Building and Environment 44 (2009) 1627–1633

Contents lists available at ScienceDirect

Building and Environment

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

Ozone removal by green building materials

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ARTICLE INFO

Article history:
Received 27 July 2008
Received in revised form
19 October 2008
Accepted 20 October 2008

Keywords:
Indoor air quality
Green building materials
Ozone
Deposition velocity
Reaction probability

ABSTRACT

There is a rapidly expanding market for green building materials. Such materials are intended to be environmentally friendly, with such characteristics as low toxicity, minimal chemical emissions, ability to be recycled, and durability. In addition, green materials often contain recycled and/or bio-based contents. Consequently, some green materials may undergo significant oxidation with potential for reduction of indoor ozone. In this study, 48-L electro-polished stainless steel chambers were used to study the reactive consumption of ozone by ten common green wall, flooring, ceiling, and cabinetry materials (perlite-based ceiling tile, unglazed ceramic tile, natural cork wall-covering, aluminum tinted cork wallpaper, bamboo, UV-coated bamboo, wheat board, UV-coated wheat board, sunflower board, and UV-coated sunflower board). Ozone removal was quantified in terms of deposition velocity and reaction probability. Ozone removal decreased with time after initial exposure, but for several materials the ability to react with ozone was regenerated after a period of zero ozone exposure. Test materials found to have the highest ozone reaction probabilities were a perlite-based ceiling tile, natural cork wall-covering, and wheat board.

1. Introduction

Indoor environments dominate total human exposure to many air pollutants due to the amount of time that most people spend indoors and the relative levels of indoor and outdoor air pollution. Zhang and Lioy [1] conducted a comprehensive study of ozone in residential air in New Jersey and found that indoor residential exposure alone accounts for 57% of the total exposure to ozone. Numerous other researchers have confirmed that the concentrations of volatile organic compounds (VOCs) and other pollutants are generally higher indoors than outdoors [2–4]. Also, 60% of total volatile organic compounds (TVOCs) in non-industrial buildings originate from building materials and furnishings [5]. Conventional building materials can produce formaldehyde and other toxic or irritating chemicals, and can react with ozone to produce secondary emissions [6,7].

Heterogeneous (surface) reactions between ozone and indoor materials are potentially important in terms of perceived indoor air quality [8–13]. Thus, it is important to understand the factors that influence reactions between ozone and indoor materials. The rate of ozone removal onto the surface of building materials is governed by a sequence of two steps:

- Transport of ozone to the material surface, which is dependent on the degree of mixing in core room air and the nature of the near-surface air flow.
- Ozone uptake onto the surface, defined by a reaction probability (γ), i.e., number of reactions of a molecule colliding with a surface divided by the total number of collisions.

The rate of ozone uptake by material surfaces has typically been quantified in terms of a deposition velocity, and the reactivity of materials is typically quantified in terms of a reaction probability. Ozone deposition velocity onto materials is defined as the flux of ozone to a surface divided by its mean concentration in air:

$$v_d = \frac{J}{C_f} \tag{1}$$

where v_d is the ozone deposition velocity (m/s), J is the flux of ozone to a surface (mg/m^2/s), and C_f is the mean concentration of ozone in air (mg/m^3).

The inverse of deposition velocity is taken to be an overall resistance to heterogeneous reactions, and is equal to the sum of two process resistances in series:

$$\frac{1}{v_d} = r_o = r_t + r_s = \frac{1}{v_t} + \frac{1}{v_s} = \frac{1}{v_t} + \frac{4}{\gamma\langle v\rangle} \tag{2}$$

where r_o is the overall resistance to removal at a surface (s/m), r_t is the transport resistance (s/m), r_s is the surface uptake resistance (s/m), v_t is the transport-limited deposition velocity (m/s), v_s is the reaction-limited deposition velocity (m/s), γ is the reaction probability (−), and $<v>$ is the mean Boltzman velocity (360 m/s for ozone at 25 °C).

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doi:10.1016/j.buildenv.2008.10.007

Equation (2) reflects both the effects of ozone transport to a surface and its interaction with that surface. If the transport-limited deposition velocity (v_t) is large and/or reaction limited deposition velocity (v_s) is small, the removal process should largely be influenced by reactions at the surface. This situation might occur, for example, in the presence of overhead fans and/or relatively low-reactivity materials. Conversely, if the transport-limited deposition velocity is small and/or the reaction-limited deposition velocity is large, the removal process should largely be influenced by the processes that affect ozone transport to a surface. An example might be a relatively "stagnant" room (little air motion) containing carpet or other fleecy materials that are highly reactive with ozone. Several authors have provided insightful discussions of the meanings of deposition velocity and reaction probability, and the relationship between the two [13–17].

Equation (2) can be rearranged to solve for reaction probability:

$$\gamma = \left[\frac{\langle v \rangle}{4}\left(\frac{1}{v_d} - \frac{1}{v_t}\right)\right]^{-1} \tag{3}$$

The reaction probability is often estimated by determination of v_d and v_t through laboratory experiments. In these cases, v_d is determined first for a test specimen and then for the same or similar specimen that is chemically modified to substantially increase its reactivity. In the latter case, v_d is taken as v_t. The transport-limited deposition velocity is specific to the experimental system, while reaction probability, and hence v_s, should be specific to a given material.

Several researchers have reported deposition velocities and reaction probabilities for ozone and conventional (non green) building materials. However, there is a paucity of published research related to ozone deposition onto green building materials (green materials), despite the fact that green materials are one of the most important components of green buildings.

There are several directories of green building products and materials to help customers and builders to choose green products [18–20]. However, criteria used to select green products are subjective, and a product may perform well under one criterion but poorly under another. One criterion that is sometimes used for green materials is that they are low emitting. This criterion generally applies to so-called "primary" emissions, typically of volatile organic compounds (VOCs), which are emitted from the actual components of the manufactured product. However, measurement of primary emissions of indoor materials alone may not be sufficient, since secondary emissions that are generated from ozone reactions with those materials may dominate over the time that a product is in use [21]. Understanding ozone reactivity with green materials is an important first step toward understanding the potential for secondary emissions from such materials, as well as for determining green materials that effectively remove ozone without significant formation of by-products. In this paper we focus only on the ozone reactivity of green materials. Deposition velocities and reaction probabilities are presented for ten green building materials.

2. Materials and methods

2.1. Green building materials

The selection of green building materials was based on three main criteria.

- The materials are certified by a third party or listed on a well-established directory of green materials.
- The materials are prevalent in residential buildings and schools, and are commonly used for ceiling, flooring, wall-coverings, or cabinetry.
- The materials are available as both unfinished and finished products (tinted or UV-coated).

Ten green building materials were selected for this study. Specific materials are listed in Table 1. Some materials contained bio-based constituents (sunflower board, wheat board, cork wall-coverings, and bamboo), while some were inorganic, e.g., perlite-based ceiling tile. The green ceiling tile consisted of 100% recycled and non-fibrous materials, including a blend of perlite and an inorganic binder. Ceramic tiles contained stoneware clays, minerals, and refractory contents with 50% recycled materials. Sunflower board and wheat board were produced from rapidly renewable resources, e.g., sunflower seed husks and wheat-straw, respectively. In addition, bamboo flooring was made from 100% rapidly renewable bamboo. Cork wall-coverings were produced from renewable cork oak.

All materials were unused when obtained; either shipped directly from manufacturers (ceiling tiles, ceramic tiles, and cork wall-coverings) or donated by a green builder in Austin, Texas (bamboo, wheat board, and sunflower board). Upon collection, materials were wrapped in multiple layers of plastic sheeting and stored for periods of up to several weeks before an experiment. Test materials and abbreviations used in this study are listed in Table 1.

2.2. Experimental system

A diagram of the experimental system is provided in Fig. 1. Two 48-L electro-polished stainless steel chambers were operated in parallel. The two chambers were identical, with dimensions of 25 cm × 38 cm × 50 cm. After different materials were placed in each chamber, the chambers were sealed with face plates secured by a Viton™ gasket and 20 bolts and wing nuts. A port on each face plate allowed air to be introduced to each chamber through a perforated Teflon tube that extended across the interior length of each chamber. Prior to each experiment, the chambers were cleaned with deionized water and dried with a heat gun in order to remove gases that had adsorbed onto, or particles deposited on, the chamber walls.

Laboratory air was pumped through a Perma Pure PD-series™ Nafion gas dryer to remove water vapor from the air, then through

Table 1
Test materials, designations and applications.

Material	Designation	Manufacturer/model	Indoor Application
Unglazed ceramic tiles	Ceramic	Fireclay Tile/Debris series	Flooring
Perlite-based ceiling tiles	Ceiling	Chicago Metallic/Novum	Ceiling
Unfinished bamboo	Bamboo	Smith & Fong/Plyboo	Flooring and/or others
UV-coated bamboo	Bamboo_UV	Smith & Fong/Plyboo	Flooring and/or others
Unfinished sunflower	Sunflower	Environ Biocomposites/Dakota Burl	Cabinetry and/or furniture
UV-coated sunflower	Sunflower_UV	Environ Biocomposites/Dakota Burl	Cabinetry and/or furniture
Unfinished wheat	Wheat	Environ Biocomposites/Biofiber™ wheat	Cabinetry and/or furniture
UV-coated wheat	Wheat_UV	Environ Biocomposites/Biofiber™ wheat	Cabinetry and/or furniture
Natural cork	Cork_Na	Innovations, in Wall-coverings/Invironmentals	Wall covering
Aluminum-tinted cork	Cork_Alum	Innovations, in Wall-coverings/Invironmentals	Wall covering