Structural Insulated Panels:
Sustainable Design Incorporating Impact on Indoor Air Quality

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Abstract

The use of Structural Insulated Panels (SIPs) to create tight building envelopes will help reduce the environmental impact and energy use of new housing. However, the tighter building envelopes may result in degraded indoor air quality and the potential release of volatile contaminants from SIPs must be considered. A physically based diffusion model that successfully predicts emissions from a single layer of vinyl flooring is now being applied to predict the emission rate of contaminants from multi-layer systems such as SIPs. This will enable the impact on indoor air quality to be taken into account in the design process. A sustainable systems framework for the design of structural assemblies should then be developed (integrating structural properties, energy consumption, humidity control and the transport of water vapor, possible contaminant diffusion barriers, chemical exposure, environmental impact, and life-cycle assessment) to ensure health and comfort, and to preserve the environment for future generations.

Keywords: Comfort, contaminant, health risk, life-cycle assessment, SIPs

Introduction

One of the primary goals of the Partnership for Advancing Technology in Housing (PATH) is to cut the environmental impact and energy use of new housing by 50 percent. The use of Structural Insulated Panels (SIPs) to create very tight building envelopes will help realize this goal. Typically, SIPs are constructed from oriented strand board (OSB) and rigid foam in multi-layered sandwich-like structures. The environmental advantages of SIPs include:

?? less job-site waste;
?? lower energy consumption;
?? greater use of fast-growth harvested farm trees rather than old-growth forests;
?? reduced consumption of dimensional lumber.

These advantages make panelized systems very attractive from both environmental impact and energy use perspectives. However, degradation of indoor air quality is an important and well-documented result of tighter building envelopes and the use of engineered wood products as construction materials (Hodgson et al., 2001; Hodgson, 2003).

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Indoor sources of volatile organic compounds (VOCs) are one determinant of residential indoor air quality (Hodgson et al., 2000). Many materials used to construct and finish the interiors of new houses emit VOCs. These emissions are a probable cause of acute health effects and discomfort among occupants (Andersson et al., 1997). Ventilation is another determinant of indoor air quality in houses (Hodgson et al., 2000). Ventilation serves as the primary mechanism for removal of gaseous contaminants generated indoors. The trend in new construction is to make house envelopes tighter. This practice improves energy efficiency by decreasing the infiltration of unconditioned outdoor air. Consequently, natural ventilation rates in new houses without supplemental forced ventilation can be relatively low with a related potential for degraded indoor air quality (Hodgson et al., 2000). In many cases, these ventilation rates may be below recommended guidelines (ASHRAE, 1989).

There have been very few investigations of VOC contamination in new houses. In one recent study (Hodgson et al., 2000), the concentrations and emission rates of VOCs were shown to be similar among 11 new manufactured and site-built houses in four different locations. This was attributed to strong similarities in construction materials and building practices. Formaldehyde, other aldehydes, and terpene hydrocarbons (HCs) were the predominant compounds. Formaldehyde concentrations had a geometric mean value for all houses of 40 ppb. Exposures to formaldehyde are of concern because formaldehyde is a potent sensory irritant and is classified as a probable human carcinogen (Lui et al., 1991; U.S. EPA, 1994). The State of California has set an allowable daily formaldehyde exposure limit of 40 ?g, which equates to an indoor air concentration of just 1.6 ppb (Kelly et al., 1999). Higher molecular weight aldehydes can produce objectionable odors at low concentrations. The odor thresholds for hexanal and other aldehydes are often exceeded in new houses and may remain elevated for months after construction (Lindstrom et al., 1995; Hodgson et al., 2000). Terpene HCs are of potential concern because they react with ozone to produce ultrafine particles (Weschler and Shields, 1997). Animal studies also indicate that strong sensory irritants are formed by terpene-ozone reactions (Wolkoff et al., 2000). Wood and engineered wood products (e.g., particleboard, medium density fiberboard, plywood and OSB) are the likely major sources of aldehydes and terpene HCs in new houses (Hodgson et al., 2001).

OSB is a source of formaldehyde emissions approximately equivalent to phenol-formaldehyde plywoods (Kelly et al., 1999). OSB also emits pentanal and hexanal, two odorous aldehydes (Barry and Corneau, 1999). These contaminants originate in the wood drying process through the breakdown of wood tissue (Otwell et al., 2000) and are, thus, inherent to most engineered wood products. In SIPs applications, the OSB is typically finished with a layer of gypsum board. However, gypsum board and other interior finishes may not provide an effective barrier for volatile contaminants released by OSB. The large surface area of installed SIP systems, combined with the resulting decrease in ventilation rate due to very low infiltration exacerbates the potential problem.

The ability to predict and consequently minimize the potential impact of panel systems on indoor concentrations of contaminants of concern would be extremely useful. A physically-based model that predicts emissions from vinyl flooring, a single-layer, diffusion-controlled VOC source, has been developed (Little et al., 1994; Little and Hodgson, 1996) and successfully validated (Cox et al., 2001a; Cox et al., 2001b; Cox et al., 2002; Kumar and Little, 2003a). The model validation process achieved a much higher degree of scientific integrity than previous emission models because the key model parameters were determined in a completely independent fashion. A logical and promising extension of this approach is to apply the model to predict emissions from multi-layer systems such as SIPs. The multi-layer model will be valuable when designing new panel systems because the emission characteristics can be predicted based on a few simple and direct measurements of the model parameters. In addition, the model can be used to develop strategies to design panel systems in such a way as to reduce or eliminate emissions.

Current State of the Art

In a recently completed study (Hodgson, 2003) specimens of newly produced SIPs and associated panel adhesives were obtained from two relatively large manufacturers. Additionally, specimens of the oriented strand board (OSB) used as the inner and outer sheathing and the extruded polystyrene core for the SIP were obtained from one manufacturer. Using small-scale chambers, emissions of formaldehyde, acetaldehyde, acetic acid and other VOCs from SIPs, OSB, and polystyrene were measured over a period of four months. The measured emission factors were then used to estimate the concentrations of VOCs in SIP-based manufactured houses. To do this, a small, rectangular-shaped, detached house with 120-m^2 floor area was assumed, with approximately 200 m^2 of SIP exposed to an interior volume of 360 m^3 (Hodgson, 2003). The ASHRAE minimum ventilation rate of 0.35 h^{-1} was assumed. Indoor concentrations in parts per billion (ppb) were estimated using the VOC emission factors measured at four months for the SIPs overlaid with gypsum board, and are shown in Table 1. The estimated concentrations of acetic acid, pentanal, hexanal, phenol, toluene, and styrene approach or exceed their respective maximum concentrations measured in recent studies of indoor VOC concentrations for new non-SIP U.S. single-family residences (Lindstrom et al., 1995; Hodgson et al., 2000) as summarized by Hodgson and Levin (2003).

Table 1. Estimated indoor concentrations of VOCs in a hypothetical house constructed using SIP panels from two manufacturers. Also shown are geometric mean (GM) and maximum (Max) indoor concentrations from two studies of new non-SIP U.S. houses.

		Concentration (ppb)			
		Estimated[a]		Measured[b]	
	Chem.	Manuf. A	Manuf. B	New Houses (n=17)	
Compound	Class	House	House	GM	Max
Acetic acid	Acid	1,380	210	71	280
Formaldehyde	Ald	<1	7.5	32	62
Pentanal	Ald	7.2	9.0	2.5	9.8
Hexanal	Ald	38	34	15	36
Phenol	Alc	<1	6.3	1.8	5.8
Toluene	Aro	52	<1	8.5	68
Styrene	Aro	11.9	12.6	0.6	7.8

a. based on VOC emission factors measured after four months
b. summarized by Hodgson and Levin (2003)

The estimated indoor concentrations of several of the VOCs associated with SIP materials are of potential concern. The odor of acetic acid can be detected at very low concentration. The 100% odor detection threshold for acetic acid is 10 ppb (Cometto-Muñiz et al., 1998). Fifty percent odor detection thresholds (a more commonly reported number) are approximately one-order of magnitude lower (~1 ppb) (Cometto-Muñiz, 2000). Acetic acid also is a sensory irritant at relatively low concentration. The time-weighted average Threshold Limit Value (TLV) for industrial exposures to acetic acid is 10 ppm based on irritation as the effect (ACGIH, 2000). A downward scaling factor for estimating the effect for the general population is often considered to be in the range of 10 – 40 (Alaire et al., 2000; Nielsen et al., 1995). Use of a scaling factor of this magnitude suggests that an appropriate indoor guideline concentration for acetic acid to protect against irritation may be 250 – 1,000 ppb. Neilsen et al. (1998) set an indoor guideline for sensory irritation at 1,000 ppb for acetic acid. Hexanal is another highly odorous compound. The odor threshold for hexanal, summarized from the literature, is 14 ppb (Devos et al., 1990). This value is consistent with the more recently reported 100% odor detection threshold for hexanal scaled for 50% detection (Cometto-Muñiz et al., 1998). Chronic exposures to toluene affect the nervous and respiratory systems. Both the Agency for Toxic Substances and Disease Registry and the Cal-EPA Office of Environmental Health Hazard Assessment have recommended 80 ppb as an acceptable concentration for chronic exposure of the general population, including sensitive individuals, to toluene (ASTDR, 2003; Cal/EPA, 2002). Styrene is considered a possible human carcinogen (IARC, 1994).

The ability to predict the potential impact of SIPs on indoor air concentrations will be extremely useful. The physically-based model that predicts emissions from vinyl flooring, a single-layer, diffusion-controlled VOC source, is currently being applied to predict emissions from multi-layer systems such as SIPs. Using the multi-layer model, the emission characteristics can be predicted in advance, based on a few simple and direct measurements of the key model parameters. The emissions model for a hypothetical multi-layer SIP system (with 4 discrete layers) is shown schematically in Figure 1.

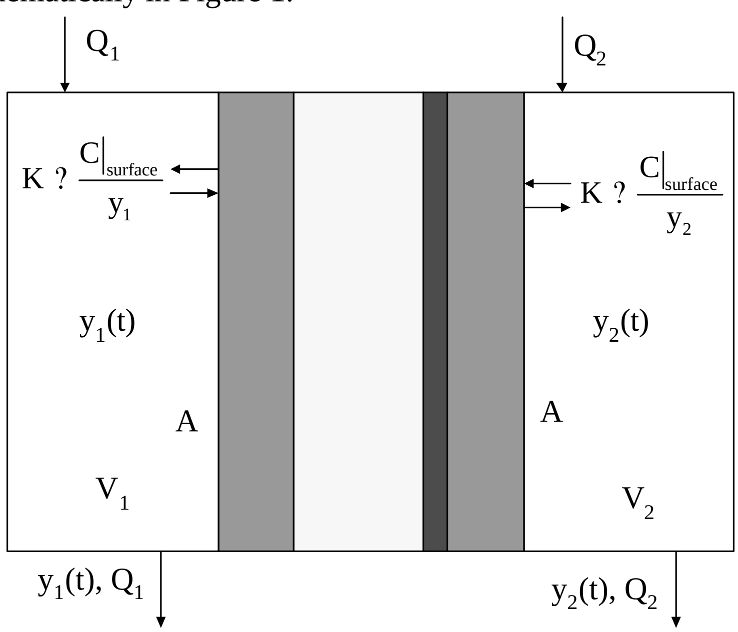

Figure 1. Multi-layer SIP assembly located between two rooms in a house

Referring to Figure 1 and the equations listed below, C(x,t) is the material-phase VOC concentration, t is time, x is distance, y(t) is the gas-phase VOC concentration in the well-mixed room air, D is the material-phase diffusion coefficient, K is the material/air partition coefficient, Q is the volumetric flow rate of air through the room, V is the room volume, A is the exposed surface area of the SIP, and L is the specific material thickness. It is assumed that each layer has uniform physical properties and that the material-phase concentrations at the interfaces between the layers are in equilibrium at all times.

The one-dimensional diffusion equation predicts the movement of contaminants in each of the N layers (for more details on the model assumptions, see Kumar and Little, 2003b), or

$$\frac{?^2 C_i}{?x^2} ? \frac{1}{D_i}\frac{?C_i}{?t} \qquad \text{i = 1 to N}$$

The initial material-phase concentration within each of the N layers is

$$C_i \ ? \ f_i(x) \quad \text{at t = 0 and } L_{i-1} \ ? \ x \ ? \ L_i$$

The boundary conditions for the various layers are

$$D_i \frac{?C_i}{?x} ? D_{i?1}\frac{?C_{i?1}}{?x} \quad \text{at x} = L_i$$

$$C_i \ ? \ K_{i/i?1} C_{i?1} \quad \text{at x} = L_i$$

$$V_1 \frac{?y_1}{?t} ? Q_1 y_{1in} ? D_1 A \frac{?C_1}{?x} ? Q_1 y_1 \quad \text{at x = 0}$$

$$V_N \frac{?y_N}{?t} ? Q_N y_{Nin} ? D_N A \frac{?C_N}{?x} ? Q_N y_N \quad \text{at x} = L_N$$

where the preceding two equations represent mass balance conditions on the accumulating contaminant in the indoor air within each room. Material/air partition coefficients are used to describe the equilibrium that exists between the exterior material surface and the air within each room, or

$$K_{1/air} \ ? \ \frac{C_1|_{x?0}}{y_1} \qquad\qquad K_{N/air} \ ? \ \frac{C_N|_{x?L_N}}{y_N}$$

This system of equations can be solved and then used to predict the gas-phase concentrations in the indoor air within each room. All that is required is a good estimate of the material-phase diffusion coefficients (D_i) in each material phase, the material/air partition coefficients between each material and air ($K_{i/air}$), and the initial concentration distribution of each contaminant within the respective layers ($f_i(x)$). Procedures to determine these quantities have recently been developed (Cox et al., 2001a; Cox et al., 2001b). Once the gas-phase concentrations have been predicted as a function of time, the resulting concentration/time profiles can be used to estimate human exposure, and hence the associated health risks and comfort criteria for each of the volatile indoor-air contaminants initially present in the materials used to manufacture the SIPs.

Future Research Directions

The model provides a means to predict the combined effect that material transport properties have on overall emission rates. The approach needs to be confirmed by a field study of SIP houses. Since there are numerous potential sources of the compounds of concern, an opportunity should be sought to conduct a controlled study in which VOC concentrations and emission rates in several newly constructed SIP houses are compared to values in conventional houses, closely matched with respect to age, size, interior finishes, furnishings and occupancy. The development of source control measures for SIPs to reduce their emissions of VOCs into indoor air may be warranted, particularly if SIP houses are shown to have relatively high VOC concentrations. Potentially effective measures include the substitution of the inner OSB skin with a lower emitting and possibly less permeable material and the introduction of a diffusion barrier between the OSB and the gypsum board interior finish material. In developing such strategies, humidity control and the transport of water vapor through the wall assembly should be considered (Hodgson, 2003).

In the last few years, important advances have been made in quantifying the significant economic impact that poor indoor air quality has on productivity and health (Fisk (2000); Spengler and Chen (2000); Mendell et al. (2002); Fanger (2003); Spengler and Samet (2003); and Wyon (2003)). For example, in blinded, controlled, randomized experimental studies, it has been shown that the unobserved presence of a 20-year old carpet, or of several 3-month old computers, causes a significant decrease in worker output (for a brief review of these and other related studies, see Fisk (2000) and Fanger (2003)). Providing high indoor air quality, compared with the mediocre air that is present in many existing office buildings worldwide, may increase productivity by an estimated 5 – 10% (Fanger, 2003). The economic losses associated with decreased productivity of this magnitude will generally far outweigh all other costs related to the construction and operation of a building (Fanger, 2003). The economic consequences have been evaluated by Fisk (2000) who estimated that in the United States alone, the potential annual savings and productivity gains associated with a better indoor environment are $6 to $14 billion from reduced respiratory disease, $1 to $4 billion from reduced allergies and asthma, $10 to $30 billion from reduced sick building syndrome symptoms, and $20 to $160 billion from direct improvements in worker performance that are unrelated to health. Although SIPs are usually used in residential construction (where worker productivity does not have the same direct economic consequence) it is nevertheless clear that poor indoor air quality has a significant impact on the health, comfort and well-being of all residents.

Sustainable design and "green building" practices are increasingly being adopted by the building industry. The sustainable built environment includes dimensions that are social, cultural, economic and ecological. To make choices that are environmentally-sensitive, designers and builders need to include health and environmental consequences in a life cycle analysis from raw material to end-life use for each product. Life cycle assessment (LCA) should be capable of identifying actions that can lower the overall risk without creating additional risks elsewhere. Although a building-related LCA has recently been used in combination with risk assessment (Nishioka, 2002), the health risks considered were those associated with a decrease in power plant emissions (resulting from reduced energy consumption associated with improved insulation) of particulate matter, NO_x and SO_x. LCA assessment has not yet been integrated with the risks associated with indoor air quality, and SIPs provide a very good test case. Thus, we suggest that an integrated LCA be conducted for SIPs considering extraction of raw material and processing through manufacture/construction, useful life, and re-processing/disposal. This will promote the concept of healthy living by developing a sustainable assessment systems framework for structural assemblies (incorporating structural properties, energy consumption, humidity control and the transport of water vapor, chemical exposure, and environmental risk using an integrated LCA approach) that ensures health and comfort, improves energy efficiency and preserves the environment for future generations.

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