

FIRE AND SMOKE TEST METHODS FOR INTERIOR BUILDING FINISHING MATERIALS: ARE THEY SUFFICIENT TO EVALUATE MODERN BUILDING MATERIALS?

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ABSTRACT

Many contemporary building materials, including synthetic flooring materials, have been developed within the last few years. While some have become popular with widespread use, there has been limited research conducted on how these materials behave before, during and after a fire.

Current fire testing and US building code requirements are based on material ignitability, surface flame spread, and smoke release rate test methods. Though useful for assessing some aspects of a fire, these test methods alone are not sufficient for comprehensive fire safety evaluations. Mass loss, chemical effluent production, and toxic gas emissions should also be considered.

Fire research conducted on modern synthetic flooring shows that some synthetic floorings burn quickly under certain conditions, and they release a host of chemicals that are hazardous to humans and pets. No discoverable research though has characterized their smoke constituents or chemical emissions when these modern synthetic flooring materials are subjected to increased temperatures but before they combust.

Preliminary research by Tile Council of North America (TCNA) Laboratory shows that floor coverings comprised of plastic based materials (PBM) are thermally unstable and release toxic gases at pre-flash over temperatures. Further, this research indicates that hazardous gases from certain plastic (e.g., vinyl) flooring materials are released at levels of concern to building occupants' health and wellness, before and during combustion.

This paper will review existing fire and smoke test methods applicable to floor coverings and their deficiencies in relation to fire and smoke toxicity evaluations, and present the needs for measuring mass-loss and chemical effluents at elevated temperatures, with the chemical effluents assessed for their toxicity.

This paper will also present TCNA preliminary test results towards toxicity-based fire safety evaluations on various flooring materials, including ceramic tile, allowing a comparison between synthetic flooring after exposure to various fire conditions.

1. BUILDING MATERIALS

Whether synthetic or natural, many building construction materials combust when exposed to high temperatures or excessive heat loads. However, noncombustible materials, such as ceramic tile, concrete, gypsum and metal alloys do not ignite, release heat, or spread the fire at higher temperatures. Concrete is a material integral in most construction (Garas, Allam, and Mamdouh 2009). Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is another noncombustible material. However, at high temperatures, gypsum can undergo calcination due to the loss of the water of hydration, leading to deformation of the structure. Therefore, to use gypsum in building materials, it has to be used with clay to give better stability. A mixture of gypsum and kaolin clay enhances gypsum's stability by reducing the thermal conductivity of gypsum. Nevertheless, gypsum boards in a building are considered sprinklers during fire accidents because the gypsum can become an anhydrate at high temperatures close to 125 °C providing water for fire prevention (McGraw and Mowrer 2000; Just, Schmid, and König 2010). Another noncombustible material used in buildings are metal alloys. Metal alloys, mainly aluminum alloys, are used extensively in construction.

The interior of a structure (i.e., building compartments) often utilizes synthetic materials that are combustible. Due to modernization and varying consumer preferences, such materials often leverage cheap and affordable composites such as plastics (Pohl 2010). In general, plastics are synthetic organic polymers with higher molecular weights. These plastics are polymers of ethylene, propylene, styrene, amides, and urethane. Monomers, with or without further chemical modifications, can be used to fabricate different plastics such as high-density and low-density polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyamides (nylon), and polyurethane (PUR) polymers. Approximately 18-24% of annual global plastics produced are used in constructions (Liu et al. 2020; Biron 2018). Stone Plastic Composites or wood plastic composites (SPC and WPC products) comprise PVC, calcium carbonate, and wood particles. These SPC and WPC could provide visual characteristics such as stone and wood looks to mimic ceramic tile and wood products. The other additives in these products include plasticizers, polyurethanes, stabilizers, and UV protecting agents. Because SPC and WPC products are solid mixtures of different components, these products melt and degrade with a moderate rise in temperature (exceeding 100 °C). This degradation adversely affects PVC and other additives' chemical properties, resulting in smoke and toxic fumes, further complicating evacuation and relief efforts. An essential point to remember is that plastics are fuels (Wong et al. 2015) that could facilitate fire growth and spread. In recent fire incidents across the globe, different forms of plastics were directly linked to fire breakout and spread (NTSB 2017; McKee 2017).

2. FIRE TEST METHODS

Current fire testing and US building code requirements are based on material ignitability, surface flame spread, and heat-smoke release rate test methods. Though they help assess different aspects of a fire, these test methods alone are not sufficient for comprehensive fire safety evaluations of the above-mentioned modern construction materials. The following are fire test methods relevant to modern interior building finishing materials, including plastic-based materials are discussed to show their strengths and weaknesses.

a. Non-combustibility and ASTM E136

Non-combustibility has been a central focus on both British and US building material fire testing. The first non-combustibility test method was developed in the UK as part of BS 476 ("Fire Resistance, Incombustibility, and Noninflammability of Building Materials and Structures (BS 476)" 1932), and in the US, ASTM E136 (Standard Test Method for Assessing Combustibility of Materials Using a Vertical Tube Furnace at 750°C, 1965). Briefly, the non-combustibility test method of the ASTM E136 test uses 750 °C exposure temperature to test materials. It has three pass or fail criteria for the tested materials. They are: (1) Neither the temperature on the surface nor in the middle of the sample may rise by more than 30 °C above the furnace temperature. This requirement is because noncombustible materials do not emit heat or are non-exothermic at 750 °C. (2) There be no flaming from the specimen after the first 30 seconds of exposure - to ensure that the material tested is not ignitable at high temperature. (3), No more than 50% of the specimen mass loss is observed during testing. This criterion ensures that the tested material is not losing weight by releasing volatile gases or sublimation. Chow et al. has shown that organic polymers, such as PVC and polymethyl methacrylate (PMMA), could lose 89.4 to 100% mass under heat conditions (Chow et al. 2004). Preliminary experiments using thermogravimetric analysis (TGA) showed plastic-based flooring materials lose more than 50% weight even before 750 °C (unpublished data). Although PVC and other plastics are combustible, these materials do not need combustibility tests to apply as interior building finishing materials.

b. Ignitability-Flame spread and ASTM E84-ASTM E648

In the past, floor coverings were not considered a fire hazard, given that all combustibles are usually located above floor coverings. However, there have been reports that of flooring contributing to flame spread, and smoke and heat evolution (Johansson, Axelsson, and Hertzberg 2007). When under influence of a high thermal load, flooring can act as a means of transferring fire and its products from its point of origin to areas that would otherwise be inaccessible to the fire. Fire researchers were aware of the existing floor covering test methods.

However, those testing methods, such as ASTM E84 (Standard Test Method for Surface Burning Characteristics of Building Materials) for ceilings and wall coverings, were unsuitable for testing floor covering products. Incompatibility in specimen orientation — for example, while ceiling specimen face downwards, floor covering specimen need to face upwards to heat sources. To address this issue, ASTM E648/NFPA 253 (Standard Test Method for Critical Radiant Flux of Floor-Covering Systems Using a Radiant Heat Energy Source) was developed to test floor covering ignitability and fire spread appropriately.

International Building Code (IBC) requires interior floor finish and floor covering materials per Section 804.4.2 to fulfill Class I or II ratings on ignitability/flame spread tests for covering materials on stairways and ramps, exit passageways, and corridors. However, IBC does not require flame spread or heat release from the floor covering materials used in other interior floor finishing areas. For the areas that do require IBC required tests, plastic-based flooring products could be designed to prevent ignitions and flame spread by loading inorganic carbonates such as limestone and other fire-retardant materials. Material ignitability is a factor for fire spread; however, PBM floor covering could melt, release toxic gases, source of heat during a fire. Similarly, ignition and flame-spread tests do not assess "wrinkling and peeling of the laminate layer during tests, material loss, or any testing on any toxic gases emitted during or after tests.

Flame spread fire hazard over a combustible surface dependent on two factors, (1) how rapidly fire spreads (2) whether such a spread is over a sizable area. In addition, it is dependent on the surface temperature of ignition (T_{ign}), apparent thermal inertia (kpc), and flame spread parameter (ω). The ASTM E84 flame spread test compares the surface burning behavior of exposed building materials such as walls and ceilings.

In this test, the approximately 25 feet specimen is exposed to ignition sources for 10 minutes to determine the material's relative burning behavior by observing flame spread and smoke generation. Based on flame spread and smoke generation, they could be Class A (flame spread 0-25), Class B (flame spread 26-75), and Class C (flame spread 76-200); a smoke-developed index (SDI) is 0-450. This method acknowledges that testing materials that are dripping or delaminating cause the flame front to stop, resulting in low flame spread indices. In summary, although both ASTM E648 and E84 test methods determine material ignitability and flame spread, these test methods do not evaluate levels of thermal effluents, toxic gases, and viscous-elastic behavior of materials during testing or afterward.

c. Heat and smoke release test methods

The heat of combustion is the heat quantity released from combustible material. For example, entirely combustible materials such as wood get converted to carbon dioxide, carbon monoxide, and water vapor during a fire while releasing all its energy as heat and light. The heat of combustion (HC) and heat release rate (HRR) are two parameters to determine energy release from combustible material. In an entirely combustible material, such as natural materials (e.g., wood), most start materials get converted to gases and water vapor during a fire while releasing energy as heat and light (Terrei et al. 2019; Qie et al. 2011). However, in certain products, such as a synthetic organic polymer (e.g., PVC), the charring of products prevents all heat release. In general, concrete, ceramic tile, and cement mortars have very low HC and HRR as they are noncombustible. Combustible materials such as wood and PBM floor coverings could take seconds for ignition and release up to 138 MJ/m² total heat with a peak heat release rate of 470 kW/m² (Carpenter and Janssens 2005).

The smoke release rate and total smoke released from a heated material are dependent on material chemical composition and applied heat fluxes. For example, PVC will not generate smoke at a heat flux of 20 kWm⁻² and will need higher heat fluxes (Chow 2004). However, using a range of PVC materials showed that total smoke release (TSR) increased with increasing heat fluxes from 20 to 70 kWm⁻² (Marcello 2017). Therefore, tests methods such as ASTM E648 with lower heat fluxes (≤ 10 kWm⁻²) may not capture smoke release potentials of plastic polymers such as PVC.

The smoke densities are a function of their dissipation rates. For example, ASTM D2843 (Density of Smoke from the Burning or Decomposition of Plastics) has a sealed volume and shorter path length which are not ideal for smoke density measurement. Similarly, the ASTM E84 test method is not ideal for smoke density measurement as smoke could escape or be diluted because of its long-distance tunnel. In general, PVC materials release higher smoke than wood. On the other hand, steel, concrete, and ceramic tiles typically do not generate any smoke.

d. Fire and smoke toxicity tests

The heating and burning of combustible materials generate toxic gases. Those toxicants are two groups: (1) narcosis-producing toxicants and (2) sensory and pulmonary irritants (ISO 13571:20:2012(E) 2006). Smoke generated from any fire contains carbon monoxide (CO), carbon dioxide (CO₂), and particulate matter (or soot). Smoke can also contain other chemicals, including acid gases, sulfur dioxide, nitrogen oxides, benzene, toluene, styrene, and dioxins (Hartzell 1996). The type and amount of particles and chemicals in smoke vary depending on how the materials burn such as how much oxygen is available, and the burning temperatures. CO₂ and CO are narcosis-producing toxicants, and at sublethal dosages, narcosis-producing gases can cause depression and loss of consciousness (Hartzell 1996). Hydrogen chloride (HCl), a pulmonary irritant, can cause eye and upper respiratory tract irritations (Hartzell 1996).

The effects of these and other toxic gases could be evaluated by three models: mass-loss, fractional effective dose (FED), and individual gas toxicity. This ISO 13571 (ISO 13571:20:2012(E) 2006) mass-loss model determines whether the thermal effluent released during combustion are at concentrations that could cause toxicity potentials. Although this method does not distinguish between different fire effluent components' toxic effects, it could be a valuable model to rank combustible materials' toxic potentials.

Unlike the mass-loss model, FED in ISO 13571 encompasses all toxicants in smoke over time to assess the combined toxicity effect. The FED is the ratio of the concentration and time product for a gaseous toxicant produced in a given test to that product of the toxicant that has been statistically determined from independent experimental data to produce lethality in 50% of the test animals within a specified exposure and post-exposure period. The higher the FED values, the more is the significant toxicity of those materials releasing toxic gases. For example, Chow et al. have shown beech-maple, teak, and oak with FED values of 0.80, 0.66, 0.75, and 0.80, respectively (C. Chow and Lu 2004). However, the same study has shown PVC has a FED value of 1.20 (C. Chow and Lu 2004). Therefore, PVC could emit gases that are more toxic than those released by timber products.

A variety of other test methods could also evaluate smoke toxicity. They are EC₅₀, LC₅₀, IC₅₀, LT₅₀, and IT₅₀. EC₅₀ is the dose concentration of the measured chemical, that can cause a 50% effect (e.g., immobilization) in a standard toxicity test on the specified species over a specific period. LC₅₀ is the dose concentration of the measured chemical that can cause 50% mortality in a standard toxicity test on a specified species over the specified period. IC₅₀ is the dose concentration of the measure chemical that can cause 50% inhibition of activity in a standard toxicity test on the specified species over a specific time. The LT₅₀ and IT₅₀ are the mean times to death and incapacitation and are derived from statistical methods to arrive at the meantime to a human effect at a particular concentration. Because the FED value gives relative toxicities, actual toxicity could be expressed from LC₅₀ values; toxic gas concentrations that cause 50% mortality. Therefore, lower the value LC₅₀ value means more significant toxicity. For the timber products, LC₅₀ values range from 99 to 147 gm⁻³ (C. Chow and Lu 2004). However, it takes only 31 gm⁻³ for PVC to cause 50% mortality (C. Chow and Lu 2004).

3. PRELIMINARY RESEARCH RESULTS

The current existing fire and smoke test methods for testing floor covering materials are deficient in two main criteria: firstly, the applied heat fluxes are not sufficient to increase tested materials temperatures above 100 °C; hence, those tests may not reflect real pre-flashover temperatures (~200- 400 °C). Secondly, smoke measurements are not a true reflection of harmful heat and toxic chemicals in them. To identify appropriate methods for floor coverings that can take into account these two deficiencies, a study was conducted to (1) quantify floor coverings' thermal effluent release and their concentration under pre-flashover temperature (100 to 400 °C) conditions using the mass-loss model (2) identify and quantify toxic chemical compounds in those thermal effluents.

METHODS

Samples: For this study, five plastic-based material floor covering samples (S1 to S5) collected from October 2018 to March 2019 from retail locations in South Carolina, USA, were used. Pure chemicals used were analytical or higher grade from Sigma Aldrich and VWR Scientific. These chemicals were used without purification.

Sample size and oven details: Sample sizes for this experiment were determined based on the ranch house's specification mentioned in an international study (Richard and Kathryn 2001). Floor areas of living & dining rooms (36.45 m²) and kitchen (10.26 m²) were added to arrive at a total of 46.71 m². A ceiling height of 2.4 m was used (Richard and Kathryn 2001). For this experiment, a LINDBERG/BUE (Model Number: BF51732PC) internal oven volume of 16.4 L was used. Using the dimensions of the house used in the study as mentioned earlier (surface area × height), a proportionately similar specimen with respect to the oven chamber was used for the experiments. The size of the specimen was calculated to be of an area of 66.66 cm² (or 3.26 × 3.26 inches).

Temperature: All PBM samples of were prepared by cutting to a size of 66.66 cm² pieces and were stored at 25 °C and 50% relative humidity until tested. The oven was preheated to test temperatures for 30 minutes. Then, the sample (in a 1 L glass beaker) is placed in the oven and temperature is maintained for another 30 minutes at atmospheric pressure. The empty glass beaker and the sample before and after temperature treatment were recorded to the nearest one milligram.

Thermal Effluent Capture: The oven was kept at atmospheric pressure throughout the experiment to avoid any pressure build-up due to the heat. The effluent released from the sample in the oven at 400 °C was captured in a 0.1 M sodium hydroxide (NaOH) solution connected through a 70 torr (9332 Pa) vacuum pump (Welch Model number 2534B-01). All thermal effluent captured solutions were then stored at 25 °C until high-performance liquid chromatography (HPLC) analysis.

Carbon and Chlorine Analysis: A carbon analyzer was used to determine carbon percentages in the PBM samples. The X-ray fluorescence (XRF) (Perform'X Sequential X-Ray Fluorescence Spectrometer, ThermoFisher Scientific) spectroscopy analysis was performed on all PBM samples to ascertain presence of choline in samples before heat treatment.

Thermogravimetric and Fourier Transformed Infrared Spectroscopy (TGA-FTIR): All test samples were individually heated (in gradual increments 10 °C per minute) and in the presence of air of 20% oxygen and 80% nitrogen, and analyzed for CO₂ and HCl gases released by TGA-FTIR (Vector 22, Brucker Corporation).

Thermal Effluent Identification and Quantification: The high-performance anion-exchange liquid chromatography (HPAE) separation and conductivity detection of chloride, bromide, and cyanides was carried out by ThermoFisher Scientific Dionex ICS 5000+ high-performance liquid chromatography with a conductivity detector. The separation was achieved using an IonPac AS23 analytical column (250 × 4 mm) equipped with (50 × 4 mm) guard column (ThermoFisher Scientific) and an anion suppressor ASRS 300 4-mm (ThermoFisher Scientific). The mobile phase was 4.5 mM sodium carbonate (Na₂CO₃) and 0.8 mM sodium bicarbonate (NaHCO₃) at a 1.0 mL min⁻¹ flow rate with a total run time of 25 min. Linear calibration curves from 10 to 100 ppm with R² values over 0.99 were used to quantify unknown sample concentrations.

RESULTS AND DISCUSSION

Chemical Composition

Chemically PBM floor coverings are primarily PVC, calcium carbonate/wood, and other additives. All five samples contained carbon from 24.7 to 27.3% (Table 1). All five samples evaluated in this study showed the presence of chlorides by XRF. Because XRF does not give bulk chlorine values and tends to overestimate elements on sample surfaces, an indirect method based on carbon and chlorine ratio in PVC was used to determine bulk chlorine percentages. This indirect chloride value from the experiments conducted on the PBM floor coverings ranged from 29.2 to 40.4% (Table 1). Although this study did not analyze PVC, it could be further calculated that the PBM floor coverings samples have PVC from 51.4 to 58.2%. The United States Patent Application Publication No. US2016/0207835 AJ states a plastic stone composite can comprise about 30-50 parts of PVC. Therefore, derived PVC values are not that far off from the patent-reported values. The individual sample data, mean, and ranges are shown in Table 1.

Sample ID	Carbon %	Chloride %*	Chloride %**	PVC %***
S1	24.7	29.2	78.5	51.4
S2	27.3	40.4	87.3	58.1
S3	26.0	38.5	73.7	54.7
S4	25.6	37.9	80.0	53.6
S5	25.2	37.3	94.4	52.7
Mean	25.8	36.7	NA	54.1
Range	24.7-27.3	29.2-40.4	NA	51.4-58.2

Table 1: Carbon, chloride, and PVC percentages of study samples S1 to S5.

*Based on atomic weight ratios (35.5/24) of chlorine and carbon in a typical PVC molecule after deducting 5% carbon for phthalates and other carbon additives

**X-ray fluorescence spectroscopy 2019 January data from National Brick Research Center, Clemson University

***Based on atomic weight ratios (62.4/24) of PVC monomer and carbon after deducting 5% carbon levels from phthalate and other carbon additives

Thermal Effluent Release

The molecular-level changes that occur in materials with rising temperatures determine thermal effluent released from these materials. Although ambient temperature (or heat loads) affects chemical bonds, most of those changes are minor. Rarely, even those physical property changes are barely visible to the naked eye. However, at higher temperatures ($>100\text{ }^{\circ}\text{C}$), organic molecules such as PVC and filler organic compounds in floor coverings volatilize and break into smaller molecules through heat-induced chemical reactions. For example, commonly used phthalate plasticizers in PVC products are liquids at room temperatures; therefore, they could be highly volatile or easily ignitable. At elevated temperatures, those released volatile compounds degrade and release more heat (exothermic energy). When the temperature reaches a critical point, most bonds fail, resulting in material disintegration, heat generation, and combustion (flaming).

Mass loss from a heated material could be measured in real-time using weight sensors of ovens that carry the sample or determining the weight difference of the actual sample tested by before and after temperature treatment. Both of these methods have their advantages and limitations. Thermogravimetric analytical instruments and small-scale benchtop equipment such as moisture meters use real-time sample weight losses with applied temperatures. Real-time sample weight difference measurements could provide more accurate data; however, a small sample quantity results could be a limitation to apply those results even to small fires. For example, in TGA, sample quantities are limited to milligram levels. However, the second method of determining weight differences could potentially cause weighing errors; that method will not limit sample size as long as the testing oven has volumes to accommodate. Our study determined weight loss by measuring before and after exposure to temperatures under atmospheric air and pressure conditions. The weight losses and oven volume after 30 minutes of set temperatures were then used to arrive at thermal effluent concentrations. Data in Table 2 shows that the PBM floor coverings are reasonably stable at $100\text{ }^{\circ}\text{C}$ as the thermal effluent release ranged from 5 to 11 g/m^3 . However, when the same samples were at $200\text{ }^{\circ}\text{C}$, the effluents released increased sharply 20 to 89 g/m^3 . Therefore, these preliminary results show that at temperatures above $200\text{ }^{\circ}\text{C}$, PBM floor coverings release effluent concentrations that may be potentially toxic.

Sample ID	Thermal Effluent Concentration (g/m ³) with temperature			
	100 °C	200 °C	300 °C	400 °C
S1	5	20	600	843
S2	5	51	420	523
S3	10	35	1021	1361
S4	11	89	474	602
S5	11	50	653	774
Mean	8	49	633	820
Range	5-11	20-89	420-1021	523-1361

Table 2: Thermal Effluent Concentration (g/m³) for 30 min at each temperature.

Six porcelain and wall tiles tested under the same experimental conditions lost up to 0.2% of total weight. Since porcelain tiles are impervious ($\leq 0.5\%$ moisture), the weight losses are likely due to the evaporation of any adsorbed water. Therefore, the water vapor released has the potential to be ceramic tile thermal effluents.

The international study lead by NIST (Richard and Kathryn 2001) on the sublethal effects of fire smoke on survivability concluded that for an unknown mixture of combustibles, a smoke concentration of 30 ± 20 g/m³ for a well-ventilated flaming fire and 15 ± 3 g/m³ for a flashover fire would incapacitate a rat of average smoke sensitivity in 30 minutes. Incorporating these values, the NIST international study panel estimated that the corresponding value for the concentration of smoke that would incapacitate smoke-sensitive people in 5 min would be 6 g/m³ for well-ventilated fire and 3 g/m³ for post-flashover fire (Richard and Kathryn 2001). The results from our study on PBM floor covering samples show that all samples except for S1, release more than 30 g/m³ of thermal effluents at ≥ 200 °C. The S1 sample released toxic levels at 300 and 400 °C. These results indicate that during pre-flashover fires PBM floor coverings have potentials to release thermal effluents that could incapacitate humans. More studies will be needed to quantify actual release levels, including more samples and time-course experiments (5, 10, 15, and 30 minutes).

Toxic gases in thermal effluents

Thermal effluents are a mixture of water vapor, toxic gases, particulate matter or smoke, and heat. Our chemical analysis of intact PBM samples clearly shows that chlorines are present, and their levels are as high as 40.4% (Table 1). When subjected to heat, the chloride in PBMs could be cleaved off as hydrochloride (HCl), chlorine (Cl₂), and/or other chlorine compounds. This study showed that the captured thermal effluents released at pre-flash temperatures, composed mainly of chlorine and other halides as analyzed by HPAE (Table 3).

The TGA-FTIR experimental results of PBM floor covering samples S1 to S5 showed that maximum HCl release occurs at 300 °C (unpublished data). Therefore, to capture all HCl release from the PBM floor covering samples, the oven temperature was set for 400 °C. In this study, all five samples released HCl concentrations from 1.4 to 35.1 ppm with a mean value of 16.3 ppm concentrations (Table 3). According to the National Research Council of the National Academies, Hydrogen Chloride: Acute Exposure Guidelines Levels, exposure to HCl at 50 to 100 ppm for one hour is reported as maximum tolerable and 1,000-2,000 ppm for a short period (immediate) as dangerous. This study clearly shows PBM has potentials to release harmful concentrations of HCl and other chlorine compounds. In regard to tested ceramic tiles, no HCl or other chlorine compounds were detected. But more studies are needed to quantify their toxicity potential using FED and LC₅₀ models and generalize this study results.

Sample ID	Chloride concentration in captured solution (mg/L)*	HCl concentration in thermal effluents (mg/m ³)**	HCl concentration in thermal effluents (ml/m ³ or ppm)***	Other chlorine	Hydrogen bromide
S1	35.2	2.1	1.4	Present	Not detected
S2	728.3	44.4	29.8	Present	Not detected
S3	858.0	52.3	35.1	Present	Not detected
S4	292.1	17.8	11.9	Present	Not detected
S5	78.9	4.8	3.2	Present	Not detected
Mean	398.5	24.2	16.3		
Range	35.1-858.0	2.1-52.3	1.4-35.1		

Table 3: HCl concentrations in mg/m³ and ml/m³ and other halide compounds

*HPLC analysis of 0.1 M sodium hydroxide 1 L solution

** converting milligrams in sodium hydroxide solution and oven volume of 16.4 L

*** mg/m³ value converted to mL/m³ using a density of 1.49 for hydrochloride gas as per OSHA/CDC.

4. SUMMARY

Our review of the existing fire and smoke test methods show that there is a lack of appropriate test methods to assess modern building materials including PBM flooring at high heat fluxes ($>10 \text{ kW/m}^2$) or temperatures ($>100 \text{ }^\circ\text{C}$). Preliminary test results from this study suggest PBM flooring have potential to release toxic level of harmful gases at pre-flash over temperatures. Perhaps more studies could initiate debate to reconsider of those exempted materials (e.g., vinyl) from fire and smoke tests in the IBC (804.1) codes as they could release toxic level of thermal effluents and harmful chemicals at preflash over temperatures.

Based on the review of fire and smoke test methods, IBC codes, and preliminary results, it is evident that further research is needed to understand the behaviors of modern building materials in real fires and in development of new test methods. Suggested next steps are:

1. More studies based on ISO 13571 guidelines on mass loss or toxicity-based tests are needed to assess true fire and smoke toxicity dangers.
2. Tests on toxicity and fire ignition/spread, that reflect temperatures or heat fluxes of preflash-over fire conditions would show true performances of modern flooring materials in real fires.

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