Science of the Total Environment 409 (2011) 3403–3408

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Influence of temperature on styrene emission from a vinyl ester resin thermoset composite material

Shaun Crawford, Claudiu T. Lungu *

University of Alabama at Birmingham, RPHB 530, 1530 3rd Avenue South, Birmingham, AL 35294-0022, United States

ARTICLE INFO

Article history:
Received 19 December 2010
Received in revised form 13 April 2011
Accepted 20 May 2011

Keywords:
Vinyl ester resin
Volatile emissions
Environmental test chamber
Styrene
VOC
Emission factor

ABSTRACT

Composite materials made with vinyl ester resins are lighter, stronger and corrosion resistant compared to most metals, and are increasingly being used as building materials and in public transportation. Styrene monomer is used as both a diluent and strengthener in the production of vinyl ester resin (VER) composites. Some researchers contend that free styrene in VER composites is available to diffuse out of the material into air, perhaps leading to adverse health effects via inhalation exposures in humans, yet there is no known data on styrene emissions from these materials in the literature. In this study, a typical VER composite made with resin containing 38% by weight styrene, reinforced with E-glass fiber and formed using a vacuum assisted resin transfer method was characterized for styrene emissions by environmental test chamber (ETC) methodology. Styrene concentrations in the ETC were measured over a temperature range of 10 to 50 °C. Initial evaporative styrene emissions increase with increasing temperature. There is a nearly linear relationship in the total mass of styrene emitted and emission factor as emissions increase with increasing temperature. Styrene emission factors appear to vary for different materials, which could indicate more complex processes or the influence of material physical properties on emission rates. These results can be used to validate and improve mass transfer emission models for the prediction of volatile organic compound concentrations in indoor environments.

Published by Elsevier B.V.

1. Introduction

The emission of volatile organic compounds (VOCs) from building materials, especially composite materials that contain binders or adhesives, has been well documented and researched over the past few decades. Thermoset composite materials typically consist of chopped, wound or woven fibers infused with a liquid resin which hardens to form a rigid material capable of withstanding high stresses and temperatures without failure. Novel composites are lighter and stronger than most metals of similar dimensions (ex. thickness), and are being developed for military, transportation and civilian uses.

Vinyl ester resins are formed by reacting an epoxy resin with methacrylic acid. Styrene, a volatile organic compound (Table 1), is used in large quantities in the processing of vinyl ester resin thermoset composite material (VERTCM). Vinyl ester resin generally contains 30 to 60% styrene by weight. Styrene in vinyl ester resin serves as a diluent to reduce the viscosity of the resin and enabling processing by methods such as vacuum assisted resin infusion, and enhances linear chain extension in the resin allowing for liquid mold processing and room temperature curing. Styrene in vinyl ester resin also acts as a "bridge" during the crosslinking process. Crosslinking occurs when an initiator opens up double carbon bonds on both the vinyl ester and styrene molecules, allowing these free radicals to link and crosslink, resulting in a cured material with high strength and resistance to degradation. However, complete cure is unrealistic, and some "free" styrene remains in the polymer and has the potential to diffuse out of pore spaces within the material.

As vinyl ester resin is subjected to increased post-manufacture temperatures, hydrogen bonding is overcome and styrene diffuses through and is emitted from the material more rapidly with increase in temperature. Some researchers have shown that as much as 50% by weight of the styrene remains un-reacted in VERTCM and could result in unhealthy levels of styrene emitted into indoor environments (Ziaee and Palmese, 1999). Because styrene is categorized as a central nervous system toxicant and hepatotoxin (ATSDR, 1992), ototoxin (Johnson et al., 2006), and possible human carcinogen (IARC, 2002), there is a need to study the emission characteristics of styrene and determine the potential indoor air concentrations of styrene emitted from composite materials that are increasingly finding their way into contact with human populations.

Emission testing of indoor building materials using small environmental test chamber (ETC) methodology is well documented since the 1980s (Matthews, 1987; Colombo et al., 1990; Guo et al., 2004) There are standards and guidelines available for referencing ETC construction and analysis. The American Society for Testing and Materials (ASTM) issued a standard Guide for Small-Scale

* Corresponding author. Tel.: +1 205 934 2072; fax: +1 205 975 6341.
E-mail address: clungu@uab.edu (C.T. Lungu).

0048-9697/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.scitotenv.2011.05.042

Table 1
Properties of styrene (CAS# 100-42-5) syn. vinylbenzene.

Structural formula	$C_6H_5CH{=}CH_2$
Molecular weight (g/mol)	104.2
Boiling point (°C, 1 atm)	145.0
Vapor pressure (mm Hg, 23 °C)	5.0
Specific gravity (g/mL, 20 °C)	0.906

Environmental Chamber Determinations of Organic Emissions From Indoor Materials/Products in 1997 (D 5116-97) and a revision in 2006 (D 5116-06). The Greenguard Environmental Institute issued its own guidelines for small chamber testing, a portion of which are relied upon in the completion of this project (GEI, 2006).

Styrene emissions from building materials have been associated with carpet backing, carpet adhesive and styrene-containing resin. Hodgson et al. (1993) measured volatile emissions at room temperature from two new carpet samples using a large scale environmental test chamber and determined emission factors for styrene over 168 h of 0.002 and 0.016 mg m^{-2} h^{-1}. Wallace et al. (1987) reported styrene emissions from carpet adhesive of 0.006 mg m^{-2} h^{-1}. La Scala et al. (2006) measured evaporation rate and calculated the diffusion coefficient (D) of styrene from resins of varying styrene concentration over a temperature range. Evaporation rate and diffusion coefficient both increased with increased temperature and styrene concentration in the resin.

Change in temperature has been cited as one of the most important factors influencing the diffusion and partitioning of VOC from dry building materials (Zhang et al., 2007 and Deng et al., 2009). To date, there is no known research in the scientific literature examining the effect of temperature on styrene emissions from finished vinyl ester resin thermoset composite material or other dry building material. The objectives of this research were to characterize, over a temperature range, styrene emissions from a vinyl ester resin thermoset composite material (VERTCM) using environmental test chamber methodology, and to quantify emission factors for points along the temperature range.

2. Materials and methods

2.1. VERTCM manufacture

Vinyl ester resin thermoset composite material (VERTCM) panels were prepared at the UAB School of Engineering's Department of Materials Science and Engineering laboratory. Squares of E-90 course weave glass fiber (E-glass) measuring approximately 120 cm × 120 cm were cut to size and set aside for layup. Fiber panel layup consisted of cleaning the glass layup area with acetone and applying three coats of a releasing interface (Freekote 700-NC, Henkel Corp.) with a lint-free cloth. The resin used consisted of Derakane 510A-40 (Ashland Chemical) containing 38% styrene by weight mixed with promoter (Trigonox 239, AkzoNobel Polymer Chemicals), accelerator (Cobalt Nap-all, Ashland Chemical) and inhibitor (Acetylacetone + 99%, Sigma- A) in ratios to every gram of resin of 0.015, 0.002 and 0.001, respectively.

To form the panels, one layer of E-glass was placed onto the work area on top of a Teflon panel and the resin mixture applied by hand pouring and spreading with a plastic trowel until the fiber was completely covered and saturated. This process was repeated until eight layers of fiber formed the panel, with the resin amount equal to approximately twice the fabric weight. Each fiber layer weighed approximately 350 g. After layup, the panels were topped with Teflon and breather cloth and sealed under vacuum to allow for overnight curing at room temperature.

The following day, the cured panels were removed from the work area and cut on a wet saw to form test panels suitable for upright placement in the environmental chamber (Fig. 1). The final cured panel thickness measured approximately 0.55 cm and panel width ranged from 19.2 to 26.0 cm. After cutting, all four edges of the test panels were sealed with a non-VOC emitting metallic tape. Individual panels were immediately wrapped in two layers of heavy-duty aluminum foil, double-bagged in sealed 4 MIL polyethylene sheeting, marked with identification numbers, and stored at −80 °C.

2.2. Environmental test chamber (ETC) performance

The ETC used in this research consisted of a LH-6 Laboratory Humidity Chamber (Associated Environmental Systems, Inc., Ayer, MA) modified to meet the definition of an environmental test chamber for use in emission studies. The chamber has an internal volume of 175.5 l (0.176 m^3) and is temperature (0–90 °C ± 1 °C) and humidity (10–98% RH, ±5%) controlled. The interior consists of stainless steel walls with a retrofitted door of anodized aluminum. Ports for inlet air (split inlet) are located on one side of the chamber, and air sampling ports are located on the top of the chamber. Chamber air is mixed with two internal fans and a diffuser, as well as the split inlet air supply. In order to meet the requirements of an air-tight and well-mixed chamber, performance verification tests were conducted to ensure that the chamber to be used met these definitions.

The air tightness of the chamber was evaluated by closing the chamber, plugging all port openings and pressurizing the chamber with supply air. Using an inclined manometer attached to the chamber, a pressure loss of 0.5 in of water over 525 s was recorded. By the Ideal Gas Law at constant temperature ($P_1V_1 = P_2V_2$), the rate of volumetric air loss inside the chamber was calculated to be 4.04 L h^{-1}. The Greenguard Environmental Institute (2006) standard stipulates that the chamber should have an air leakage rate of less than 0.03 air changes per hour (ACH). For a 175.5 L chamber, the leakage rate should be less than 5.26 L h^{-1}. The calculated leakage rate of 4.04 L h^{-1} confirms that the chamber meets the definition of being air tight.

An air mixing test was performed by injecting inert sulfur hexafluoride (SF_6) gas into the inlet air of the chamber. When an equilibrium concentration was reached, the SF_6 supply was stopped and the decay rate of gas in the chamber was monitored and logged for a period of 1 h with a MIRAN Sapphire infrared spectrometer. The comparison between the theoretical model for a well mixed chamber

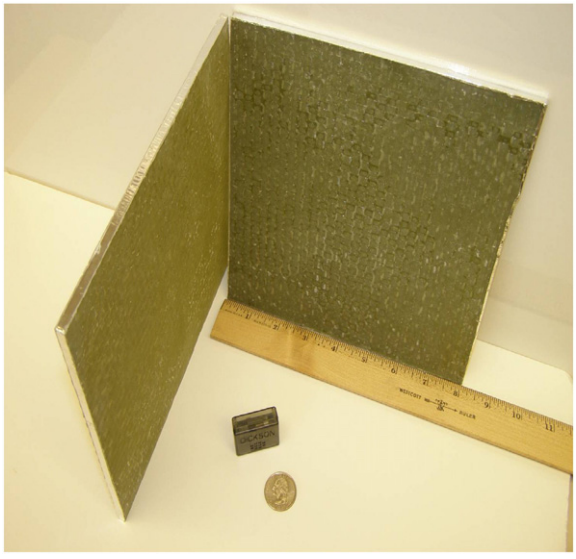

Fig. 1. E-Glass VERTCM panels used for chamber emission data.

Table 2
Chamber test conditions, panel surface area and loading factor.

Temperature (±1 °C)	Relative humidity (±5%)	Exposed panel surface area (m^2)	Loading factor (m^{-1})
10	50	0.32	1.82
23	50	0.41	2.33
30	50	0.33	1.88
40	15	0.33	1.88
50	10	0.32	1.82

and the chamber data indicated that the chamber achieved 92.4% mixing, well above the minimum 80% suggested for a well-mixed chamber (ASTM, 2006).

2.3. VERTCM panel testing

Previous research has shown styrene and other VOC emissions to be temperature dependent (La Scala et al., 2006; Zhang et al., 2007). Therefore, panel emission tests were conducted at 10 °C, 23 °C, 30 °C, 40 °C and 50 °C (±1 °C) with an air exchange rate of 1 ACH (±5%). Because high relative humidity levels at high temperature (≥40 °C) were observed to be affecting the absorptive capacity of the charcoal sampling tubes, test chamber relative humidity values for the 40 °C and 50 °C tests were reduced to 15% RH and 10% RH, respectively. All other chamber tests were conducted at 50% RH. While humidity may have a slight influence on the evaporative phase of the volatile emission process, humidity has been shown to have a negligible influence on the diffusive emission rate process (Wirten, 2006). Ultimately, all tests were conducted within a humidity ratio range of 0.004 (10 °C) to 0.014 (30 °C) grams of water per grams of dry air.

The chamber was allowed to condition to the test parameters overnight. Panels were allowed to reach room temperature before being unsealed and placed into the chamber. Before placing a test panel into the chamber, a 12 L background sample of chamber air was collected for analysis of VOC. After collection of the clearance sample, four VERTCM panels were suspended upright in the chamber, along with a temperature and humidity data logger (Dickson TK120, Addison, IL). The air velocity over the face of the panels was measured with a hot-wire anemometer (TSI 8386, Shoreview, MN). The total average velocity of five measurements over each panel face ranged from 0.40 m s^{-1} to 0.65 m s^{-1}. Table 2 contains the various panel properties for each sample run, including test temperatures, humidity, exposed panel surface areas and the loading factor (exposed material surface area per volume of chamber air, or m^2 m^{-3}).

The experiment start time began immediately upon closing the chamber door. Interior chamber air was sampled at 1, 2, 4, 6, and 12 h the first day, as well as on days 2, 3, 4, 5, 8, 9, 10, 11 and 12, for a total of 14 sample points over 264 h. Three simultaneous samples of chamber air were collected on SKC 226-01 (Lot 2000) charcoal sorbent tubes using SKC AirChek XR5000 personal sampling pumps pre-calibrated to 1.0±0.05 L per minute for a minimum 12 L air sample. The pumps were post-calibrated to average sampling flow rate. Chamber inlet flow, temperature and humidity were monitored and recorded for the duration of each test. The air flow and sampling train are illustrated in Fig. 2.

Chamber air analysis for styrene was conducted using gas chromatography with flame ionization detection (Agilent 5860, Atlanta, GA). Desorbed samples were analyzed by 1.0 µL syringe injections onto a splitless inlet at 250 °C. The capillary column (Agilent 19091Z-413E) of 0.25 µm internal diameter was heated to 70 °C for 0.5 min and ramped at 60 °C per minute for 2.5 min to a maximum temperature of 250 °C. Styrene elution time was approximately 1.90 min. Chromatograph peaks were quantified with a flame ionization detector at 250 °C against a 6-point calibration curve with a minimum correlation of $R^2 = 0.997$ and a limit of quantification (LOQ) of 0.1 µg. No significant peaks other than the desorbent carbon disulfide (CS_2), an internal standard of 4-Chlorobenzotrifluoride (4-CBTF) and styrene were observed over a total method run time of approximately 5 min. Reported styrene concentrations are adjusted and presented here based on a laboratory desorption efficiency (DE) study conducted over the temperature range.

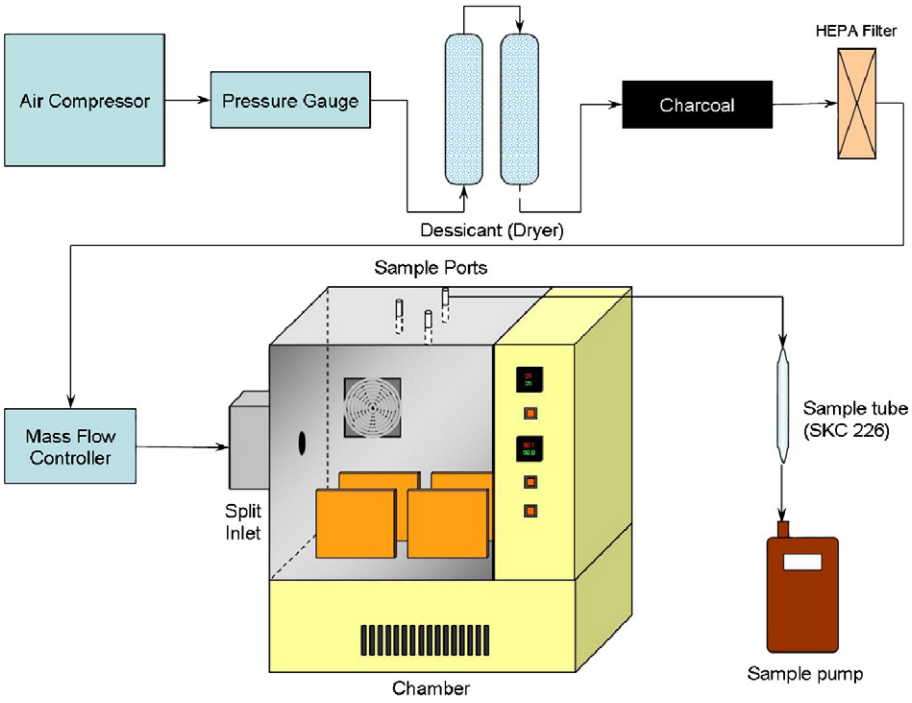

Fig. 2. Air flow and sampling diagram for small test chamber experiment.

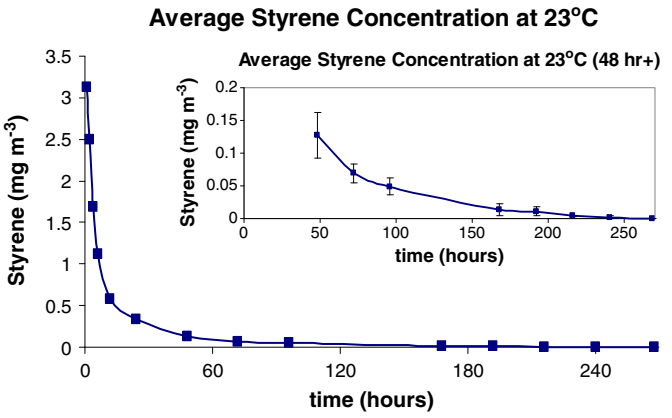

Fig. 3. Styrene emission profile at 23 °C.

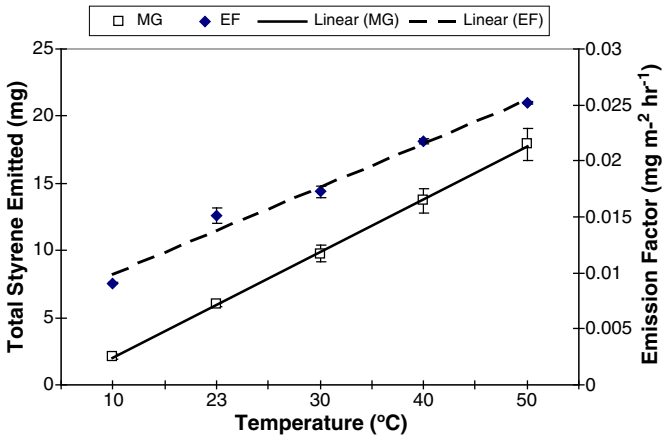

Fig. 4. Total mass of styrene emitted (MG) and emission factor (EF) over temperature range.

2.4. Determination of emission factor

Emission factor (EF) is the amount of styrene emitted from the exposed surface area of a material over time (mg m^{-2} h^{-1}) and was derived from the chamber concentration data using the following equation:

$$\text{EmissionFactor}: EF(t_i) = \frac{(\Delta C_i / \Delta t_i + NC_i)}{L} \quad (1)$$

where $EF(t_i)$ is the emission factor over the time interval $t_{i+1} - t_i$ (mg m^{-2} h^{-1}), $\Delta C_i/\Delta t_i$ is the slope of the time–concentration curve over the time interval $t_{i+1} - t_i$, N is the air change rate (h^{-1}), C_i is chamber concentration at time t_i (mg m^{-3}), and L is the loading factor (m^2 m^{-3}). The emission factor is not a constant and varies over the emission profile. Emission factor is higher during the early stages of the test (1 to 48 h) and represents an evaporative emission process occurring at the surface of the air–material interface.

Determination of the emission factor during the latter stages of the emission profile, where the slope of the profile becomes quasi-linear, allows for the calculation of potential indoor air concentrations given a known material exposed surface area and room air exchange rate at a specific point in time. For these materials, emissions after 48 h were chosen as representative of diffusion-driven emissions where styrene migrates through and out of the material, which is the primary process relevant to longer term indoor air quality concerns (Deng et al., 2009).

3. Results and discussion

The styrene concentrations and profiles reported here represent an average of three simultaneous samples for any given sampling period during the panel tests. An example of the 23 °C averaged styrene emission profile is given as Fig. 3. An example of the 23 °C averaged styrene emission profile from 48 h to 264 h, representative of the diffusive emission profile used to generate emission factor in this study, is given as an insert in Fig. 3. The results for total mass of styrene emitted and emission factor derived from the profiles are provided in Table 3. Total mass of styrene emitted from the panels was derived by integrating the mass emitted as a function of time (mg m^{-3} min) and multiplying by the flow rate of air into the chamber (m^3 min^{-1}). The total styrene mass emitted as well as emission factors for the five test temperatures are illustrated as Fig. 4. Fig. 5 depicts the styrene emission profiles for each test temperature between 48 and 264 h of the experiment.

The maximum initial concentration of styrene measured in the chamber air increased with increased temperature (Table 4). In the first 48 h, the styrene concentration profile is predominantly representative of an evaporative emission process, while after 48 h the emissions are expected to become more diffusion driven. The total mass of styrene emitted and emission factor both increased with increasing temperature. As observed from the data in Table 3 and Fig. 4, the emission factor increases nearly linearly between 10 °C and 50 °C ($R^2 = 0.997$), while the total mass of styrene emitted appears to increase linearly ($R^2 = 0.993$) over the temperature range as well.

At 48 h after test initiation, the average styrene concentrations for all three test temperatures were less than 0.20 mg m^{-3} (Table 4). Chamber air styrene concentrations converged for all test temperatures at approximately 192 h (Fig. 5). While large amounts of VERTCM at elevated temperature may contribute to odor complaints in indoor environments in the initial emission stage, styrene concentrations in the chamber air at ≥48 h are below the Agency for Toxic Substances and Disease Registry's (ATSDR) Minimal Risk Level (MRL) of 0.25 mg m^{-3} for continuous non-occupational inhalation exposures

Table 3
Styrene emission parameters at varied test temperatures.

Temperature (°C)	Total styrene (mg)	Emission factor (10^{-3} mg m^{-2} h^{-1})
10	2.11	9.10 (±0.1)
23	5.98	15.1 (±0.7)
30	9.77	17.3 (±0.5)
40	13.73	21.7 (±0.2)
50	17.87	25.2 (±0.1)

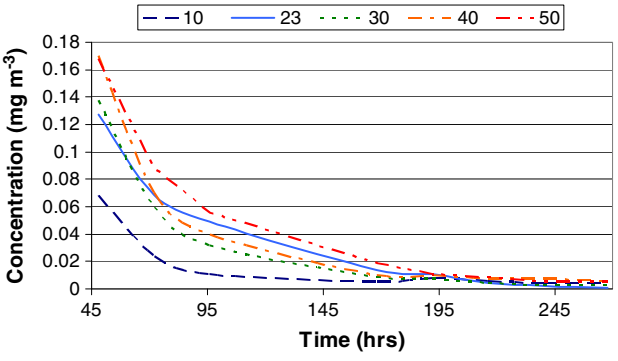

Fig. 5. Styrene emission profiles over temperature range (48–264 h).

Table 4
Chamber styrene concentration data.

Temperature (°C)	Chamber concentration at 1 h (mg m^{-3})	Chamber concentration at 48 h (mg m^{-3})	48 h parts per million equivalent
10	0.74 ± 0.1	0.068 ± 0.007	0.015
23	3.13 ± 0.6	0.127 ± 0.014	0.029
30	8.85 ± 0.7	0.137 ± 0.023	0.033
40	14.4 ± 0.7	0.166 ± 0.020	0.041
50	22.4 ± 1.4	0.168 ± 0.032	0.043

to styrene below which no appreciable increased risk is expected (ATSDR, 1992).

Preliminary analysis of the VERTCM emission properties using high surface area loading (2.67 m^2 m^{-3}) at the highest emission factor (0.025 mg m^{-2} h^{-1}) and a conservative air exchange rate (1 ACH) indicates that indoor air concentrations of styrene emitted from VERTCM would not likely exceed ATSDR chronic exposure guidelines (0.25 mg m^{-3}). This suggests that, with limited material loading (exposed surface area) and sufficient air exchange rate, after the initial evaporative emissions of styrene have ceased, it is possible that inhalation exposures to styrene emitted from like VERTCM composites in enclosed spaces can be controlled to below the most conservative current regulatory guidelines for chronic inhalation exposure to styrene.

As observed in Table 5, the styrene emission factor (EF) between Hodgson's 1993 data for Carpet 4 and this study correlates well, despite large differences in environmental test chamber (ETC) volume, average air velocity over the surface of the material, and loading factor of material into the chamber (all of which should be independent of the diffusive emission properties of VOC from a dry building material). There is some difference in the total mass of styrene emitted (ME) between Carpet 4 and VERTCM, and significant differences in EF and ME between Carpet 1 (1a and 1b are duplicate samples) compared to Carpet 4 and VERTCM. There may be physical parameters present which could explain these differences.

According to Hodgson, the source of styrene from Carpets 1 and 4 was the styrene–butadiene rubber (SBR) latex adhesive on the carpet backing (Van Ert et al., 1987). No explanation for the differences in mass of styrene emitted and styrene emission factor was given between Carpets 1 and 4 in the 20 m^3 chamber experiments. It could be that other carpet properties affected styrene emissions between Carpets 1 and 4 (construction, fiber type, fiber treatment, etc.). Large differences were observed in the emission factors and profiles for styrene in this study and preliminary studies of VERTCM with Kevlar™ fibers as described below. While these differences could be explained by differences in experimental and analytical procedures, material physical properties may be influencing the diffusion and emission process of volatiles from dry building materials.

In a preliminary study conducted by the investigator, emission profiles from panels of VERTCM containing woven Kevlar™ fibers were constructed using small environmental test chamber (ETC) methodology. Panels of un-coated, room-temperature cured VERTCM manufactured at the UAB School of Engineering, Department of Materials Science and Engineering measuring approximately 24 × 15 × 0.3 cm were placed upright in the chamber and monitored for approximately 5 days to determine total mass of styrene emitted and emission factor at 23 °C and 35 °C. The total styrene amount emitted was 6.37 mg at 23 °C and 7.39 mg at 35 °C. The highest styrene concentration measured in the chamber was 1.4 mg m^{-3} at the lowest temperature and 1.6 mg m^{-3} at the highest temperature. The average emission factor was determined to be 0.66 mg m^{-2} h^{-1} at 23 °C and 0.91 mg m^{-2} h^{-1} at 35 °C.

In the preliminary study of Kevlar™ VERTCM, the emission factor for styrene was determined to be much greater than that described in this study. Analysis of the porosity and density of the Kevlar™ VERTCM and E-glass VERTCM showed the Kevlar™ VERTCM to be less dense and more porous than the E-glass VERTCM (Table 6). Unfortunately, little was known about the original material properties (initial styrene content of the resin, etc.) of the Kevlar™ VERTCM panels other than that they were manufactured three years prior to emission testing.

There may be other limitations which explain the differences in emission factors for VERTCM between the Kevlar™ and E-glass experiments. Two different chambers were used (although chamber size and configuration should have no influence on the calculated results) and a third-party laboratory was used to analyze the charcoal tube samples in the Kevlar™ experiment (although the laboratory used was an American Industrial Hygiene Association IHLAP certified laboratory). As well, the tested Kevlar™ panels did not have sealed edges in the chamber, which may have facilitated diffusion and emission of styrene along the orientation of the fiber strands.

A recent study by Zhang et al. (2007) demonstrated that density and porosity may be important material factors in volatile emissions processes. In that study, a dry board that was more dense and had a larger percentage of micropores and mesopores (as opposed to larger macropores) had a higher formaldehyde partition coefficient (K) than a dry board with similar initial formaldehyde concentration and a larger percentage of macropores. Pore size has an effect on the bonding potential of a volatile to a substrate. If material density and porosity have a significant effect on the diffusion and emission of volatiles from dry building materials, then these two physical parameters, and possibly other unidentified physical parameters, may have to be considered in the application of emission models currently proposed for predicting volatile emissions from dry building materials.

One limitation of the analyses performed here is that the materials tested were research quality materials and not products made for consumer consumption, even though these materials are of similar composition and production to many of those found in the marketplace. La Scala et al. (2006) state that most commercial resins used at the time of their study had styrene contents in the 50% range, so these results may underestimate typical styrene emission concentrations for some materials, although the industry trend over the past few years has been to decrease the styrene content of the vinyl ester resins. Initial styrene concentration in the resin and cured panel (Co) is an important input variable into the mass transfer models used to predict indoor air VOC concentrations and influences the emitted mass and emission factor (EF) in chamber studies (increased Co typically increases EF); however, the models assume that all volatile compounds in the material are eventually emitted. In this study, only

Table 5
Comparison of Hodgson (Carpet) and VERTCM experimental and styrene emission parameters (23 °C, 50% RH, 1 ACH).

Sample type	ETC volume (m^3)	Air velocity (cm s^{-1})	Loading factor (m^2 m^{-3})	ME (mg)	EF (10^{-3} mg m^{-2} h^{-1})
Carpet 1a	20.0	5–10	0.44	2.20	2.0 ± 0.2
Carpet 1b	20.0	5–10	0.44	3.41	3.5 ± 0.2
Carpet 4	20.0	5–10	0.44	25.9	16.1 ± 0.6
VERTCM	0.176	40–65	2.33	14.6	15.1 ± 0.7

Table 6
Emission factor, density and porosity (at a pressure of 0.54 psi Hg) characteristics of two different types of vinyl ester resin.

Material	Emission factor (10^{-3} mg m^{-2} h^{-1})	Density (g cm^{-3})	Total pore area (m^2 g^{-1})	Average pore diameter (μm)
E-Glass VERTCM	15.1	1.93	10.4	0.01
Kevlar™ VERTCM	660	1.37	18.3	0.04

a fraction of the initial concentration of styrene in the panel was emitted, even at the highest test temperatures. This was also shown by Xiong and Zhang (2010).

Because of the potential differences in styrene content, material density and porosity, and changes in emission factor and emission rate over a temperature range, until further analysis verifies continuity among materials and validates existing physical-based mass transfer models, it would be prudent to test individual finished materials intended for consumer applications using environmental test chamber methodology for the prediction of volatile concentrations in indoor air, especially when characterizing potential human exposures.

4. Conclusions

Total mass of styrene emitted and styrene emission factor increased with increasing temperature in the chamber. The emission factor (EF) for styrene emitted from VERTCM at 23 °C correlated well with one EF derived for styrene from a carpet backing adhesive sample in a previous study, but did not correlate well with the EF derived for another carpet backing adhesive sample, or with an EF for styrene from a carpet adhesive in another study. Given this chamber data for styrene emissions from a thermoset composite material, the mass transfer models and other physical-based emission models constructed at 23 °C can be validated against the data derived here. Also, these models can be modified and improved to scale over a temperature range such that volatile emissions from dry building materials can be better anticipated, modeled and controlled.

Additional potential confounders such as density and porosity of the material, which may account for differences in emission factor of styrene reported in the literature, need to be considered. Ultimately, a functional model that can be scaled not only to the amount of exposed material, room size and air exchange rate, but also to other material properties and conditions over a temperature range, will be useful for controlling indoor air quality complaints and perhaps protecting humans from unhealthy levels of volatile organic compounds in indoor environments.

Acknowledgments

The authors of this study wish to acknowledge the contributions of Dr. Uday Vaidya, Evan Floyd, Jo Anne Balanay, and Micromeritics Instrument Corporation in Norcross, GA. This research was supported by Grants #T42OH008436 and #307043.15 from the National Institute for Occupational Safety and Health (NIOSH) and the Deep South Center for Occupational Health and Safety (DSCOHS), and by the American Industrial Hygiene Foundation (AIHF). The opinions and conclusions made in this publication do not necessarily represent those of NIOSH, the DSCOHS or AIHF.

References

Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological profile for styrene. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service; 1992.

American Society for Testing and Materials (ASTM). ASTM designation: D 5116-06. Standard guide for small-scale environmental chamber determinations of organic emissions from indoor materials/products; 2006.

Colombo A, De Bartoli M, Pecchio E, Schauenburg H, Schlitt H, Vissers H. Chamber testing of organic emission from building and furnishing materials. Sci Total Environ 1990;91:237–49.

Deng Q, Yang X, Zhang J. Study on a new correlation between diffusion coefficient and temperature in porous building materials. Atmos Environ 2009;43(12):2080–3.

Greenguard Environmental Institute (GEI). Laboratory qualifications and proficiency requirements. Greenguard product certification program. GG Publications, Inc.; 2006.

Guo H, Murray F, Lee SC, Wilkinson S. Evaluation of emissions of total volatile organic compounds from carpets in an environmental chamber. Build Environ 2004;39:179–87.

Hodgson AT, Wooley JD, Daisey JM. Emissions of volatile organic compounds from new carpets measured in a large-scale environmental test chamber. J Air Waste Manag 1993;43:316–24.

International Agency for Research on Cancer (IARC). 2002. IARC Monographs Volumes 1–88. Styrene [100-42-5]; 60(82).

Johnson AC, Morata TC, Lindblad AC, Nylen PR, Svensson EB, Krieg E, et al. Audiological findings in workers exposed to styrene alone or in concert with noise. Noise Health 2006;8(30):45–57.

La Scala UC, Orlicki J, Jain R, Palmese G, Vaidya U, Sands JM. Emission modeling of styrene from vinyl ester resins. Clean Technol Environ Policy 2006. doi:10.1007/s10098-006-0076-1.

Matthews TG. Environmental chamber test methodology for characterizing organic vapors from solid emission sources. Atmos Environ 1987;21(2):321–9.

Van Ert MD, Clayton JW, Crabb CL, Walsh DW. Identification and characterization of 4-phenylcyclohexene — an emission product from new carpeting. USEPA-OTS report; 1987.

Wallace L, Pellizzari E, Leaderer B, Zelon H, Sheldon L. Emissions of volatile organic compounds from building materials and consumer products. Atmos Environ 1987;21(2):385–93.

Wirten L. Influence of moisture and substrate on the emission of volatile organic compounds from wall structures. Doctoral Dissertation. Helsinki University of Technology; Espoo, Finland, 2006.

Xiong J, Zhang Y. Impact of temperature on the initial emittable concentration of formaldehyde in building materials: experimental observation. Indoor Air 2010;20:523–9.

Zhang Y, Luo X, Wang X, Qian K, Zhao R. Influence of temperature on formaldehyde emission parameters of dry building materials. Atmos Environ 2007;41:3203–16.

Ziaee S, Palmese GR. Effects of temperature on cure kinetics and mechanical properties of vinyl ester resins. J Polym Sci 1999;37:725–44.