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Evaluation of thermal fire hazard of 10 polymeric building materials and proposing a classification method based on cone calorimeter results

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SUMMARY

The use of polymeric building materials has been grown in many countries of Middle East in recent years. However, there are only a few fire testing laboratories in this region. Therefore, development of a method for controlling the reaction to fire of materials with bench scale tests is necessary. Providing a framework for classification of thermal fire hazard of materials based on bench scale heat release rate results was attempted. The fire behavior of 10 polymeric building materials was tested with cone calorimeter. The relationship between reaction to fire variables and physical properties of tested samples was examined. The thermal fire hazards of materials were assessed using methods presented by different researchers and with Conetools software. The results revealed that time to ignition, peak rate of heat release, and total heat release are essential variables for determining the fire hazard of materials. A classification method is proposed, which can be used in building codes in countries where the full-scale test facilities are not available. The method also can be used for quality control purpose and evaluation of fire behavior of materials in bench scale by manufacturers. An example of potential requirements for interior finishes for some occupancy types is also presented. Copyright © 2013 John Wiley & Sons, Ltd.

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KEY WORDS: reaction to fire; fire hazard; building code; cone calorimeter; Conetools; polymeric building materials

1. INTRODUCTION

The building finishes play an important role in fire growth. Especially the most polymeric building materials, if not well formulated with proper type and percent of flame retardants, may contribute severely in fire growth. In recent years, the use of polymeric building materials have had burgeoning growth in most Middle East countries because of key objectives such as energy saving, higher speed of construction, etc. Therefore, it is necessary to investigate their fire properties and regulate their application in buildings. For this purpose, a classification or ranking method is needed so the materials can be classified from safe (no contribution in fire) to hazardous (not allowed to be used without a proper protection) classes. However, in most countries of this region, there is no well equipped fire laboratory. As the authors know, there are only some fire laboratories in Iran and UAE. Therefore, it seems to be helpful to develop a reaction to fire classification method, which can be applied with least needed equipment and preferably bench scale tests. As heat release rate (HRR) is the most important parameter, which should be considered for evaluation of fire hazard of materials [1, 2], and there are some cone calorimeter apparatuses working in the region, we attempted to define a proper classification method based on cone calorimeter results. Our focus in

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this research was on thermal parameters of fire hazard. Detailed discussions on smoke toxicity and the related test methods can be found in [3].

Different methods have been historically presented for classification of reaction to fire of materials in different countries or regions. In American Society for Testing and Materials E84 and British Standard 476–7, the flame spread has been used for this purpose in two different manners. Noncombustibility test is another method, which has been used in many countries for distinguish between combustible and noncombustible materials. International Organization for Standardization (ISO) 1182 [4] is an international standard for this test. The noncombustibility concept has been used by model codes of USA, such as International Building Code [5], for distinguishing noncombustible construction types. A serious limitation for height and area of buildings with combustible construction types have been determined by these codes. Babrauskas and Janssens [6] discussed the history, applications, and aims of this categorical test and concluded that it should be replaced by HRR parameter.

It can be said that the most reasonable classification methods are those in which the potential contribution of materials in incident of flashover is evaluated. Sundström and Göransson [7] investigated fire behavior of more than 20 building materials in room corner and proposed a classification method with classes A (limited burning) to E (flashing over after 2 min of the test). However, the room corner is an expensive and time-consuming full-scale test and is not suitable for general use in building codes or for factory quality control purposes. Wickström and Göransson [8, 9] proposed a method for prediction of room corner results from the bench scale cone calorimeter test. Sundström [10] presented a method, as part of the works which lead to the European classification method [11], in which the materials were classified from class A (no contribution to fire) to F (the worst class). The heart of this classification method is the Single Burning Item (SBI) test, which itself is a medium-scale test for simulation of room corner. It is also a rather expensive test, in which about 2.25 m^2 of test specimen is needed to be evaluated [10,12]. The Conetools software (developed by SP Technical Research Institute, Borås, Sweden) was developed by SP research institute of Sweden and made it possible to predict the SBI and room corner results with the use of a cone calorimeter [13]. Conetools can be used for prediction of the reaction to fire classes of the materials according to the European classification method.

Richardson and Brooks [14] tested a number of building materials with a cone calorimeter as an attempt to define combustibility of materials on the basis of heat release. They proposed a set of criteria for classifying materials according to their degree of combustibility, when they are exposed to a radiant heat flux 50 kW/m^2 for 15 min. The categories 4 and 5 are materials with high degree of combustibility, and the category 5 needs to be protected by a thermal barrier, consisting of at least 12.7-mm gypsum board [14]. It seems that a shortcoming in Richardson–Brooks method is that they did not consider the time to ignition (TTI) variable, whereas it has an important influence on fire hazard of the materials. As far as the authors know, this method has not found an application in building codes.

Östman and Nussbaum [15] presented a simple empirical relationship for predicting the time to flashover in room fire test, on the basis of measurements of HRR in cone calorimeter. Östman and Tsantaridis [16] developed this relationship and extended it to a wider range of materials. The correlations were based on linear regressions between cone calorimeter data and time to flashover in room fire test. They found the best correlation to be as follows:

$$t_{fo} = a\frac{t_{ig}^{0.25}\rho^{1.72}}{THR_{300}^{1.3}} + b \tag{1}$$

where t_{fo} = time to flashover in room fire test (s), t_{ig} = TTI in cone calorimeter at 50 kW/m^2, THR_{300} = total heat release during 300 s after ignition at 50 kW/m^2 (MJ/m^2), ρ = mean density (kg/m^3), $a = 0.07(J/m^2)^{1.3}(kg/m^3)^{-1.72}s^{0.75}$, and b = 60 s.

Some researchers [such as 17, 18] used the ratio of the peak of HRR to TTI (PHRR/TTI) as indication of propensity to flashover, introduced as parameter x. Higher values of parameter x are associated with higher propensity to flashover. However, PHRR and TTI are not the only parameters that determine the fire hazard of materials. If the combustible content or surface density of a material is small, the total heat evolved from the combustion would not be enough to raise

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flashover. Therefore, as Petrella [19] mentioned, a combination of parameter x and total heat release (THR) would give better indications of fire hazard of the material. Petrella presented a rating system as follows (Table I). However, a shortcoming of Petrella's method is that two separate classifications are presented using two fire parameters (x parameter and THR, separately).

Chow [20] used the Petrella's method for assessment of fire hazard of sandwich panels used for constructing temporary accommodation units. Bakhtiyari, Taghi-Akbari, and Barikani [21, 22] investigated the fire hazard of expanded polystyrene and polyurethane foams with cone calorimeter, using the same method.

Cleary and Quintiere [23] developed a framework for utilizing fire property tests. They developed a series of equations to describe fire spread over surfaces and the released energy. For this purpose, they included ignition, heat release, burning time, and flame spread properties from cone calorimeter and lateral flame spread tests. The model was shown to yield reasonable prediction of real large-scale results [6,23]. Cone calorimeter is used in Japan for classification of reaction to fire of building materials. In this system, a noncombustible material is a material that has a maximum HRR of 200 kW/m^2 and a THR of 8 MJ/m^2 or less, when it is tested with cone calorimeter at 50 kW/m^2 heat flux for 20 min. The other classes that are defined with use of bench scale HRR in this system are quasi-noncombustible and fire retardant [6,24].

2. EXPERIMENTAL

2.1. Materials

The tested materials are listed in Table II. Samples were provided from the market. Apart from the epoxy flooring (no. 9 in Table II), which is mostly used only in industrial occupancies, the others are being used in different kinds of buildings and occupancy types. Some samples, including medium-density fiber board (MDF) and polyvinyl chloride (PVC), were provided from both internal produced and imported products. The other products were provided only from internal manufacturers. The use of MDF and PVC sheets as wall coverings have been considerably grown in assembly occupancies.

2.2. Test method

The tests were carried out using a Dual Cone Calorimeter apparatus, made by Fire Testing Technology Ltd, West Sussex, UK; according to ISO 5660–1:2002 test method [25]. The design of the apparatus is based on the oxygen consumption theory [25–27]. The sizes of specimens were 10 × 10 cm and held in a retaining frame. The tests were carried out at 50 kW/m^2 incident heat flux. This heat flux has been recognized as a proper level for evaluation of fire hazard of building materials and used by many researchers. Babrauskas [28] discussed the heat fluxes for bench scale heat release testing and presented the considerations, which govern the correct choice of heat flux. He showed that the heat fluxes of 25–50 kW/m^2 are proper for most research purposes. Thureson [29] used 25, 35, 50, and 75 kW/m^2 heat fluxes in the project 4 of 'European reaction to fire classification (EUROFIC) fire research program'.

Table I. Rating system for propensity to flashover [18].

THR	Flashover propensity
0.1–1.0 = very low	0.1–1.0 = low
1.0–10 = low	1.0–10 = intermediate
10–100 = intermediate	10–100 = high
100–1000 = high	

THR, total heat release.

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Table II. Tested materials.

No.	Code of sample	Description and important applications	Density kg/m^3	Surface density, kg/m^2
1	MDF-1	Internal medium density fiber board; wall covering, kitchen cabinets	784	6.4
2	MDF-2	Imported medium density fiber board; wall covering, kitchen cabinets	777	7.1
3	HDF	High density fiber board; floor covering	917	7.6
4	PVC-1	Internal polyvinyl chloride wall covering double sheet	1777	3.2
5	PVC-2	Imported polyvinyl chloride wall covering double sheet	1435	2.8
6	PVC-F	Polyvinyl chloride floor covering	1844	3.7
7	Textile covering	Polypropylene textile floor covering; sometimes used also as wall covering	183	0.93
8	PC	Fire retarded polycarbonate; light transmitting sheet, skylight, roof panel	204	1.3
9	Epoxy	Epoxy based industrial floor covering	1591	15.2
10	Fabric stone	Fabric stone consisting fire retarded polyester resin and fine color aggregates	2370	29.8

3. RESULTS

The test results are depicted in Table III. The reported results are average values obtained from testing three specimens. The given tolerances are standard deviation of three results. The end of test time for calculation purposes was based on the mass loss rate criterion, that is, the time that the average mass loss rate drops to lower than 150 g/m^2 in a 1 min period.

4. DISCUSSION

4.1. *Time to ignition and duration of flame*

The ignition time shows ease of flaming of a material. The shorter the ignition time, the easier the material ignites and the flame spreads on the surface of material with a higher velocity. Good repeatability was seen for the TTI results for most tested specimens. All specimens were ignited at 50 kW/m^2. The shortest TTI occurred for MDF-1, which ignited only 6 s after start of the test. The MDF-2, PVC, and textile covering were the next hazardous materials, from TTI point of view. Among the tested materials, fabric stone was the only material with an ignition time of more than 1 min.

The duration of flame is another parameter, which can be used for assessing the fire hazard of materials. It represents the time between TTI and flameout. Duration of flame depends upon different parameters, such as the type of the material and density. The flame duration for the tested materials is shown in Figure 1.

The epoxy floor covering showed the longest flame duration (1021 s) among the tested specimens, and after that, MDF-2 had a flame duration of 985 s. The fabric stone also showed a long flame duration (about 792 s), although this material was ignited later than the other specimens. Long flame duration may have several reasons; the most important ones are as follows:

(1) For a material with higher density, there is more available mass, which can contribute in combustion reactions.
(2) Some materials, especially wood and cellulose materials produce char on their surface while burning. This char layer protect the layers below from heat and the access of oxygen; therefore, the rate of burning decreases and the time of burning may increase.
(3) The materials with high amounts of combustible contents will burn for a longer time.

Considering the aforementioned text, a longer time of flaming does not necessarily mean higher fire hazard, and more parameters should be considered for this aim, which is discussed in more detail in the following text.

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Table III. The test results.

Fire parameter	MDF-1	MDF-2	HDF	PVC-1	PVC-2
ρ	785.8	768.6	911.0	1776.6	1434.9
t	8.1	9.2	8.3	0.8	0.8
TTI	6 ± 2.3	14 ± 7.2	36 ± 0.6	12 ± 2.2	9 ± 0.3
FO	788 ± 105.8	986 ± 232.5	753 ± 64.3	175 ± 111.5	177 ± 10.2
m_i	61.27	68.38	72.68	31.60	26.92
ML	47.33	52.17	55.60	15.32	13.67
Av. RHR	150.7	150.1	154.6	60.8	103.8
PHRR	274.0 ± 50.2	291.0 ± 31.3	589.8 ± 111	154.3 ± 28.4	146.1 ± 8.8
T PHRR	227	395	49	71	39
THR	69.8	78.8	81.8	12.2	17.9

Fire parameter	PVC flooring	Textile covering	PC	Epoxy	Fabric stone
ρ	1877.5	185.7	203.6	1547.9	2372.0
t	2.0	5.2	6.1	9.1	12.6
TTI	27 ± 1.5	14 ± 1.5	50 ± 2.5	30 ± 6.4	234 ± 4.3
FO	165 ± 121.2	373 ± 30.1	623 ± 168.7	1021 ± 144.6	792 ± 34.5
m_i	35.94	9.63	12.52	141.16	292.56
ML	10.20	6.57	7.83	66.20	24.67
Av. RHR	114.7	210.9	178.3	283.4	141.4
PHRR	223.9 ± 17.0	476.8 ± 49.0	627.1 ± 8.6	408.5 ± 43.9	213.1 ± 11.5
T PHRR	65	65	64	341	393
THR	16.33	26.20	18.40	196.10	57.03

MDF, medium-density fiber board; HDF, high density fiber board; PVC, polyvinyl chloride; TTI, time to ignition; PHRR, peak ofheat release rate; THR, total heat release; PC, polycarbonate; FO, Flame out; ML, Mass Loss.

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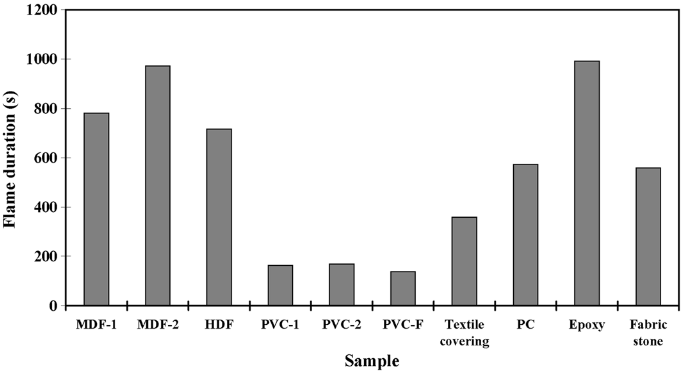

Figure 1. Flame duration on the tested materials at 50 kW/m^2.

4.2. Heat release rate

The average and peak values of HRR of the burned specimens are given in Table III. The curves of HRR are depicted in Figure 2. Generally, the HRR values are low before ignition of the material because the temperature of the surface of the material is still not high enough for pyrolysis and burning. After ignition, the HRR rapidly rises and reaches its peak value, which depends upon the type of the material and its combustible content. Afterward, a layer of char may form on the surface, which can interrupt a major part of the combustion reactions, and subsequently, the HRR value decreases. In continuation, a decrease of the combustible content of specimen results in lower values of HRR, and finally, the flame will extinguish. Sometimes, a considerable volume of gasses may be produced behind the hot char layer formed on the surface of the burned material. The produced gas pressure and thermal effects can cause cracks, and eventually, the flammable gasses escape and burn. It can produce another peak(s) in the HRR curve, sometimes higher than the first one. As it can be seen in Figure 2, there is more than one peak in most of our specimens.

The polycarbonate (PC) sheet showed the highest PHRR among the tested specimens, with an average PHRR of 627.1 kW/m^2. This value is very high and represents a dangerous material in case of fire. After that, high density fiber board (HDF), textile covering, and epoxy flooring showed highest PHRR values. The PHRR of HDF was much higher than MDF specimens were. This could be due to higher density of HDF (910 kg/m^3 in comparison with 770 kg/m^3).

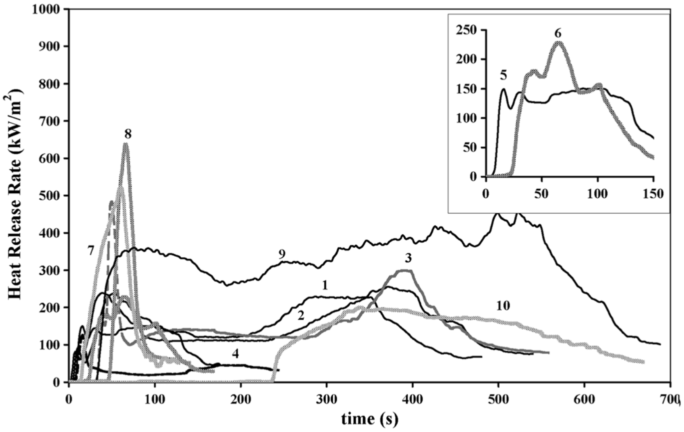

Figure 2. The curves of heat release rate of the burned specimens at 50 kW/m^2 (the specimen numbers are in accordance with ones given in Table II).

4.3. Total heat release

The THR data of the tested materials are given in Table III. Higher THR means more contribution in fire growth. Among the tested samples, the epoxy flooring showed the highest THR. The relative residual mass of the specimen, that is, the remaining mass at the end of test divided by initial mass versus time was examined and compared with THR and HRR curves. Although the textile covering and PC samples had very high PHRR, their initial masses were very low; therefore, they could not have a high contribution to fire growth. A low mass means low THR, and hence, the material cannot enter a high energy into fire. The epoxy flooring was a relative dense sample, and its initial mass was about 141 g. It also showed a high PHRR, but as seen in test results given in Table III, only 50% of the sample was combustible, and about 50% of its mass was unburned at the end of the test. For fabric stone, only about 10% of the material was burnt. It showed that considerable parts of these materials were composed of noncombustible mineral fillers. The relative residual mass of PVC samples were also about 50% and showed that about half of the mass of these materials were filled with mineral powders.

4.4. Assessment of relationship between reaction-to-fire parameters

The relations of the reaction-to-fire results were examined (the related curves and full discussions are not depicted in this paper). Mouritz *et al.* [30] investigated the relationships between HRR and other reaction to fire properties of polymer composite materials. They showed that there is a linear relationship between average and peak HRR. Therefore, we omitted average HRR from our assessments. The graphs of PHRR and THR versus TTI were examined, but no relationship was recognized between these heat release parameters and TTI. Then, the effect of density (ρ) was added. It was assumed that the THR should be proportioned with ρ and inverse of TTI ($THR \approx \rho/TTI$), but no reasonable relationship was attained. For including the influence of thickness and available mass of combustibles, the surface mass was substituted instead of volume density, and a much better correlation was attained. As THR is an integral of curve of HRR versus time, higher PHRR can mean higher THR. Therefore, the diagram of THR versus product of PHRR and surface density divided by TTI was plotted. A relatively reasonable correlation with a correlation coefficient of 0.95 was achieved, which revealed that the THR of a burned material was proportional to PHRR, surface density, and inverse of TTI. It showed that in any equation or classification system for fire hazard of materials, at least THR, TTI, and PHRR need to be considered. Ignoring each of these variables in a classification system can lead to confusing results.

5. FIRE HAZARD ASSESSMENT AND CLASSIFICATION

The thermal fire hazards of the tested materials were assessed with the use of the methods of Östman–Nussbaum (Equation 1), Petrella (Table I), Richardson, and Conetools software. The values of THR_{300s}, THR_{900s}, and x parameter are given in Table IV. The time to flashover and the reaction to fire classes of the tested materials, predicted by different methods, are given in Table V.

5.1. Ranking with use of Östman equation and Conetools

The tested materials were ranked according to time to flashover results acquired from Östman's equation and Conetools software. The comparison of the resulted rankings is presented in Figure 3. In these rankings, number 1 represents the material with the lowest hazard, and number 10 indicates the most hazardous one (with shortest time to flashover) among the tested materials.

According to the Östman's equation, PVC-F, PVC-1, and the fabric stone had relatively the lowest, and MDF-1, PC, and textile covering had the highest relative thermal fire hazard. Whereas with use of Conetools, the fabric stone, PVC-1, PC, and PVC-F had the lowest relative hazard, and in other side, MDF and textile covering were the most dangerous materials. As in the Östman's equation, the time to flashover is predicted on the basis of the material's properties; therefore, a time to flashover is always

Table IV. Needed data for the applied fire hazard assessment methods.

Code of sample	THR_{300s} (MJ/m^2)	THR_{900s} (MJ/m^2)	x parameter ($kW/m^2.s$)
MDF-1	45.7	69.8	45.7
MDF-2	40.2	78.8	20.8
HDF	46.1	81.8	16.4
PVC-1	12.2	12.2	12.9
PVC-2	17.9	17.9	16.2
PVC-F	16.3	16.3	8.3
Textile covering	26.2	26.2	34.1
PC	18.4	18.4	12.5
Epoxy	92.4	196.1	13.6
Fabric stone	48.9	57.0	0.9

THR, total heat release; MDF, medium-density fiber board; HDF, high density fiber board; PVC, polyvinyl chloride; PC, polycarbonate.

Table V. Prediction of time to flashover and reaction to fire classes of the tested materials by different methods.

	Time to flashover predicted by		The reaction to fire class according to	
Code of the sample	Conetools (s)	Equation 1	Richardson's method	EN classification (Conetools)
MDF-1	67	133	4	E or F
MDF-2	95	162	4	E or F
HDF	177	205	5	D
PVC-1	269	2018	4	C or D
PVC-2	104	827	3	D or E
PVC-F	180	1870	4	D
Textile covering	78	75	5	E or F
PC	245	100	5	D
Epoxy	133	200	5	E or F
Fabric stone	—	1173	4	A2 or B

MDF, medium-density fiber board; HDF, high density fiber board; PVC, polyvinyl chloride; PC, polycarbonate; EN, European standard.

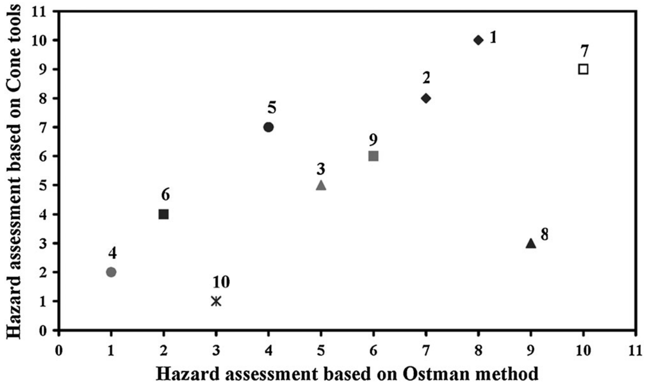

Figure 3. Ranking of the tested materials according to time to flashover, acquired from Conetools and Östman's equation (from less to most hazardous specimen).

achieved with the formula, regardless if flashover occurs or not. The calculated time to flashover is more than 20 min for materials that do not raise a flashover, according to Östman [16].

Some differences between two resulted rankings are considerable. The most noticeable difference is ranking of PC in Conetools and Östman methods, 3 and 9, respectively. This is because of the different importance of TTI in these two methods. In Östman's equation, TTI is raised to the power of 0.25, so with a 10 times increase of TTI (for example from 10 to 100 s), time to flashover increases only 1.78

times. Whereas in Conetools, the flame spread is calculated on incremental area elements, based on HRR values of cone calorimeter, and it is assumed that the burning area growth is proportional to the inverse of TTI [13]. Therefore, the high TTI of PC, which was the second longest TTI among the tested materials after the fabric stone, has led to a longer time to flashover in Conetools in comparison with Östman's equation. As the Conetools is based on a stronger theory, its predictions are more reliable.

5.2. *Hazard assessment by Petrella's method*

The needed data for the Petrella's classification method is presented in Table VI.

Only for fabric stone, a low propensity to flashover was achieved. The reason is the relative high TTI of the material, so despite its relatively high PHRR (about 213 kW/m^2), the resulted x parameter was less than 1. This is in good agreement with the results of Conetools and shows the importance of TTI in fire hazard of materials.

For PC and all three types of PVC specimens, the x parameter was relatively high; however, their THR was not too high. For this reason, the resulted class of fire hazard assessment was medium for them. The main reason that the fire hazards of PVC samples fall in medium class was their low thicknesses. It should be mentioned that PVC-1 and PVC-2 samples were hollow double sheet and the thicknesses of two sheets were very low (less than 1 mm). This resulted in low mass per square area (there was only low mass for combustion), and therefore, reduction of the fire hazard. The reason of the attained medium fire hazard for PC was different from PVC samples. The PHRR of the tested PC was higher than 620 kW/m^2. However, its TTI was about 50 s; therefore, the achieved x parameter was 12.5, and the resulted THR was also relatively low (about 18.4 MJ/m^2). This can be a sign that the tested PC was flame retarded.

A shortcoming of Petrella's method is that two separate classifications are presented using two fire parameters (x parameter and THR). Therefore, it cannot be easily used for comparison of hazard of different materials. For example, in our experiments, epoxy was the only specimen that both x parameter and THR were placed in high hazard classes for it. But it was not possible to conclude that it had a higher fire hazard than MDF-1, because although the THR of MDF-1 was much less than epoxy, its x parameter was higher.

5.3. *Comparison of Richardson's and Conetools results*

A comparison of the resulted classes according to Conetools and Richardson's method is depicted in Table VII.

None of the specimens were placed in classes 1 or 2 of Richardson's method. The PVC-2 was the only specimen which was placed in class 3. Actually, the difference between the PHRR of PVC-1 and PVC-2 was not significant (154 and 146 kW/m^2, respectively). However, as these values were in two sides of the border of classes 3 and 4 (150 kW/m^2), they were placed in classes of 3 and 4, respectively. In general, all the PVC specimens fall in the border values of classes 3 and 4 of Richardson's method and classes C and D of the European system according to Conetools.

Table VI. Fire hazard of tested materials by Petrella's method.

The code of specimen	THR (MJ/m^2)	x parameter (kW/m^2.s)	Class of propensity to flashover	Class of fire hazard assessment
MDF-1	69.8	45.7	High	Medium
MDF-2	78.8	20.8	High	Medium
HDF	81.8	16.4	High	Medium
PVC-1	12.2	12.9	High	Medium
PVC-2	17.9	16.2	High	Medium
PVC-F	16.3	8.3	Medium	Medium
Textile covering	26.2	34.1	High	Medium
PC	18.4	12.5	High	Medium
Epoxy	196.1	13.6	High	High
Fabric stone	57.0	0.9	Low	Medium

THR, total heat rate; MDF, medium-density fiber board; HDF, high density fiber board; PVC, polyvinyl chloride; PC, polycarbonate.

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Table VII. Classification of tested specimens according to Conetools and Richardson's methods.

		Conetools					
		A (A2)	B	C	D	E	F
Richardson	1						
	2						
	3				PVC-2		
	4	Fabric stone		PVC-1	PVC-F	MDF-1, MDF-2	
	5				HDF, PC	Textile covering, epoxy	

PVC, polyvinyl chloride; MDF, medium-density fiber board; HDF, high density fiber board; PC, polycarbonate.

The tested fabric stone was placed in class A2 or B of Conetools, that is, a material with low hazard. This is despite that it released a PHRR of 213 kW/m^2 and a THR of 57 MJ/m^2. Because of these relative high values of PHRR and THR, it is placed in class 4 of Richardson's method, which is a considerable disagreement with Conetools. The reason of such obvious contradiction is the important influence of TTI (and subsequently the history of surface flame spread), which has been reasonably considered in Conetools but not in the Richardson's method. As it was shown experimentally in the previous text, at least three parameters TTI, THR, and PHRR need to be considered in any classification system based on bench scale HRR tests.

Therefore, it appears that the Richardson's method needs to be modified concerning this matter. For more investigation, the sensitivity of the European classification method to TTI values was studied with Conetools. For PVC-1, PVC-2, epoxy, and fabric stone, the different TTI values were entered into the software. A slight increase of TTI for PVC samples resulted in change of the class of these materials. For example, increasing of TTI of PVC-1 to 20 s improved its reaction to fire class to A2/B. In the other side, changing of the TTI of fabric stone, which was a thermally thick specimen, from 234 s to 120 s, deteriorated the attained class from A2/B to C.

From another viewpoint, it can be seen that with increase of the numerical value of TTI to vicinity of the PHRR value, the x parameter approaches to 1 and the contribution of the material in fire growth decrease. In other words, the fire hazard of the material improves with increasing TTI. These results show the important influence of the TTI on the fire hazard of materials. Ignorance of TTI in a fire hazard classification system can result in misleading predictions.

5.4. *Proposal of a new method for classification of thermal fire hazard of materials*

Considering the aforementioned discussions, we propose the following improvements on Richardson's method:

1. It is proposed that the class 1 be allocated to noncombustible materials, which are safe in case of fire and represent a class of materials without any contribution to fire. The noncombustibility test can be carried out with a simple and mostly available apparatus. However, the statement of Richardson for this class can also be kept, if cone calorimeter is the only available apparatus. Moreover, in recent years, there is a tendency to substitute the noncombustibility test with a more scientific variable such as HRR [6].
2. The classes of 2 and 3 of Richardson's method can be merged into one class. Our experiments have been shown that materials of these two classes could be classified into class A2 to C of Euro-class system.
3. In class 4 of Richardson's method, it is better to reduce the limit of 300 kW/m^2 to 250 kW/m^2, because the materials with 250–300 kW/m^2 PHRR can be very dangerous materials in practice and need to be protected with thermal barriers. For example, fire retarded expanded polystyrene foam can be mentioned [21].
4. TTI value has to be included as a parameter in the classification method. Disregarding TTI may lead to confusing results and, especially, it can cause some materials with medium hazard to be regarded as dangerous ones. The consideration of TTI is especially needed for materials with middle fire hazard classes. It is not too important for materials of very low or very high hazards, because the PHRR and THR values are explanatory for the description of these kinds of fire hazards.

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Regarding the aforementioned text, the following classification method is proposed for thermal fire hazard of building finishes:

Class 1: Noncombustible materials according to ISO 1182 test method or materials that release heat at a peak rate of 10 kW/m^2 or less and in total amounts of 5 MJ/m^2 or less, when they are tested with cone calorimeter and exposed to a radiant heat flux of 50 kW/m^2 for 15 min.

Class 2: The materials that when tested with cone calorimeter at 50 kW/m^2 heat flux exposure for 15 min, satisfy one of following conditions: (1) they release heat in total amounts of 50 MJ/m^2 or less and at a peak rate of 150 kW/m^2 or less or (2) they release heat in total amounts of 80 MJ/m^2 or less and their x parameter is 1.0 or less.

Class 3: Materials that release heat at a peak rate of 250 kW/m^2 or less and in total amounts of 100 MJ/m^2 or less, when they are tested with cone calorimeter and exposed to a radiant heat flux of 50 kW/m^2 for 15 min.

Class 4: Materials that release heat at a peak rate greater than 250 kW/m^2 or in total amounts greater than 100 MJ/m^2, when they are tested with cone calorimeter exposed to a radiant heat flux of 50 kW/m^2 for 15 min.

This method needs only cone calorimeter test apparatus therefore is suitable for building authorities of countries where the needed test apparatuses (such as SBI) for a comprehensive reaction to fire classification are not available or are rare. The limitation of application of each class in finish of walls or ceilings of different spaces can be prescribed in building regulations of each country (or by governmental building authorities) according to their conditions. The approved document B (of England and Wales) and building regulations of Sweden are good models, which can be used for getting initial ideas for the purpose. The application of reductions of requirements in spaces, which have been protected with sprinkler system can be a matter of study. Table VIII is an example of potential requirements, provided by us, that can be used by building authorities. In practice, we proposed a more conservative system for our country and did not consider trade-offs with sprinkler system, because the performance of sprinkler systems in fires has not been well studied in the country yet.

We examined this method for some other materials that were tested before in fire laboratory of Building & Housing Research Center. It seems that the method is to some extent conservative. For example it seems that for class 2, the x parameter could be increased to 1.2 or even more. However; in the absence of full laboratories like SBI, it may be better to keep a conservative level of safety.

The method was proposed as a temporary classification method (until installation and start-up of SBI in national laboratories) and was approved by technical committee of part 3 of the building regulation, which is responsible for fire safety (it should be stated that at the moment only the means of egress requirements are mandatory and the other requirements are not obligatory for all buildings in Iran yet).

The method has been used by Building & Housing Research Center for evaluation of fire hazard of considerable number of products for manufacturers and consultant engineers. Simultaneously, we have used Conetools for a better judgment. Therefore, we can say that with a conservative approach in defining the requirements, the method is very useful in improving fire safety in design process of new buildings or alterations.

Table VIII. An example of potential requirements for interior wall and ceilings finishes for some occupancy types based on bench scale results*.

	Fully sprinklered			Nonsprinklered		
Occupancy type	Exit enclosures	Corridors	Rooms	Exit enclosures	Corridors	Rooms
Assembly and hotels	2	2	3	1	1	2
Apartments	2	2	3	1	2	2
Industrial	3	3	3	1	2	2
Healthcare	2	2	2	1	1	2

*Plastic foams of class 3 need to be protected with a thermal barrier

6. CONCLUSIONS

In the absence of proper codes and national control methods in most countries of the Middle East, there are many flammable building materials in the market, which can seriously contribute in building fires. This is true for both internally produced and imported products. Ten polymeric building materials were tested with ISO 5660 cone calorimeter. The needed samples were provided from the market and selected from both internal and external sources. The results revealed that most of them were very dangerous in case of fire. Common materials such as MDF, HDF, and textile covering showed very high heat release values, both in total and at peak rates. Therefore, it is needed to rule the use of these materials in buildings. Attainment of a classification method based on cone calorimeter results and for proper application in national building codes or advisory documents was attempted. The relation between reaction to fire parameters and physical properties of the samples were examined. It was shown that THR, TTI, and PHRR are the least and most proper variables that should be considered in a classification system based on bench scale HRR test. The thermal fire hazards of the tested materials were evaluated with different methods, including the systems given by Richarson–Brooks, Petrella, and the Conetools software. On the basis of the assessment of the results, an applied classification method was proposed. This method needs only cone calorimeter; hence, it is specially suit for countries that do not have well-equipped national fire laboratories (such as SBI) yet. An example of potential requirements for interior wall and ceiling finishes for some occupancy types was also provided.

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