



**Hydromechanics Faculty
Hydraulic and environment protection department**

Thesis name:

**The determination and numerical simulation of
the optical properties of smoke generated in
fires**

**Research report no. 2
Experimental analysis of the influence of the
construction materials properties on pyrolysis
generated smoke**

Doctorate mentor

Prof. dr. ing. Andrei-Mugur GEORGESCU

Doctorate student

Dan BURLACU

burlacudan92@gmail.com

Table of contents

Cuprins	Error! Bookmark not defined.
Introducere	Error! Bookmark not defined.
Fumul generat în urma arderii materialelor de construcții...	Error! Bookmark not defined.
<i>Clasificarea produselor de construcții pe baza emisiei de fum</i>	Error! Bookmark not defined.
<i>Proprietăți ale materialelor de construcții care influențează emisia de fum.....</i>	6
Studii experimentale	Error! Bookmark not defined.
<i>Testarea la scară naturală a fumului generat artificial.....</i>	8
Metodologie.....	8
Rezultate și discuție	Error! Bookmark not defined.
Concluzii.....	12
<i>Testarea la scară redusă a fumului generat artificial</i>	Error! Bookmark not defined.
Metodologie.....	12
Rezultate și discuție	15
Concluzii.....	19
<i>Testarea la scară redusă a fumului generat prin ardere</i>	20
Metodologie.....	Error! Bookmark not defined.
Rezultate și discuție	22
Concluzii.....	26
Concluzii.....	Error! Bookmark not defined.
Bibliografie.....	Error! Bookmark not defined.

Introduction

The legislative body in construction quality assurance oversees the design and maintenance during the life cycle of various building of the mandatory fundamental compliance domain of fire safety [1]. The scientific field that deals with the application of the scientific and engineering principles in order to reduces the loss of lives and damage to goods in the case of a fire is Fire Safety Engineering. This scientific field's objectives can be reached through the quantification of the risks and dangers that are involved in a fire and by presenting an optimal solution for the application of preventive or protective measures [2].

The need to ensure the safety of the building occupants and first responders during a fire, as well as the need of some kind of predictability regarding the behavior of building materials, installations and building overall in case of a fire has led to the development of fire testing. The need for the utilization of equivalent building products in terms of fire safety, the materials and products used in constructions are subjected to standard testing in order to be separated into classes. The class that a product might be part of defines its behavior when subjected to fire, either individually, or as part of an ensemble, as it would normally be utilized.

The European union is harmonizing the testing and classification of building materials, and for reasons pertaining to free trade, these are classified in the same way in all of the European countries. This has led to the introduction of the European Reaction to Fire Classification System (Euroclasses), which constitute an hierarchical system of building materials based on their performance when exposed to fire, evaluated by using unitary testing methods, legislated through testing standards [3].

The standard testing methods often require different (sometimes great) quantities of building materials to be subjected to often destructive testing, repeating the test requiring another sample, and in order to provide the data necessary for the classification there are necessary at least three samples for any one product. In those fields where great quantities of materials are not available, such as in research, development and optimization, alternative methods of

For evaluating the quantity of smoke emitted through the exposure of building materials to fire, the smoke of a single burning item is captured according to a standardized testing methodology and the attenuation of the intensity of a white or monochromatic beam of light that travels through the smoke is measured. The dimensions of the tested sample vary between 100 and 150 centimeters for each side of the sample, leading to considerable amounts of building material that needs to be tested for an accurate result, that are often inaccessible in fields like research and development of new materials [4]. For this very reason, this paper proposes an experimental approach for the evaluation of the influence of different properties of usual building materials on the emission of flame or smolder generated smoke, through the use of a methodology for the comparison of the optical properties of smoke in different experimental scales.

Smoke generated through the burning of building materials.

The classification of building materials based on their smoke emission

The national legislation that adapts the specifications of the European legislation regarding the classification of building materials based on their performance when exposed to fire presents a list of performance criteria for the reaction to fire of building materials. Based on those performance criteria, the building materials are then classified in performance classes.

There are seven reaction to fire classes for building materials, noted from A1 to F that present the degree in which the material contributes to the development and/or spread of the fire. the classification varies from incombustible products to materials that have a significant contribution to fire. The classes are accompanied by additional information regarding the smoke emission and droplet formation of the building materials that they represent. These characteristics are represented through the letter s for the smoke emission and d for droplets. The smoke emission can be weak, represented by the s1 notation, medium, s2 or significant, s3, the final notation being in the form of B, s1, d0, B representing materials that do not significantly contribute to the fire's development, s1 meaning that the material has a weak smoke emission and d0 that it does not produce flaming droplets [5].

Among the most utilized tests for the classification of building materials in their respective fire reaction classes is the Single Burning Item test, with approximately 80% of the European building materials being tested with this method as a mandatory requirement for selling [6]. The smoke emission of a certain building material is deduced using the criteria from table I [7s].

Table I. Clasificarea emisiei de fum

No.	Smoke emission class	Smoke emission related parameters in SBI testing	
		SMOGRA	TSP _{600s}
1.	s1	$< 30 \text{ m}^2/\text{s}^2$	$< 50 \text{ m}^2$
2.	s2	$> 30 \text{ m}^2/\text{s}^2$; $< 180 \text{ m}^2/\text{s}^2$	$> 50 \text{ m}^2$; $< 200 \text{ m}^2$
3.	s3	-	-

SMOGRA stands for the speed with which the smoke emission grows in intensity (SMOke Growth Rate), is measured in m^2/s^2 and calculated according to equation 1.

$$SMOGRA = 10^4 \cdot \max \left(\frac{SPR_{av}(t)}{t} \right) \quad (1)$$

The variables in the equation are the time t measured in seconds from the start of the testing, and SPR_{av} is the average smoke emission speed (Smoke Production Rate) measured for 60 seconds, in m^2/s .

TSP_{600s} is the Total Smoke Production measured in the first 600 seconds of the testing, in m^2 , according to equation 2.

$$TSP_{600s} = \sum_{0s}^{600s} SPR(t) \cdot \Delta t \quad (2)$$

$SPR(t)$ is the smoke emission speed in time and Δt is the data acquisition interval by the measuring device, in seconds [8]. This smoke emission speed is calculated by using the smoke's light extinction coefficient and the volumetric smoke flux during the testing.

The smoke's light extinction coefficient is defined by the standard that presents the vocabulary used in fire safety engineering as the natural logarithm of the ratio of incident light intensity to transmitted light intensity, per unit light path length[9].

The equation used to determine the smoke emission speed is presented in equation (3), the one used for the smoke's light extinction coefficient in equation (4), and the one for the volumetric flux of the hot gases produced during the testing, in equation (5).

$$SPR = k \cdot \dot{V}_{T_s} \quad (3)$$

The variables in this equation are k , the smoke's light extinction coefficient, measured in m^{-1} by evaluating the degree in which the intensity of a light beam that permeates the smoke layer is attenuated, and $\dot{V}_{T_s}$ is the volumetric flux of the gases that are produced by burning of the analyzed sample, at the temperature recorded in their evacuation path.

$$k = \frac{1}{L} \cdot \ln\left(\frac{I_0}{I}\right) \quad (4)$$

The light extinction coefficient depends on the ratio between the initial light intensity of a light beam, and the one that the same beam has after going through the smoke layer for a certain distance L . In the case of the SBI standard testing, the distance traveled by the light beam is the same as the diameter of the smoke evacuation path.

$$\dot{V}_{T_s} = \frac{\dot{V}_{298} \cdot T_s}{298} \quad (5)$$

The volumetric flow of the hot gases generated by the burning of the sample is calculated taking into consideration the temperature recorded on the exhaust path in Kelvin degrees (T_s) and the flow recorded at normal temperature ($298\text{ K} = 24,85^\circ\text{C}$). Other factors that are taken into consideration for this calculation are the gases' pressure and density, the atmospheric pressure and Ambiental temperature [10]. The SBI testing stand is schematically represented in figure 1.

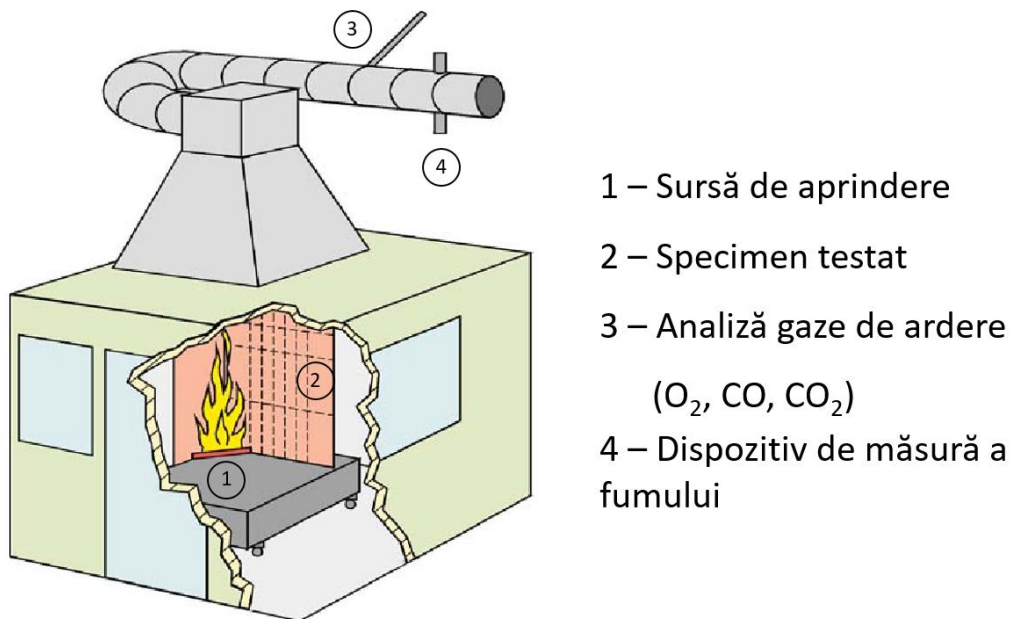


Fig 1. SBI testing stand

Building materials properties that influence smoke emission

In order to analyze the ways in which certain building materials properties influence their smoke emission, the concepts, vocabulary and characteristic measurements for the smoke resulted in case of a fire need to be presented. For the purpose of this paper, the terms, phenomena and measurements used are defined according to the Fire safety Vocabulary [9] as follows:

- Light extinction coefficient natural logarithm of the ratio of incident light intensity to transmitted light intensity, per unit light path length
- Opacity of smoke – ratio of incident light intensity to transmitted light intensity through smoke (3.347), under specified conditions. It is reciprocal of transmittance and has no measurement unit.
- Extinction area of the smoke – product of the volume occupied by smoke and the extinction coefficient of the smoke. It is a measure of the amount of smoke, its measurement unit is typically m^{-1} and it represents a quantity through which data from different experimental scales can be correlated [11].
- Smoke transmittance – ratio of transmitted light intensity through smoke to incident light intensity, under specified conditions. It is reciprocal of smoke opacity and is usually represented by percentages. In practice, it is a measure of the smoke obscuration capability, which determines a loss of visibility.
- Smoke optical density - measure of the attenuation of a light beam passing through smoke expressed as the logarithm to the base 10 of the opacity of smoke

The way that smoke is produced through burning of different materials is generally studied from two viewpoints, the chemical one, which analyses the transformation of the combustible material through the burning reaction to soot particles, and a physical one, that analyses the behavior of those soot particles that are displaced by the convection currents. This is why the factors that influence the characteristics of the fire's smoke and hot gasses can be grouped as per table II, adapted from reference [12].

Table II. Factors that influence the characteristics of fire's smoke and hot gasses

No.	Physical factors	Chemical factors
1.	Exposed surface area	Fuel type
2.	Sample weight, thickness and density	Fireproofing
3.	Sample orientation	Stratification
4.	Testing chamber volume	Functional groups
5.	Heat flux	
6.	Oxygen availability	
7.	Ventilation	
8.	Ambient temperature	
9.	Charring	
10.	Coalescence ¹ , depositing	
11.	Diffusion, dispersion	

¹ the joining or merging of elements to form one mass or whole.

The experimental determination of some of the building materials' properties that influence their smoke emission will be presented in this paper.

Regarding the surface area of the material that is exposed to the heat source that determines the burning process, one study suggests a linear growth of the smoke optical density in conjunction with a greater exposed surface area. For samples with different thicknesses, the same reference mentions the fact that the optical density of the smoke generated by the sample is directly proportional with the sample's thickness, up to a certain critical thickness, over which the optical density of the smoke does not further increase with the increase in sample thickness [13].

One of the standard tests for the determination of the smoke's optical density uses samples that are positioned vertically when subjected to fire. This position increases the speed of the burning process through facilitating flame growth, but is not preferred to be used in the case of plastic materials that may produce flaming droplets when burning. The optimal sample position for the testing of the emission of smoke has been determined to be the horizontal one, with the sample's exposed face facing up.

For the small-scale experiments, the volume of the testing chamber used for the smoke emission test is of great importance. Experimental data [14] have shown that for fibrous wood boards and oriented strand boards (OSB) that are smoldering (with a low flame or no flame), the small scale measurements for the smoke emission is similar to that determined through full scale experiments. The same thing applies for flame burning polystyrene, although the same smoke optical density values have been obtained in a longer time since ignition than in the small-scale setup, for the full-scale experiment, but the value sets are found in agreement.

The nature of the heat source also affects the smoke emission of the tested material. For obtaining smoke generated by smoldering materials through pyrolysis, radiant heat sources (25kW/m^2) that are not powerful enough to ignite a flame, but induce a smoldering state and trigger smoke emission are used. In the case of flame generated smoke emission, the standard testing employs the use of a pilot flame of propane to light up the material and the heat flux that is necessary to maintain the burning process is provided in part by the sample itself [13].

The classification of building materials takes into account the smoke emission speed of the analyzed material and the total generated smoke quantity. The effects that smoke has in fires depend not only on the quantity of smoke that has been generated [15], but also on its toxicity, [16], irritability [17] and its capability of visibility reduction [18].

This paper analyzed the impact that different building materials properties have on the capability of the smoke that they produce to lower the visibility in the experimental enclosure. The motivation behind this research effort is given by the fact that in the case of fires, the loss of visibility caused by the smoke leads to the impossibility or a delay of the evacuation and numerous human casualties. Internationally, the visibility during fires is used as an criterion for the calculation of the theoretical evacuation speed of people in case of fires [19].

Experimental research

For the purpose of determining the influence of building materials' properties on their smoke emission, small scale testing was used to vary different material properties and evaluate their impact on smoke emission. These variations were analyzed from the point of view of the influence that they have on the measured values of the intensity of a light beam that crossed the smoke layer produced by the smoldering samples.

To ensure the validation of the results, the applicability of the measurement method of the visibility loss in a smoke-filled compartment through the analysis of the loss of intensity of a beam of monochromatic light beam was first demonstrated. This has been possible through a full-scale experiment with artificially generated smoke, for a better control of the experimental conditions.

The applicability of the same methodology was further demonstrated in the case of small scale testing, for a scale of 1:10 of the testing enclosure using artificially generated smoke, and then this methodology of determining the visibility loss in a compartment for artificially generated smoke was used in the case of building materials exposed to the influence of fire, at a small scale.

Because the standard testing stand is not accessible for experimenting, this research has evaluated the influence of different building materials properties on smoke emission by comparison for some relevant properties, and not by providing standardized stand-alone values, as the standard testing produces.

Artificially generated smoke full scale testing

One of the most frequent measured optical property of smoke is its light extinction coefficient [20], which can be determined through analyzing the loss of intensity of a light beam that travels a certain distance in a smoke filled enclosure. This analysis can provide data regarding the smoke's opacity and its transmittance, two reciprocal quantities that represent the smoke's obscuration or visibility reduction capacity in the space that it occupies. The principle of measuring light intensity reduction when of a beam passing through the smoke layer is the one used in the standard testing for smoke emission of building materials, an important property in fire safety engineering.

Methodology

A testing enclosure having the length of 20 meters, the width of 4.5 meters and height of 3 meters has been limited to a length of 13 meters by using a plastic sheet that keeps the artificially generated smoke in the testing space and does not generate overpressure. A smoke machine has been utilized in this testing compartment in a repeated, timed fashion to ensure a certain smoke quantity has been produced in the compartment, corresponding to a certain amount of smoke fluid. According to the manufacturer's specifications, the smoke machine is capable to produce in a continuous 128 m³/min of smoke, by using 72 ml/min smoke fluid. In order to ensure atmospheric stability for the measurements, a 60 second pause was taken between consecutive uses of the smoke machine.

The monochromatic ray was generated with a laser pointer of 1mW power and 635 nm wavelength. The distances between the light source and the places where the light intensity was measured were set with the help of a laser telemeter installed near the light source. The described features of the experimental stand are presented in figure 2 before and during the experiment. Photos and videos of the relevant details have been taken as the experiment progressed.



Fig 2. Experimental devices

A high contrast image has been attached to a stand to provide a visual aid in subjectively evaluating the loss of visibility during the experiment through the capturing of digital images. For the measurement of the intensity of the monochromatic beam of light the Testo 480 luxmeter has been used, having a measuring domain between 0 and 100.000 Lux that has been attached to a target set at 5, 7.5 and 10 meters from the light source. The experiment has been repeated for each of those distances, the luxmeter and high contrast target being presented in figure 3 before and during the experiment.

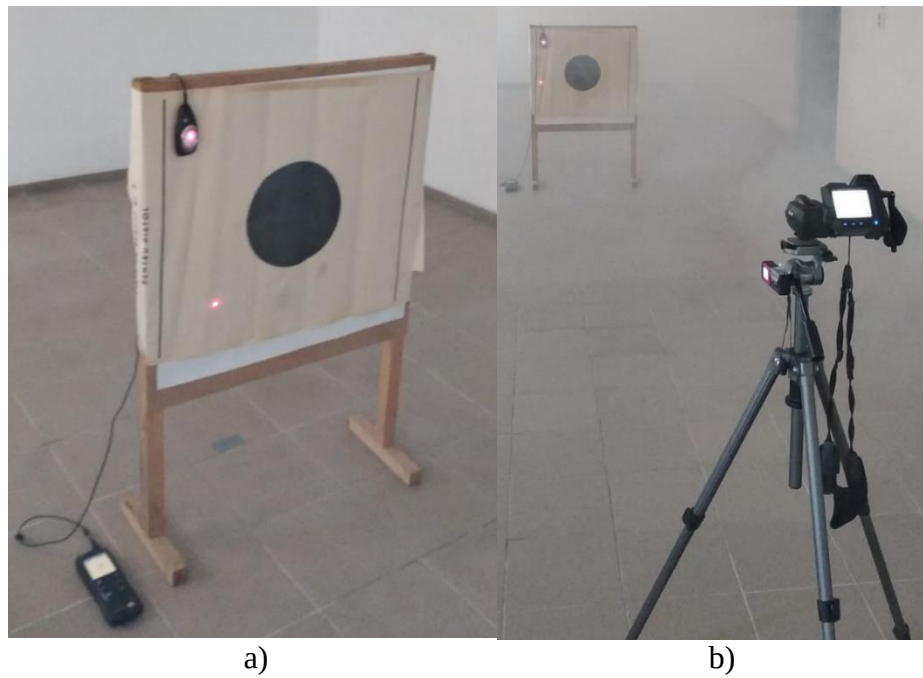


Fig 3. Luxmeter and target

The experiment has been done in normal lighting and dark room conditions, for each of the three distances of the target from the light source, and the instantaneous values of the light

intensity have been recorded after the pause period between the repeated uses of the smoke machine. The measured values of the light intensity have also been continuously logged during the experiment, for an accurate history. The instant values recorded during the natural and dark room conditions experiments are reproduced in table III.

Table III. Experimental measurements in natural and dark room lighting conditions.

Time (s)	Smoke fluid (ml)	Light intensity (lx) Natural lighting			Light intensity (lx) Dark room		
		5m	7.5m	10m	5m	7.5m	10m
0	0	917	736	462	358	242	210
5	6	769	670	322	304	210	174
9	11	743	423	297	293	140	148
18	22	601	326	191	253	110	94
27	32	564	283	164	216	85	27
36	43	556	274	139	195	59	25
45	54	462	247	129	122	50	29
54	65	383	222	117	83	42	24

Results and discussion

The measurements obtained during this experiment show that this method of assessing the variation of light intensity is adequate for evaluating the impact that artificially generated smoke has on visibility levels in a testing compartment. The light intensity values measured for the 5, 7.5 and 10 meters distances during the natural lighting condition experiment are presented in figure 4.

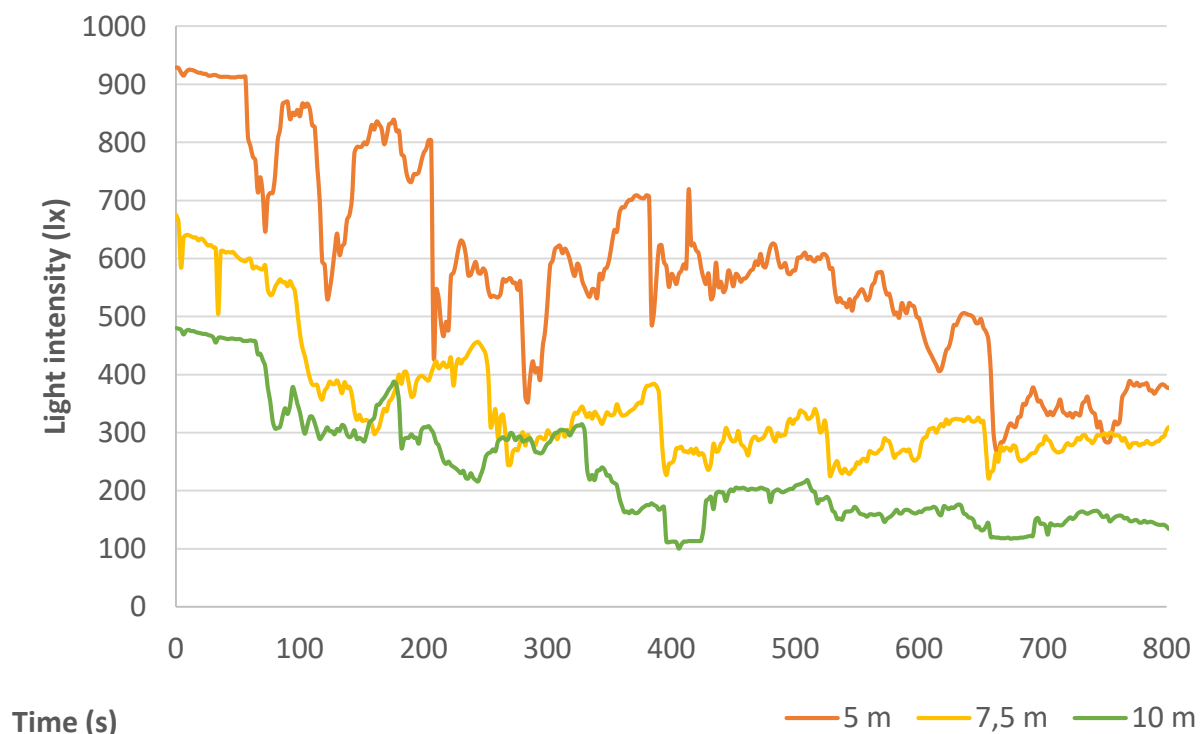


Fig 4. Light intensity full scale experiment

The visibility in the smoke-filled compartment has been calculated based on the measured light intensity, and its evolution for the natural lighting condition experiment is presented in figure 5.

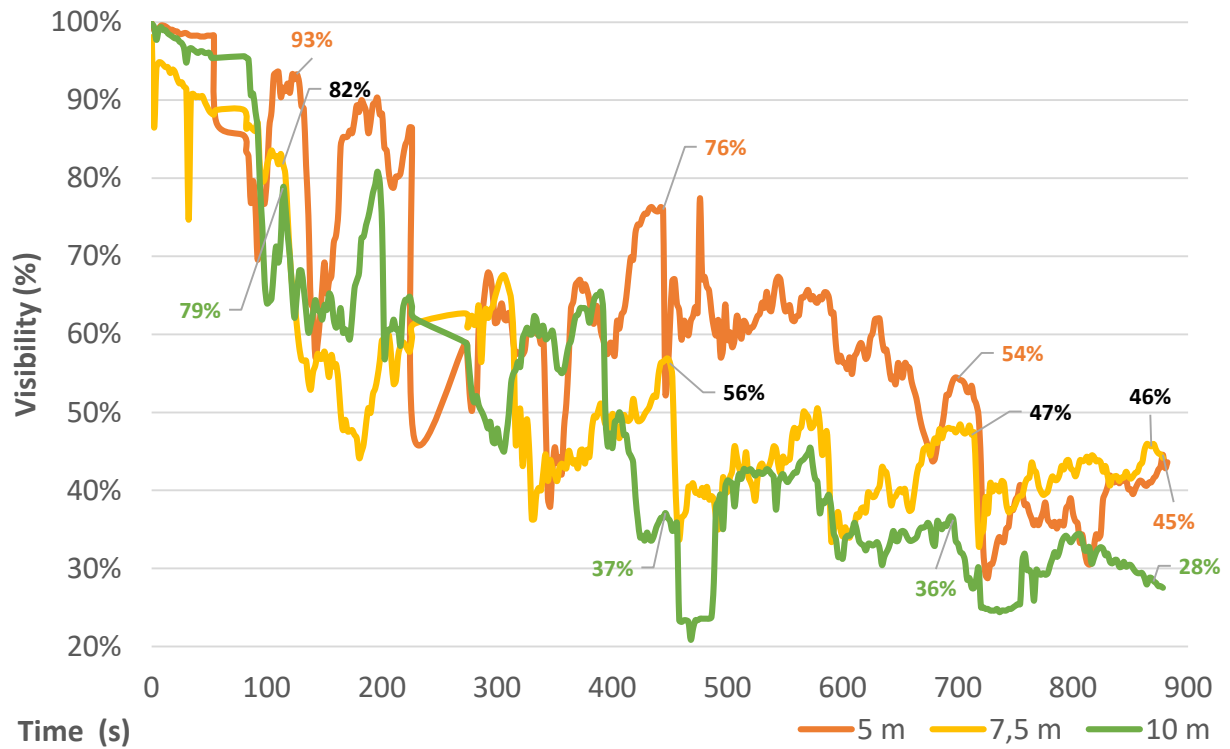


Fig 5. Full scale experiment visibility

The sudden drops in the values represent the time of smoke machine activation, after which a gradual atmosphere settling can be seen up to the point where the instantaneous measurements were carried out.

One of the most important parameters used to correlate data sets between different experimental scales is the smoke extinction area. This has been calculated for the full-scale experiment based on the measured values of light intensity and the results are presented in figure 6.

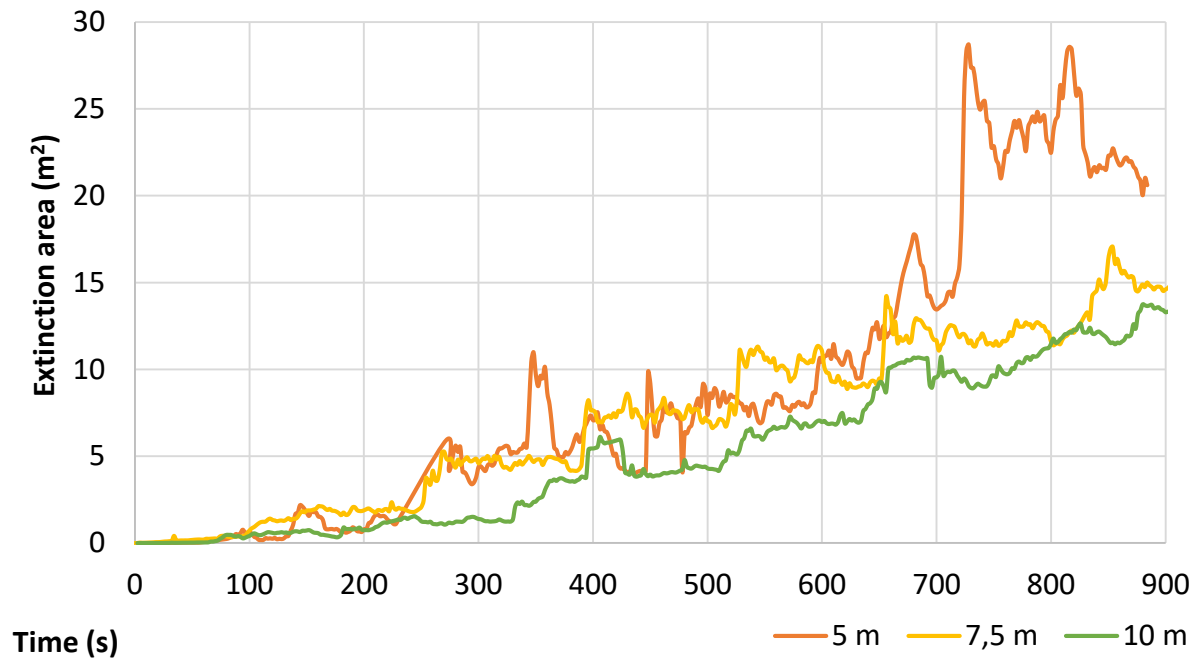


Fig 6. Full scale smoke extinction area

For each of the smoke machine's activation, the smoke fluid quantity that was used was calculated, the optical smoke extinction coefficient and an average smoke extinction area was

calculated for each of the measurement distances and lighting conditions of the experiment. The results are presented in table IV.

Table IV. Average values for the smoke extinction coefficient and smoke extinction area

Lichid de fum utilizat (ml)	Cameră întunecată		Iluminat natural	
	Coeficient de stingere mediu (m^{-1})	Arie de stingere medie (m^2)	Coeficient de stingere mediu (m^{-1})	Arie de stingere medie (m^2)
0	0.00	0.00	0.00	0.00
6	0.02	0.25	0.03	0.30
11	0.05	0.96	0.05	1.04
22	0.08	3.31	0.09	3.65
32	0.15	8.41	0.11	6.20
43	0.17	13.26	0.12	8.93
54	0.21	19.87	0.14	13.07
65	0.25	28.48	0.16	18.09

As can be seen from these values, the impact that a certain smoke quantity has on the measurement of the smoke extinction coefficient is lower in the case of a better lighting of the testing chamber, the same effect being manifested in the case of visibility, for the same amount of smoke

Conclusions

Through this full scale experiment, data regarding artificial smoke optical properties have been gathered and its influence on the visibility levels in the compartment in which it is introduced was evaluated. The smoke extinction area is a key factor that was determined through this experiment and that can be used to correlate data obtained by small scale testing.

Small scale testing of artificially generated smoke

Small scale testing of artificially generated smoke has the purpose of demonstrating the applicability of the optical properties measurement methodology for a different scale than the natural one, and to identify to what degree the obtained data can be correlated with those in the natural scale testing, and if these correlations can be utilized in the case of flame generated smoke.

Methodology

For the small scale experiments an acrylic model has been used in order to replicate the 1:10 and 1:20 scale dimensions of the testing enclosure. For the 1:10 scale experiment, the length of the model has been 100 centimeters, its width 45 centimeters, and its height 30 centimeters. The light intensity measuring device has been set at 50, 75 and 100 centimeters from the light source. For the 1:20 scale experiment, the light intensity measuring distances have been 25, 47.5 and 50 centimeters from the light source. For the greatest measuring distances in both of the cases, the measuring device was set outside the model. The lower side of the model was open in order to facilitate smoke injection and to avoid overpressure.

For the 1:20 experiment, the length of the model has been limited to 12.5 centimeters and the other two dimensions were used as is, the width of 45 centimeters and height of 30 centimeters, in order to have a total volume 20 times smaller than that of the full scale testing compartment. Figure 7 presents the experimental setup for the 1:10 scale and figure 8 the experimental setup for the 1:20 scale.



Fig 7. 1:10 experimental setup

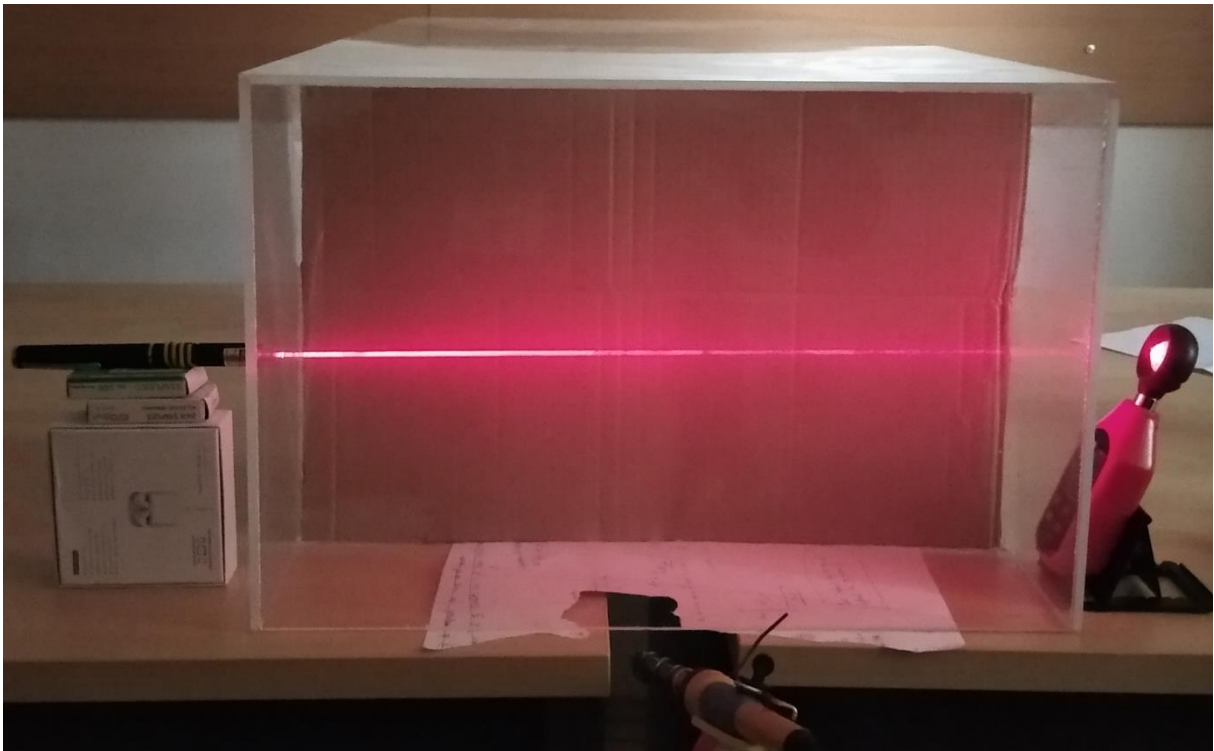


Fig 8. 1:20 experimental setup

The smoke fluid necessary to produce the smoke was the same in all of the experiments, it was glycerol-based and it produced dense and persistent smoke. The smoke fluid was dosed by using a syringe to inject the amount of smoke fluid in each of the small scale experiments representing a fraction of the amount used in the full scale experiment. The normal temperature that the smoke machine produces in order to vaporize the smoke fluid is 180°C , and in order to ensure this temperature for a lower scale vaporization, an electronic thermometer with a measuring domain between -50 and $+300^{\circ}\text{C}$ has been utilized.

The way the smoke machine works is it vaporizes the smoke fluid by heating it to about 180°C . This is why for the small scale tests, a dosed amount of smoke fluid was introduced on a copper tube with an interior diameter of two millimeters, that was heated with an electrical

resistance to produce smoke. Temperature measurement during the experiments is presented in figure 9.



Fig 9. Temperature measurements

The amount of smoke fluid that was used for the small scale experiments was 10 times, and 20 times, respectively, lower than that used in the full scale experiments, and its dosage was obtained through the use of a graded syringe. The presentation of the quantities of smoke fluid used in the full and small scale experiments, for each of the injection sessions is presented in table V.

Table V. Amount of smoke fluid used

No.	Smoke fluid amount (ml)		
	Full scale testing	1:10 scale	1:20 scale
1.	6	0.6	0.3
2.	11	1.1	0.55
3.	22	2.2	1.1
4.	32	3.2	1.6
5.	43	4.3	2.15
6.	54	5.4	2.7
7.	65	6.5	3.25

In the case of the two small scale experiments, the time between consecutive uses of the smoke generating device has been of about 120 seconds, in order for the atmosphere to settle, whereas that time in the case of the full scale experiment has been 120 seconds. Because of the differences between the two temporal scales, for the correlation of the measured values for the various experimental scales used, the amount of smoke fluid used during the experiments was used as a plotting scale.

The monochromatic light beam that passed through the smoke layer has been generated with the help of a 1mW power laser and a 635nm $\pm 5\%$ wavelength. The light intensity values were measured with a UNI-T, model UT383 BT lux meter with a measuring domain between 0 and 9,999 Lux, 1 Lux sensitivity and $\pm 4\%$ precision. The measured values were logged at an two second interval.

The experiments have been run in dark room conditions, and the instruments that were utilized for the small scale experiments are presented in figure 10.



Fig 10. Small scale experiments tools

The values of the light intensity that were measured in the small scale experiments are presented in table VI for each of the smoke injection sessions.

Table VI. Small scale experimental measurements

1:10 scale				1:20 scale			
Smoke fluid (ml)	Light intensity (Lux)			Smoke fluid (ml)	Light intensity (Lux)		
	50 cm	75 cm	100 cm		25 cm	37.5 cm	50 cm
0	3585	2261	2054	0	2922	2796	2618
0.5	2909	1771	1575	0.25	2110	1872	1793
1.5	1747	1437	1024	0.75	1687	1112	1145
2.5	1339	1106	650	1.25	1413	1065	681
3.5	1163	911	674	1.75	1399	1108	510
4.5	1107	621	321	2.25	1504	1095	445
5.5	1088	601	652	2.75	1005	1074	503
6.5	1116	570	237	3.25	1161	881	417

Results and discussion

The measured values for the light intensity during the 1:10 scale experiment for the 50, 75 and 100 centimeters are presented in figure 11, and those measured in the 1:20 scale for the 25, 37.5 and 50 centimeters are presented in figure 12.

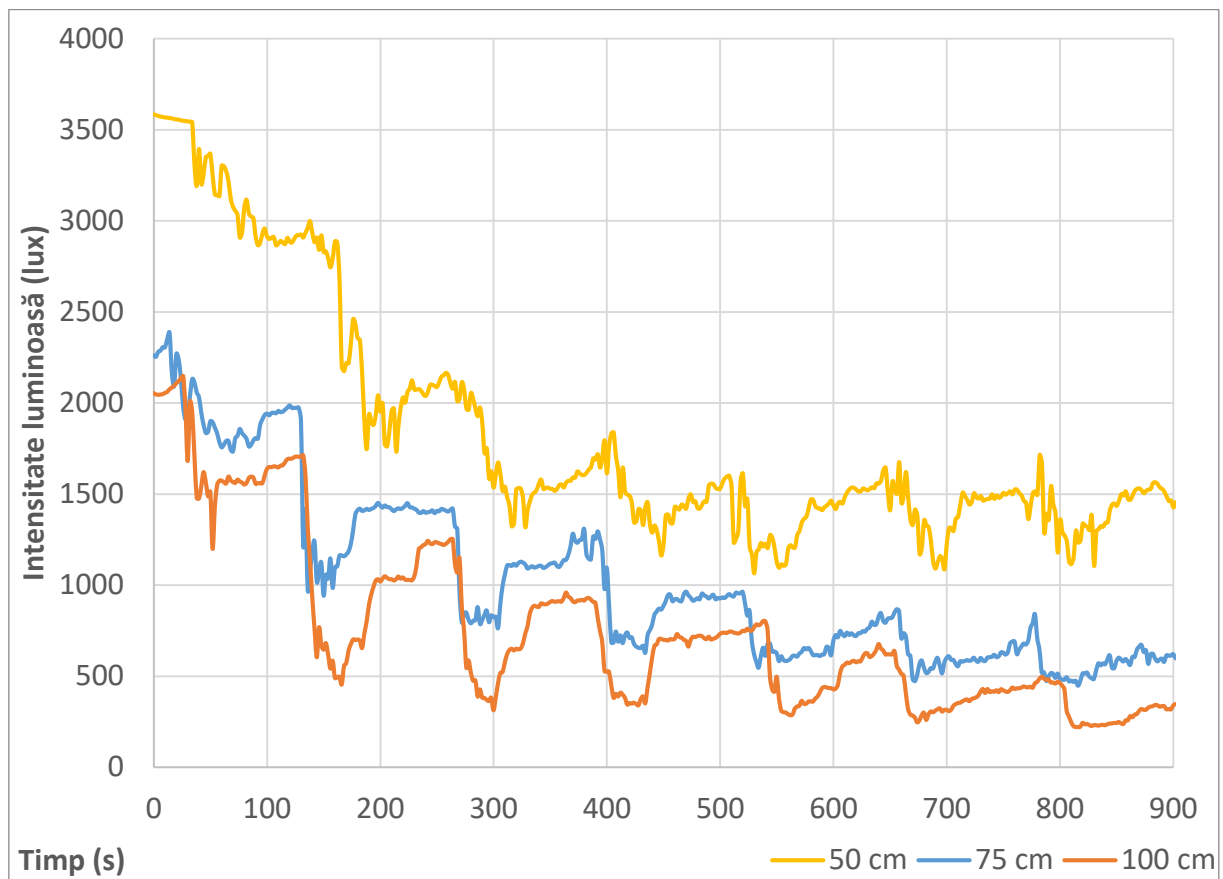


Fig 11. 1:10 scale light intensity

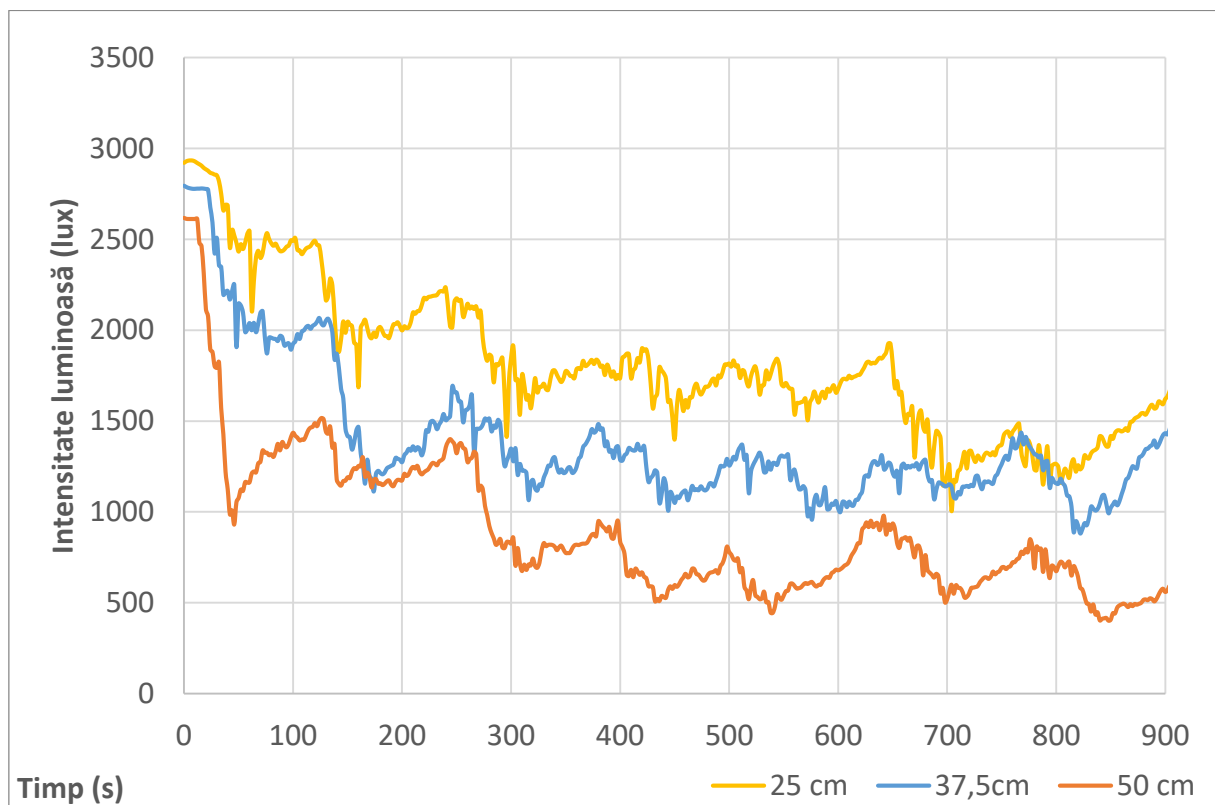


Fig 12. 1:20 scale light intensity

The variations of the visibility levels in the case of the 1:10 scale is presented in figure 13 and for the 1:20 scale in figure 14.

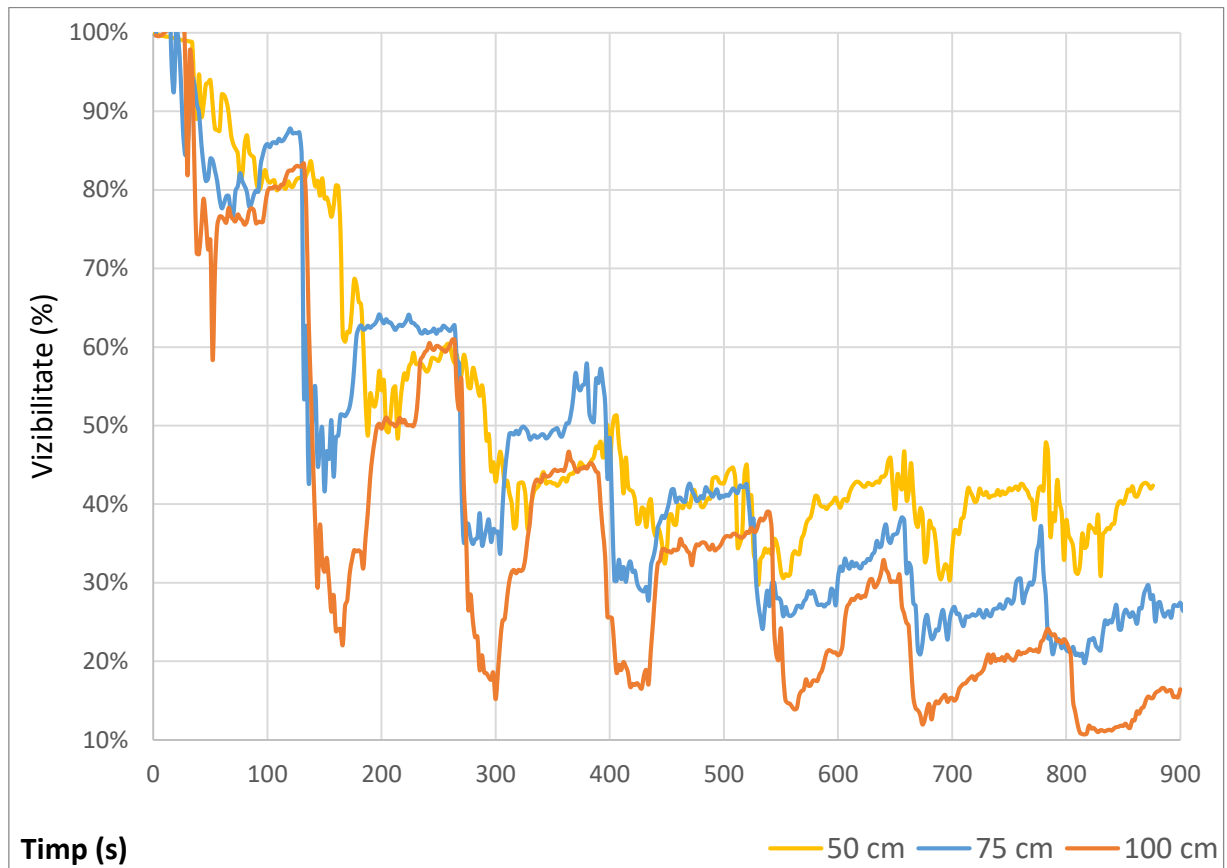


Fig 13. 1:10 scale visibility

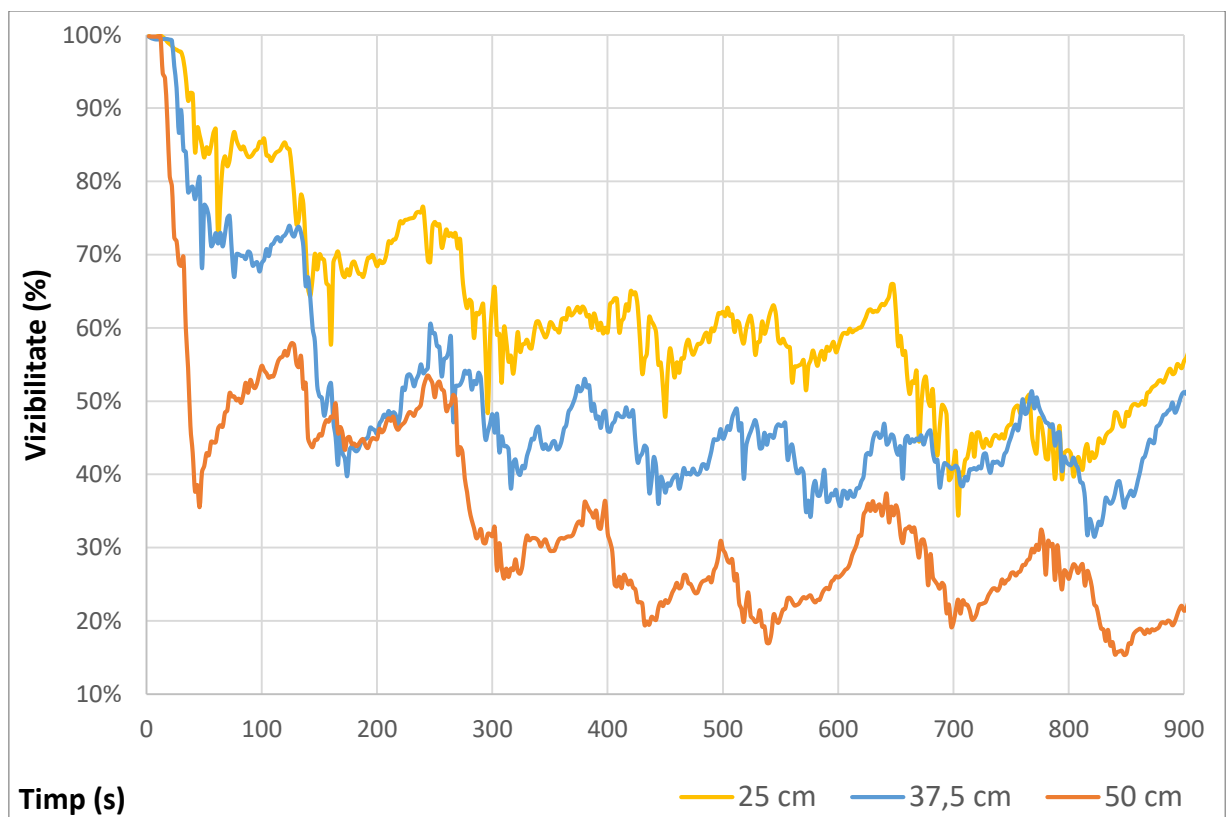


Fig 14. 1:20 scale visibility

The smoke extinction area that was determined in the small scale experiments, for the 1:10 scale the values are presented in figure 15 and for the 1:20 scale in figure 16.

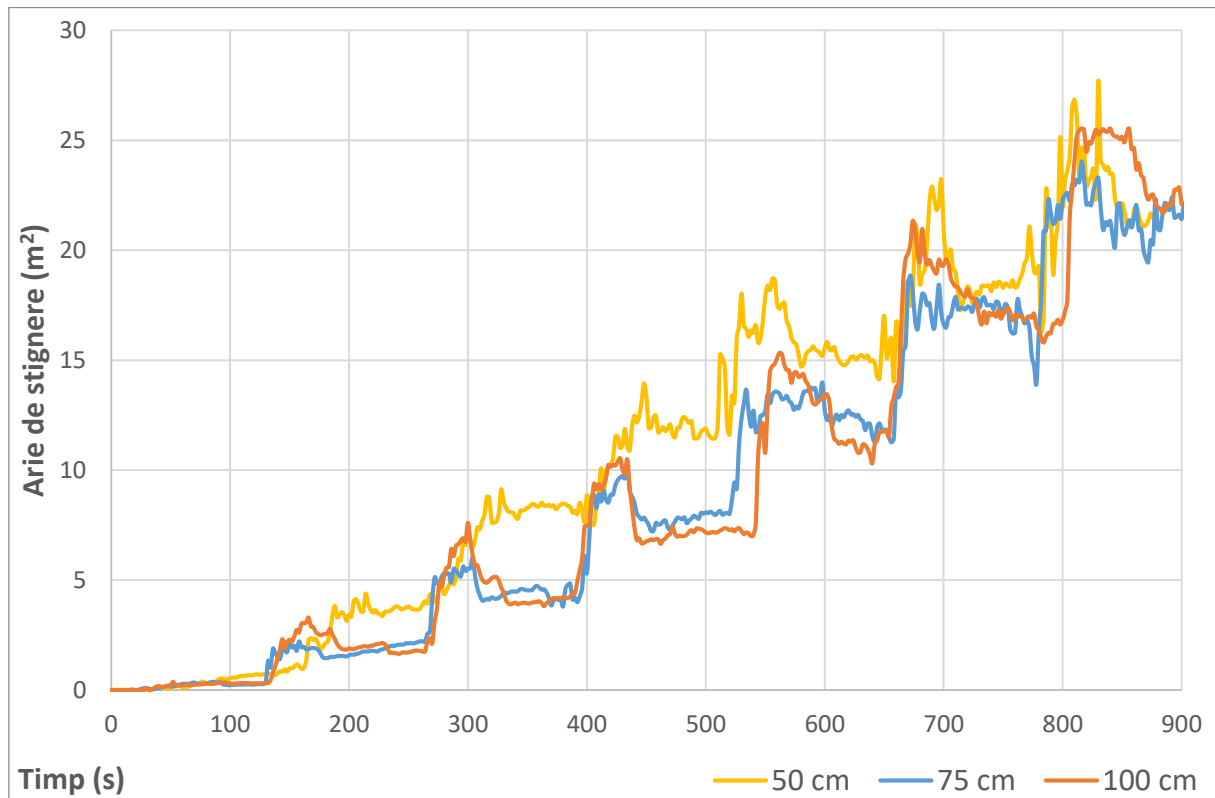


Fig 15. 1:10 scale extinction area

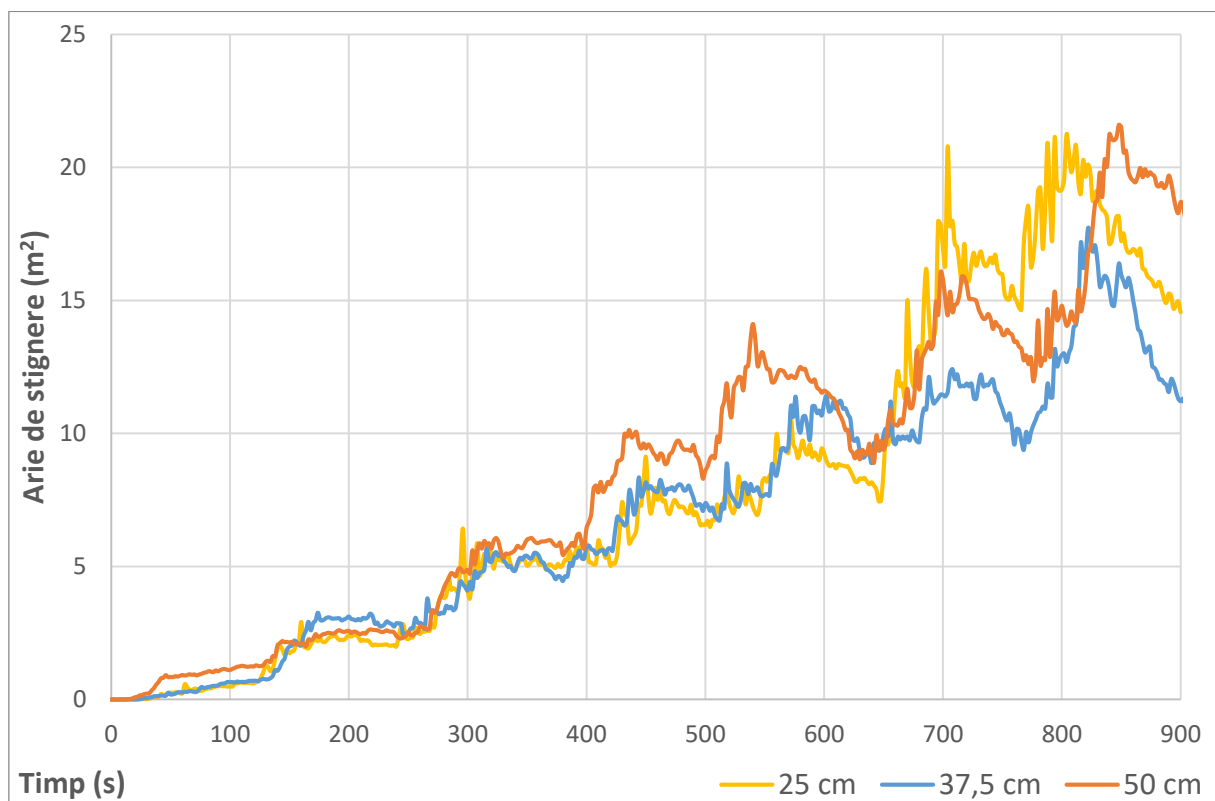


Fig 16. 1:20 scale extinction area

For each activation of the smoke generating device, the average smoke extinction coefficient (k) and smoke extinction area (A) were calculated, and the values for the three measurement distances were averaged. These values are presented in table VII.

Table VII. Average values for the smoke extinction coefficient and extinction area

Smoke fluid (ml)	1:10 scale		Smoke fluid (ml)	1:20 scale	
	Average k (m ⁻¹)	Average A (m ²)		Average k (m ⁻¹)	Average A (m ²)
0.00	0.00	0.00	0	0.00	0.00
0.50	0.34	0.30	0.25	0.52	0.23
1.50	0.91	2.42	0.75	1.05	1.40
2.50	1.36	6.01	1.25	1.36	3.01
3.50	1.53	9.45	1.75	1.45	4.48
4.50	1.98	15.74	2.25	1.45	5.78
5.50	1.77	17.20	2.75	1.69	8.21
6.50	2.11	24.28	3.25	1.74	10.01

The values from the above table imply that as the testing enclosure was smaller, the impact that a proportional amount of smoke has on visibility reduction is also lower.

Conclusions

The small scale experiments attest the fact that through the use of the smoke extinction area, the experimentally measured values for the natural, 1:10 and 1:20 scales can be correlated. Thus, through the use of small scale testing, conclusions about full scale smoke behavior can be drawn. Because smoke generation at different scales was obtained through different processes, different resting periods between subsequent uses of the smoke generating device were needed in the small scale experiments in order to ensure the measurement accuracy. That meant longer time scales for the small scale experiments compared to the full scale experiment and a necessity to use the smoke fluid quantity as a plotting reference. Figure 17 presents the evolution of the smoke extinction area for the three experimental scales compared on the same chart.

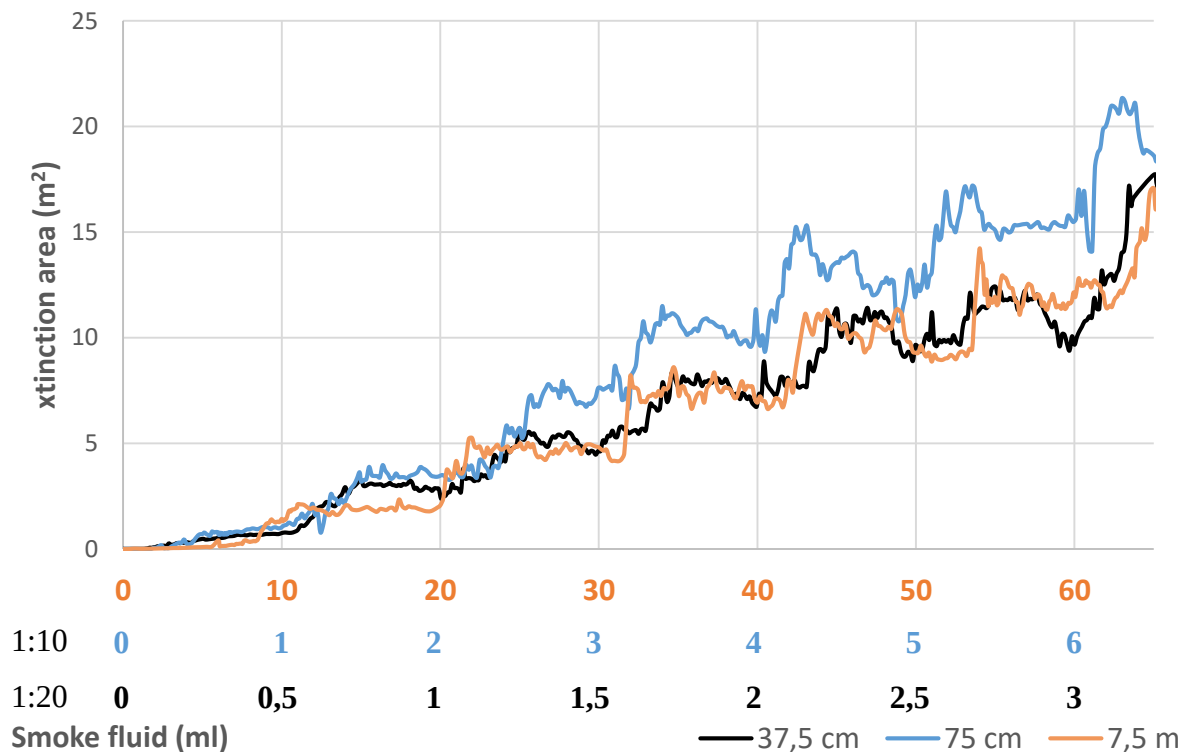


Fig 17. Comparative smoke extinction area

In order to facilitate comparison, charts for the three intermediate distances of each of the experimental scales are presented. It can be seen from the chart that for the 1:20 scale, the values for the smoke extinction area calculated on the basis of light intensity attenuation closely resemble those obtained in the full scale experiment. For each of the scales and each of the distances, the differences between the full scale and other scales values were calculated. the maximum differences, the average differences and their percentages form the maximum values are presented in table VIII.

Table VIII. Smoke extinction area differences for small scale testing

Scale	Distance	Maximum value	Average difference		Maximum difference	
			Value	% of max	Value	% of max
1:10	50 cm	28.71	2.73	9,53%	12.64	44.04%
	75 cm	24.03	2.43	10.13%	11.91	49.58%
	100 cm	25.53	4.16	16.32%	13.97	54.73%
1:20	25 cm	28.71	2.86	9.98%	16.93	58.98%
	37.5 cm	17.71	1.05	5.93%	5.38	30.39%
	50 cm	21.60	3.30	15.32%	9.81	45.43%

This data implies that for the intermediate distance in the case of each of the three scales, the most adequate for comparison is the 1:20 scale that has presented the greatest similarity to those determined in the full scale experiment. The average difference from the values in the full scale experiment is about 12% for the 1:10 scale experiment and about 10.5% for the 1:20 scale. The artificial smoke experiments prove that the smoke extinction area is an adequate parameter for the correlation of different experimental scales data.

Small scale testing of smoke generated through burning

During this testing phase, different construction materials have been exposed to fire in order to analyze the influence of their properties on smoke emission. In this regard, the smolder generated smoke's optical density (D) was determined for different building materials, by measuring the reduction in intensity of an incident light beam (I_0) that travels through the smoke layer, and comes out of it having a lower intensity (I). The smoke has been generated through exposing different building materials to a certain heat flux, and the formula used for the determination of the smoke's optical density is presented in equation 6, adapted from references [21] and [22].

$$D = \log\left(\frac{I_0}{I}\right) \quad (6)$$

Methodology

The smoke emitted by the tested samples was enclosed in a testing compartment having the 12,5 x 30 x 45 cm dimensions. In order to avoid the ignition of the samples, a thin layer of aluminum was positioned above an alcohol burner, as can be seen from figure 18. The alcohol that was used had a concentration of 70% and the distance between the light source and the lux meter was of 50 centimeters. The monochromatic light beam that crossed the smoke layer was generated with a laser of 1 mW power and 635nm $\pm$ 5% wavelength. The light intensity values were measured with a UNI-T, model UT383 BT lux meter, having a measurement domain between 0 and 9,999 Lux, a 1 Lux sensibility and $\pm$ 4% precision, at an interval of two seconds.

For the measurement of the sample's weight, a scale with the precision of 0.01 grams was used and a maximum capacity of 200 grams. Figure 19 present the weighing of the sample before the experiment, and figure 20 after the experiment was carried out.



Fig 18. Alcohol burner



Fig 19. Particle board sample weighing before testing

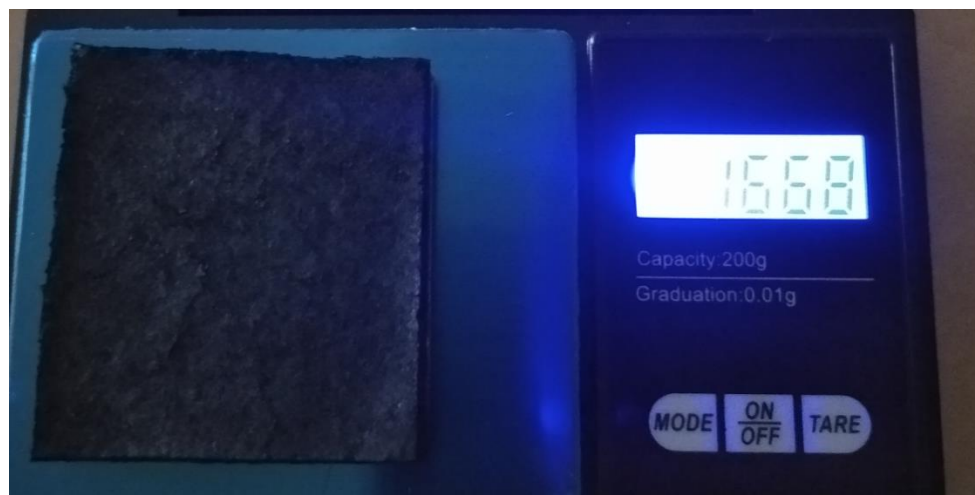


Fig 20. Particle board sample weighing after the testing

Usual testing materials have been tested, such as expanded polystyrene (EPS), extruded polystyrene(XPS), wood, particle board, polypropylene (PP), polyvinyl chloride (PVC) and plasterboard (PB) and the way in which their properties such as density or exposed area have influenced their smoke emission. As the samples have been exposed to the heat flux, the smoke

produced by them has determined a loss in light intensity, that was recorded by the lux meter. When the light intensity started to rise during the experiment, the samples have been removed from the influence of the heat flux. Table IX presents the building materials used for the samples, their dimensions, the weight of the samples, their exposed surface area and the time they were exposed to the heat flux.

Table IX. Sample building materials

No.	Material	Dimensions (cm) L x l x h	Mass (g)	Exposed surface area (cm ²)	Exposure time (s)
1.	Expanded polystyrene (EPS)	5 x 5 x 5	1.75	25	220
2.	Extruded polystyrene (XPS)	5 x 5 x 5	3.5	25	240
		10 x 5 x 2,5	3.5	50	150
3.	Wood	4 x 4 x 4	16.6	16	750
		4 x 4 x 4 Flame exposure	16.6	16	180
4.	Particle board	5 x 5 x 1.2	19.7	25	300
		5 x 1.2 x 5	18.8	11	480
5.	Polypropylene (PP)	PVC pipe D 32 mm	4.14	-	470
6.	Plasterboard	5 x 5 x 1.2	3.20	25	430
7.	Polyvinyl chloride wallpaper (PVC)	12 x 5 2 sheets	2.94	60	170
		5.5 x 5.5 4 sheets	2.94	30.25	190

Results and discussion

In order to present the influence of sample density on smoke emission, samples with the same dimension of extruded and expanded polystyrene were compared. The expanded polystyrene is characterized by a 28 kg/m³ density and the extruded one of a 35 kg/m³ one. According to the manufacturer's specifications, the extruded polystyrene is a class C fire reaction product, which means it is a combustible product that contributes to the fire's development, within certain limits. Also, its labeling of s3, d0 show that this building material has a high smoke emission, but does not produce flaming droplets when it is exposed to fire. From the obtained data, it is apparent that for a lower material density, the smoke is produced for a small amount of time, after which the smoke emission stops in a relatively abrupt fashion. In the case of the extruded polystyrene, having a greater density, the smoke emission is carried on a longer amount of time, leading to smaller smoke quantities accumulated, but a more sustained emission. Figure 21 presents the comparative chart for the smoke's optical density for the two building materials.

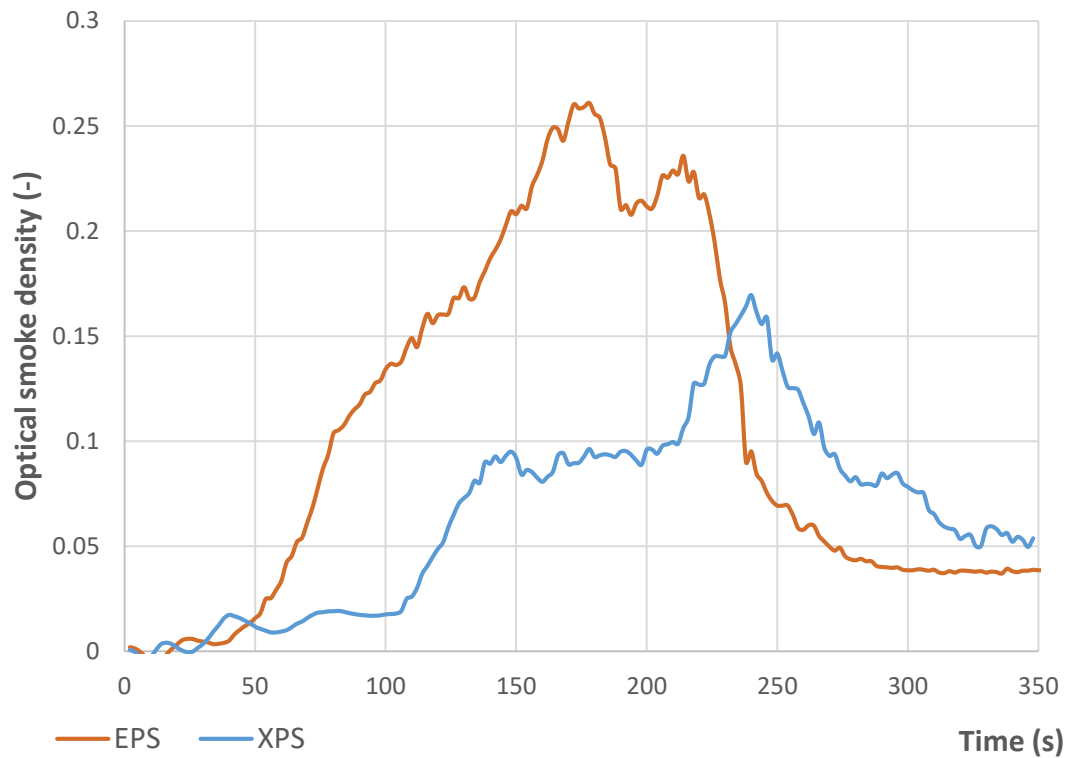


Fig 21. Different densities smoke emission

The wood sample that was exposed to smoldering did not produce significant amounts of smoke, but when it was directly exposed to the flame, the wood sample has directly contributed to the burning process and after the removal of the pilot flame, the burn did not consume the interior of the sample, but has instead deteriorated the outside of it before being self-extinguished. The smoke emission in the case of direct flame exposure was greater than that of the smoldering burn. The smoke's optical density in the case of wood is presented in figure 22.

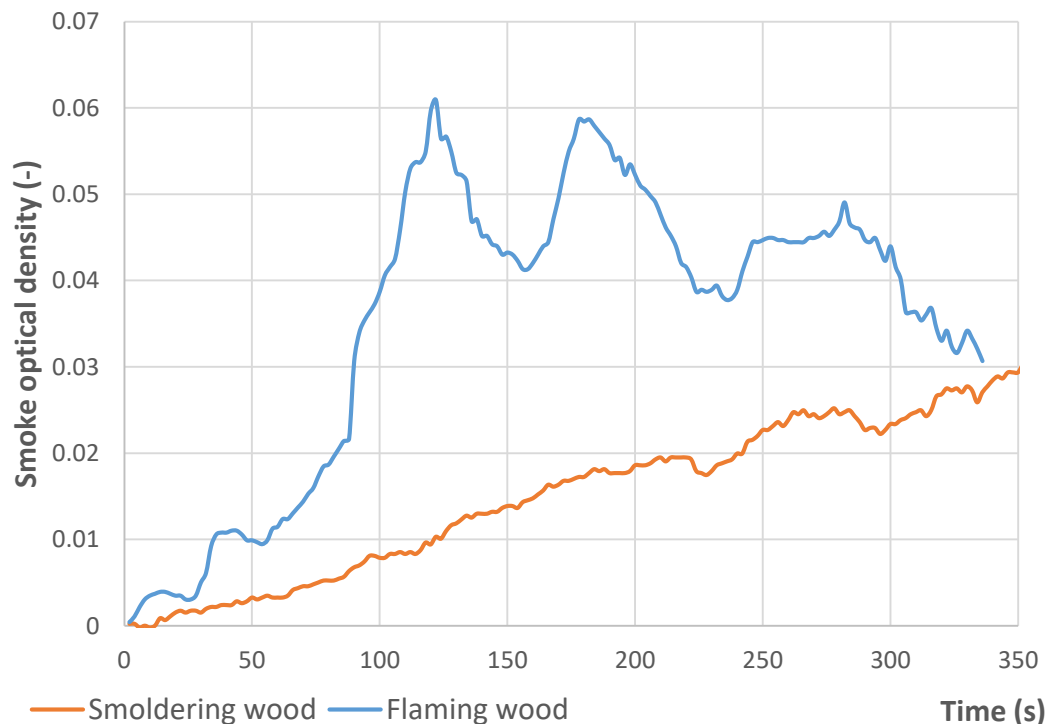


Fig 22. Wood smoke emission

The way that the flame burned only the sides of the sample without burning its interior can be seen in figure 23.



Fig 23. Flaming wood

In order to show the way that exposed surface areas influences smoke emission, same size samples of particle board were used. These were exposed to the same heat flux on different surface areas and it has been observed that a greater exposed surface area produced a significantly higher and faster smoke emission. The comparative chart for this case is presented in figure 24.

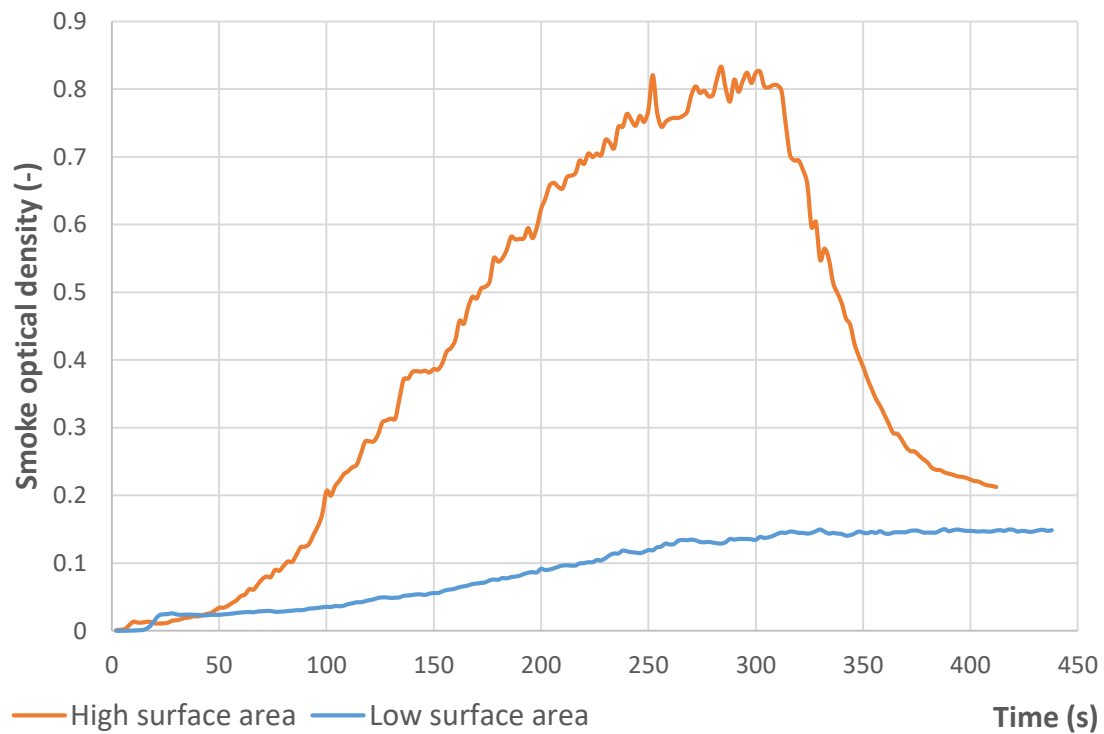


Fig 24. Surface area smoke emission

The different way in which the exposure has affected the two samples can be seen in figure 25.



Fig 25. Particle board after experiment

Another type of sample that was used to demonstrate the influence of the exposed surface area on smoke emission was the PVC wallpaper. Two samples of identical dimensions were tested, one being folded in two and the other in four sheets. This testing demonstrates the influence of the number of folds of the material and the exposed surface area. It has been observed that for a greater exposed surface area and a lower number of sheets, the smoke emission is greater. The comparative chart of the results obtained in this testing phase is presented in figure 26.

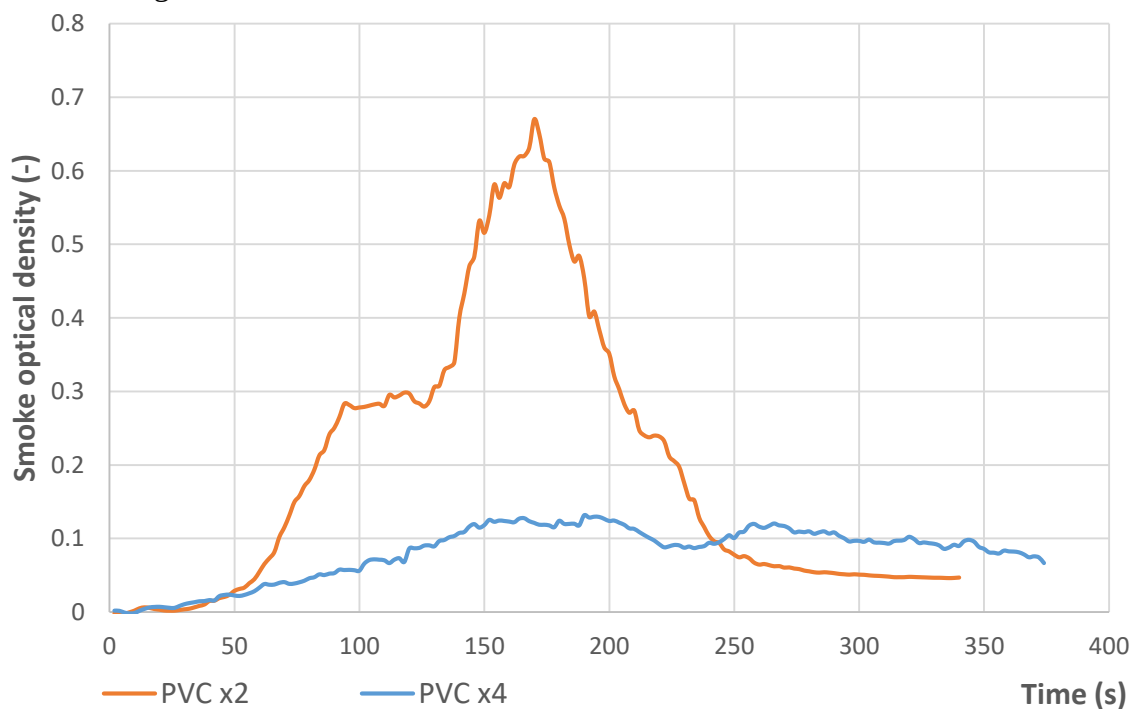


Fig 26. Exposed surface area smoke emission

When exposed to the heat flux, the plasterboard has not produced sufficient amounts of smoke, the paper in its composition being the one that has mainly contributed to its smoke emission. The sample used in the testing has the A2, s1-d0 marking, meaning that it cannot be

lighted with a flame and its contribution to a fire is extremely limited, it has a low smoke emission and it does not produce flaming droplets.

The polypropylene sample was used to obtain a profile for the optical smoke density, this material being used for the plumbing and electrical installations. After being exposed to the heat flux, the sample has melted and lost about 0.43 grams of its initial weight. As the sample did not burn with a flame, it can be assumed that the weight loss is due to the smoke production. The profile for the optical density of smoke for the polypropylene sample is presented in figure 27.

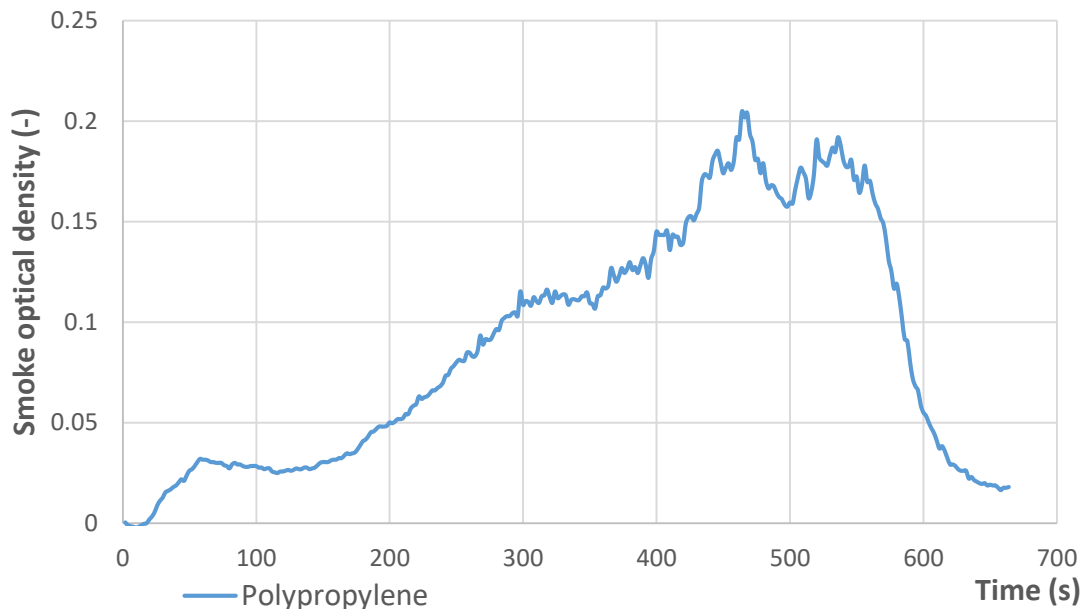


Fig 27. Polypropylene optical smoke density profile

Conclusions

Small scale testing of building materials has led to observations on the influence of their properties on smoke emission. It has been observed that the area of the surface exposed to the heat flux is directly influencing the smoke emission, this being true of the wood and for the plastic materials. The density of the sample material has influenced in an inversely proportional way the smoke emission, an intuitive phenomenon, seeing that at least in the case of the expanded polystyrene, the lower density is associated with a greater amount of air in its structure, that helps the burning process through a greater surface area in the structure of the sample that can be affected by convention and radiation phenomena.

It has been observed that flame generated smoke is produced in greater quantities than smolder generated one, in greater amounts if the flame is unstable, it cannot penetrate into the sample's mass and it is self-extinguishing.

For the usual building materials that were analyzed, the characteristic optical density profile for their smoke was obtained, for their exposure to a certain heat flux and smolder burning. These values can be correlated with those found in scientific literature and can be used in numerical simulations in order to approximate the probable behavior of these materials in similar conditions, but at full scale.

Conclusions

This paper has presented an experimental approach for the evaluation of the smoke emission of building materials, in the context of a continuous and accentuated technological evolution, for the purpose of contributing to the development of small scale testing methodology. Standard testing for existent or developing building materials needs great amounts of materials, that are not available in the research and development phase, or are rather costly. This is why small scale testing of building materials in order to evaluate their behavior when exposed to fire is necessary in order to evaluate the opportunity of industrial level production of innovative materials.

The evaluation of building material's smoke emission has been approached in this paper through the use of full scale experimental testing of artificially generated smoke, the 1:10 and 1:20 scale reduction of this experiment, and the small scale testing of the influence that building material properties gave on smoke emission.

Through the use of artificially generated smoke and the determination of its smoke extinction area, it could be demonstrated that that a relatively precise (5-10%) determination of the optical properties of smoke was possible at a small scale. Through the small scale testing of the smoke generated through the burning of building materials, correlations regarding the influence of building materials properties on the emitted smoke could be discovered.

The determination of the artificially generated smoke optical properties in full and small scale experiments, and the comparative determination of the quantities of smoke produced by the burning of building materials has been carried out through the use of a proprietary methodology, inspired by the standard testing procedures of the smoke emission of building products, in order for them to be classified in standard fire reaction classes.

The dissemination of the results presented in this paper has been carried out through the publishing of a Web of Science indexed article [23], an international databases indexed article [24], and a soon to be published article presented at a Web of Science indexed conference..

Regarding future research, the reproduction through numerical simulation of the values of the optical properties of smoke generated through the burning of building materials at small scales is of interest, as is the use of numerical simulation programs to approximate the full scale behavior of the smoke produced by the small scale burning of building materials, in order to evaluate the influence it has on compartment fire characteristics.

References

- [1] R. Parlamentul, Legea nr. 10/1995 privind calitatea în construcții, București, 1995. http://www.aicps.ro/media/content/2016-10/legea-10-1995-republicata-30-09-2016_5919ad6e1ae3c.pdf (accessed November 29, 2018).
- [2] J. Purkiss, L.-Y. Li, Fire Safety Engineering Design of Structures, Third Edition, CRC Press, 2013. doi:10.1201/b16059.
- [3] ISO, EN 13501-2:2016 Fire classification of construction products and building elements. Classification using data from fire resistance tests, excluding ventilation services, 2016.
- [4] ISO, EN 13823:2014 The Single Burning Item Test, 2014.
- [5] MTCT, MAI, Regulamentului privind clasificarea și încadrarea produselor pentru construcții pe baza performanțelor de comportare la foc, 2004. http://www.dsu.mai.gov.ro/wp-content/uploads/2015/07/Ordin_1822_2004.pdf.
- [6] R. Van Mierlo, B. Sette, The Single Burning Item (SBI) test method-a decade of development and plans for the near future, n.d.
- [7] P. Van Hees, T. Hertzberg, A.S. Hansen, Development of a Screening Method for the SBI and Room Corner using the Cone Calorimeter, (2002). www.sp.se (accessed November 1, 2019).
- [8] EUROCLASS SYSTEM, (n.d.). <http://virtual.vtt.fi/virtual/innofirewood/stateoftheart/database/euroclass/euroclass.html> (accessed November 1, 2019).
- [9] International Organization for Standardization, ISO 13943:2017 Fire safety-Vocabulary, 2017. <https://www.iso.org/standard/63321.html> (accessed December 20, 2018).
- [10] J. Axelsson, P. Andersson, A. Lönnemark, P. Van Hees, I. Wetterlund, Uncertainties in measuring heat and smoke release rates in the Room/Corner Test and the SBI, SP Swedish Natl. Test. Res. Inst. SP Fire Technol. SP Rep. 857 (2001) 501. www.sp.se (accessed November 1, 2019).
- [11] S. Karampran, D. Bun, B. Gautier, Extinction Properties of Smoke Mixtures, 2000. <http://www.iafss.org/publications/fss/6/829/view> (accessed December 27, 2018).
- [12] M.K.W. Chan, J. Mishima, NUREG/CR-2658, “Characteristics of Combustion Products: A Review of the Literature.,” 1983.
- [13] J.D. Seader, I.N. Einhorn, Some physical, chemical, toxicological, and physiological aspects of fire smokes, Int. Symp. Combust. 16 (1977) 1423–1445. <https://www.sciencedirect.com/science/article/pii/S0082078477804268> (accessed November 27, 2019).
- [14] D. Gross, J.J. Loftus, A.F. Robertson, Method for Measuring Smoke from Burning Materials, in: Symp. Fire Test Methods—Restraint Smoke 1966, ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, n.d.: pp. 166-166–39. doi:10.1520/STP41310S.
- [15] Y. Akizuki, T. Tanaka, K. Yamao, Calculation Model for Travel Speed and Psychological State in Escape Routes considering Luminous Condition, Smoke Density and Evacuee’s Visual Acuity, (2008). doi:10.3801/IAFSS.FSS.9-365.
- [16] International Organization for Standardization, ISO 13571:2012 Life-threatening components of fire — Guidelines for the estimation of time to compromised tenability in fires, 2012. <https://www.iso.org/standard/73217.html> (accessed December 14, 2018).
- [17] D.A. Purser, J.L. McAllister, Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat, in: SFPE Handb. Fire Prot. Eng., Springer New York, New York, NY, 2016: pp. 2308–2428. doi:10.1007/978-1-4939-2565-0_63.
- [18] K. Fridolf, D. Nilsson, H. Frantzich, E. Ronchi, Walking Speed in Smoke: Representation in Life Safety Verifications, Wsp.Com. (2018). <https://www.wsp.com/>

- /media/Insights/Sweden/Documents/2018/WALKING-SPEED-IN-SMOKE-REPRESENTATION-IN-LIFE-SAFETY.pdf (accessed August 30, 2019).
- [19] B. Truchot, C. Willmann, J. Guivarch, People evacuation in tunnel fires: a cross evaluation of two methodologies, *J. Phys.* (2004). doi:10.1088/1742-6596/1107/7/072004.
 - [20] G. Mulholland, Smoke production and properties, in: W.D. Walton (Ed.), *SFPE Handb. Fire Prot. Eng.*, 3rd ed., National Fire Protection Association, 2002: pp. 473–482. http://www.academia.edu/download/55183070/sfpe_handbook_of_fire_protection_engineering_edisi_2002.pdf#page=473 (accessed November 29, 2019).
 - [21] H. Ingason, B. Persson, Prediction of Optical Density using CFD, *Fire Saf. Sci.* 6 (2000) 817–828.
 - [22] J. Tissot, M. Talbaut, J. Yon, A. Coppalle, A. Bescond, Spectral study of the smoke optical density in non-flaming condition, in: *Procedia Eng.*, Elsevier Ltd, 2013: pp. 821–828. doi:10.1016/j.proeng.2013.08.131.
 - [23] D. Burlacu, A. Georgescu, A. Vartires, I. Marinescu, An Experimental Evaluation of Visibility in Simulated Smoke, in: *Int. Conf. ENERGY Environ.*, 2019: pp. 39–43. <https://ieeexplore.ieee.org/abstract/document/8937634/> (accessed January 13, 2020).
 - [24] D. Burlacu, Ștefan-N. Trache, Grid Resolution Influence On Smoke Simulation Accuracy, in: *2019 Int. Conf. Hydraul. Pneum. - HERVEX*, 2019: pp. 269–277.