duration and the traveling distance, which allows sufficient time for occupants to evacuate safely. The degree of visibility will depend upon several factors, from which, is the amount of particles in the confined space. Comparison between the curves shows the paint effect on the SOD is insignificant. Obviously, the standard approved fire retardant paints must be of low smoke generation. It is made of fire resistant materials that are acceptable for fire safety requirements. It has a comparatively lower amount of paint particles generated compared with wood mass burning rate, which is normally the dominant factor in smoke generation and determining visibility.

Fig. 10 indicates that the transmittance of around zero for SOD is equal 250. For the transmittance of 70%, the corresponding OD of sample with paint and with no paint reaches around 20. Results shown in Fig. 10 illustrated that for very high smoke concentration and SOD, the percentage of transmittance decreased to very low values since the mass burning rate is increased.

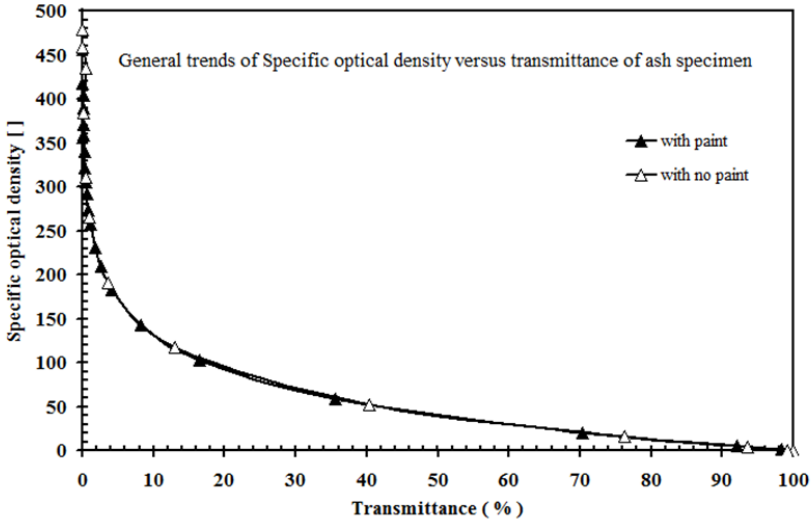

Fig. 10 Variation of SOD versus transmittance for painted and unpainted Ash samples

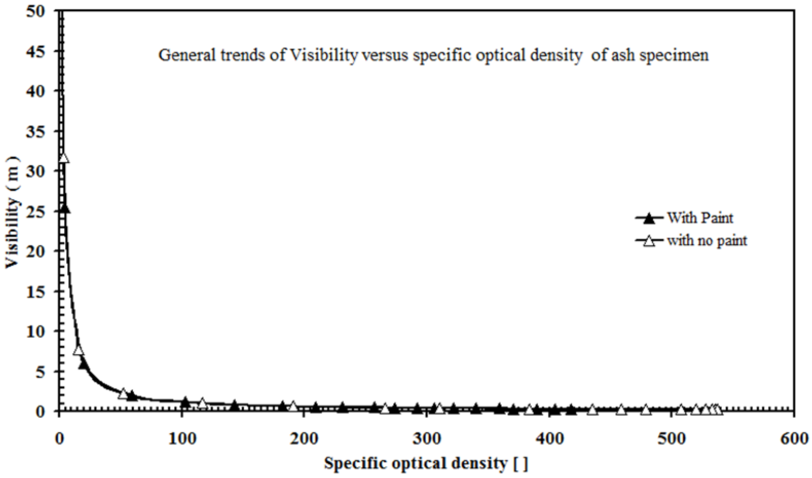

Fig. 11 variation of visibility versus SOD of Ash sample with paint and with no paint

Apparently, low visibility due to smoke release can delay an occupant's evacuation time. Assessment of smoke development is required to assess life safety considering smoke movement and visibility. For safe evacuation of people from buildings, OD should not exceed 0.1 per meter. It corresponds to visibility limit of 10 m Visibility of 10 m is often used as a critical limit and corresponds to a visibility below which the safe evacuation of people will be difficult [3]. This corresponds to an OD of about 0.13 m. Fig. 11 shows the variations of visibility with SOD for painted and unpainted Ash samples. It demonstrates the relationship, which indicated that the visibility is decreased when the concentration of smoke and SOD increased. This means smoldering condition was also increased due to the decreasing in oxygen concentration. It is found that the general trends were similar in both cases. The decrease in SOD is low initially, and then becomes more and more significant. The corresponding values of SOD for 10 m visibility are around 15 per meter in both cases, where the percentage of transmittance is around 70% in this case. Visibility of 10 m is the minimum distance for occupant to escape safely from buildings. The results show that the effect of paint on the visibility- SOD relation is insignificant.

Table III summarized the present experimental results for painted and unpainted samples. It determines the optical parameters that resulted for all samples of wood. It shows that the higher SOD, the larger smoke emission and also the smaller transmittance and visibility for the tested samples. The tabulated data indicated that the combustion samples evolved high amount of smoke in the case of painted Beech Pine. Samples of painted wood released more smoke with no significant effect for paint on smoke generation. Generally, the average SOD is less for painted samples compared with unpainted ones. This means that the percentage of transmittance measured is higher for the painted samples than the unpainted ones. The maximum value of the SOD in case of unpainted samples is for Ash wood. It corresponds to a transmittance of 0.01% and an OD of 43.739 db/m. The maximum values of the SOD in case of painted samples are for Beech Pine wood. It corresponds to a transmittance of 0.0182% and an OD of 40.912 db/m. In comparison, the maximum visibility is 0.434 m for painted White Pine Beech wood. The mass burning rate was higher for samples with paint than samples with no paint.

TABLE III
COMPARISONS OF OPTICAL PROPERTIES OF SMOKE EMISSIONS FOR PAINTED AND UNPAINTED SAMPLES AT AN INSTANTANEOUS TIME OF 10 MINUTES

Sample name		Beech	Ash	Beech Pine	White Pine Beech
Maximum SOD	Paint	365.30	417.90	493.6	277.8
	No paint	286.00	527.70	337.3	280.1
OD per meter (db/m)	Paint	30.278	34.638	40.912	23.033
	No paint	23.705	43.739	27.957	23.216
Transmittance (%)	Paint	0.17	0.068	0.0182	0.784
	No paint	0.68	0.01	0.279	0.761
Visibility (m)	Paint	0.33027	0.2887	0.244	0.434
	No paint	0.4218	0.2286	0.3577	0.432

V. CONCLUSIONS

An experimental study on the optical properties of smoke has been carried out in SDC. Four samples of natural wood (Beech, Ash, Beech Pine, and White Pine Beech) are exposed horizontally to constant vertical heat flux of (25 kW/m^2) under non-flaming conditions. The experiments were done using the procedure prescribed in ISO-5659 standard for a period of time (10 minutes). The samples are also painted with FRMs, which are manufactured by Envirograf to illustrate the effect of intumescent paint on the optical properties of generated smoke for the selected samples of wood. Quantitative analysis of smoke optical parameters for the tested samples has been achieved. The results present the optical properties of smoke generated under the effect of FRMs. SOD and transmittance are the main parameters which are taken into consideration for comparison between painted and unpainted samples. It provides the basis of predicting visibility, OD and smoke production rate. At the end of the test, the effect of FRM is dependent on species of wood. Optical properties of smoke generated from unpainted Ash and White Pine Beech is greater than that of painted ones, whereas the optical properties of unpainted Beech and Beech Pine is smaller than that of painted ones. The maximum SOD occurs for unpainted Ash sample, it reaches 527.7, corresponding to minimum transmittance 0.01% and 0.2286 m visibility. On the other hand, the maximum SOD occurs for Beech Pine and it reaches 493.6 corresponds to the minimum transmittance of 0.0182% and 0.244 m visibility. To satisfy 10 m visibility, which is the minimum distance for an occupant to escape safely from buildings, the transmittance for all samples must be greater than 70%. The results demonstrate that the optical properties of wood vary from sample to sample depending on the mass burning rates and the volumetric flow rates of smoke formation into the chamber.

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