Building and Environment 81 (2014) 226–233

Contents lists available at ScienceDirect

Building and Environment

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

Effect of ozonation on fungal resistance of bamboo and oak flooring materials☆

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ARTICLE INFO

Article history:
Received 29 December 2013
Received in revised form
21 April 2014
Accepted 18 May 2014
Available online 27 June 2014

Keywords:
Fungi
Ozone
Extractives
Flooring
Oak
Bamboo

ABSTRACT

Lignocellulosic materials are gaining increased interest as renewable sources of building materials. However, chemical and microbiological degradation can occur when lignocellulosic materials are exposed to environmental stressors such as ozone and elevated humidity. In this study, the effects of ozone treatment and solvent extraction on fungal growth rates of bamboo and oak flooring materials were investigated. One set of samples was extracted with a mixture of cyclohexane and ethanol solvents for 72 h to remove extractable compounds. Another set of materials was exposed continuously to ozone (2000 $\mu L\ m^{-3}$ or 2000 ppb_v) for one to five weeks. Solvent-extracted and ozone-treated samples were incubated in closed chambers at 85% or 55% RH and 30 °C. Incubated samples were removed at regular time intervals for fungal growth evaluation. Ozone treatment caused chemical changes in bamboo and oak, which appeared to reduce bamboo's resistance to fungal attack. Longer ozone exposure led to higher susceptibility to fungal growth. Untreated and ozone-treated oak showed no evidence of fungal growth, suggesting that this material may contain fungi-inhibitory compounds that are not removed by these treatments. Also, a delay in fungal growth on cyclohexane/ethanol-extracted bamboo was observed, probably due to the extraction process removing substances that enhanced fungal growth.

1. Introduction

Cellulose-based materials have been used for centuries for many functions such as framing, furniture and flooring in both residential and commercial construction. Traditional materials for interior applications include oak, pine and maple. Recent emphasis placed on the use of renewable building materials have led to increased interest in fast growth, abundant lignocellulosic species such as bamboo for interior applications [35]. However, the susceptibility of cellulose-based building materials to mold growth is a potential concern. Research has shown that mold growth on various products, e.g., plasterboards, cellulose insulation, cellulose-containing ceiling tiles, particleboards, and cellulose-based flooring materials can be significant [13,20,49,26]. Recent studies by Hoang et al. [22] and Johansson et al. [25] indicated that cellulose-rich materials are highly susceptible to mold growth when they are exposed to liquid water or high relative humidity (RH). Different cellulose-based materials support mold growth at different levels, perhaps due in part to some species containing natural antifungal compounds that prevent or minimize fungal growth. The principal components of lignocellulosic material are high molecular masses of lignin and carbohydrates and a small amount of low molecular mass extractives [37]. Although extractives make up only minor, nonstructural components, they are often important in contributing to many material characteristics for interior uses, such as odor, color, wettability, permeability, and resistance to decay and insects [24]. The effects of extractives on fungal growth have been studied, and different extracted compounds appear to be inhibitory to selected fungal species [40,65].

Ozone is a powerful oxidizing agent and readily reacts with unsaturated organic compounds [2,3,63]. Ozone has an oxidation potential of 2.07 V at 25 °C, and a viable disinfectant in both aqueous and gaseous phase [15,28]. It has been used as an alternative disinfectant and reactant in several processes such as

☆ Certain commercial product or equipment is described in this paper in order to specify adequately the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that it is necessarily the best available for the purpose.

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http://dx.doi.org/10.1016/j.buildenv.2014.05.025
0360-1323/

wastewater treatment, odor elimination, and pesticide removal. Because it possesses bactericidal properties and deactivates fungal spores, ozone has also been used to disinfect buildings [10,39,48,50]. Dyas et al. [14] showed that ozone concentrations as low as 0.3 μL L^{-1} to 0.9 μL L^{-1} (0.3 ppm_v to 0.9 ppm_v) had useful bactericidal action against human pathogens. Taylor and Morrell [58] reported that ozone appeared to deactivate fungi on cellulose-based surfaces. Foarde and Eaton [17] observed that the biocidal efficacy of ozone against selected organisms deposited on a glass slide was higher than against the same organisms on a gypsum wallboard, partly because gypsum reacts with ozone and protects the spores. Unfortunately, because of its high oxidizing potential, ozone has been identified as a common indoor pollutant at relatively low concentrations, from less than 5 μL m^{-3} (5 ppb_v) to 50 μL m^{-3} (50 ppb_v) [63].

The effects of ozone reactions with building materials have been reported. For example, exposure to ozone has been found to cause chemical degradation and generate secondary products from cellulose-based materials [21,31,44,50,41]. Poppendieck et al. [50] studied the reaction of 24 building materials with ozone at high concentrations and observed elevated releases of reaction products from many materials. Ozone is commonly used for delignification of lignocellulosic products in the paper industry. In addition, ozone can oxidize other components, such as cellulose and hemicelluloses [4,30,36]. As such, ozone can change the chemical composition of cellulose-based materials, a process that might alter the susceptibility of materials to fungal growth. For example, terpenoids in oak are believed to protect this material from fungal attack as well as from ozone damage [32]. These compounds are highly reactive with ozone and reactions with ozone lead to the formation of carbonyls and carboxylic acids [18,21,45,50,63]. Currently, little information exists with regard to the effects of ozone treatment on fungal resistance or surface chemistry of hardwoods (e.g. oak) or bamboo commonly used for flooring.

The main objective of this study was to assess the influence of ozone exposure on fungal resistance, surface chemistry, and water sorption of bamboo and oak flooring materials. These properties, i.e., surface chemistry, moisture content, and type and amount of extractives, all play an important role in fungal resistance. Another objective was to determine the effect of solvent extraction on the fungal growth of these two cellulose-based materials. An elevated ozone concentration of 2000 ppb was used in this study, consistent with the extensive oxidation chemistry that may occur in buildings during fungal remediation or odor elimination. This rapid oxidative "aging" approach might also be considered as a screening assessment tool to identify materials for which longer-term oxidation at lower ozone concentrations may alter material susceptibility to fungal attack.

2. Experimental methodology

Oak and bamboo flooring materials were chosen to evaluate the effects of ozone treatment or solvent extraction on fungal resistance. Each material was purchased from a home improvement store. Upon purchase, the materials were wrapped in multiple layers of plastic sheeting before the experiments. Both oak and bamboo flooring materials were prefinished products that had a polymeric coating on one side, referred herein as the front side. The back side of each test specimen was polished with sand paper (Super fine 400 Grit) prior to conducting the experiments. The materials were cut to identical specimen sizes of 2.5 cm × 2.5 cm × 0.4 cm for oak and 2.5 cm × 2.5 cm × 1.1 cm for bamboo. The specimens were treated either with ozone or extracted with a mixed organic solvent as described below.

2.1. Ozone treatment

Six samples of each selected material were placed in a 4-L glass flask (Fig. 1) that was ventilated continuously with inlet air containing 2000 μL m^{-3} (2000 ppb) ± 63 μL m^{-3} (63 ppb) of ozone for periods of one, three, or five weeks (equivalent to the ozone doses of 340 μL L^{-1} h, 1000 μL L^{-1} h, and 1600 μL L^{-1} h respectively). Ozone was produced and monitored by a photometric ozone calibrator (Teledyne Instruments, M703E). Flow rate and lamp intensity were adjusted to deliver the specified ozone concentration. Since the air change rate of the chamber was high (45 h^{-1}–75 h^{-1}), the concentrations of ozone in the flask and at the flask exhaust inlet were similar. The relatively high concentrations of ozone used in experiments were intended to accelerate the effects of surface chemistry and fungal resistance. Chemical changes at or near the material surfaces that were induced by the ozone treatment were measured by Fourier transform infrared (FTIR) spectroscopy in the attenuated total reflection (ATR-FTIR) mode. FTIR spectra were recorded at a 4 cm^{-1} resolution using dry air as a purge gas and a spectrometer (Nexus 670, Thermo Nicolet) equipped with a liquid nitrogen-cooled mercury cadmium telluride (MCT) detector. A ZnSe prism was used for the ATR-FTIR measurement. All spectra were the average of 128 scans. The peak height was used to represent the infrared intensity, which is expressed as absorbance (A).

2.2. Solvent extraction

Another set of specimens (triplicate samples of each selected material) was extracted with a mixture of cyclohexane and ethanol (cyclohexane/ethanol) in a soxhlet extractor. The extraction procedure was adjusted from ASTM D1105-96 [1]; with a slight modification of the solvent content (cyclohexane: ethanol = 2:1 by volume). The extraction was carried out for 72 h with approximately 12 cycles (siphonings) per day. When the extraction was completed, extracted specimens were preserved for fungal resistance testing. The extractive-containing solvent remaining in the flask was dried to a constant mass for determining the percentage of the extract removed from the lignocellulosic materials. Component groups in extracts were analyzed by thermal desorption gas chromatography/mass spectrometry (GC/MS).

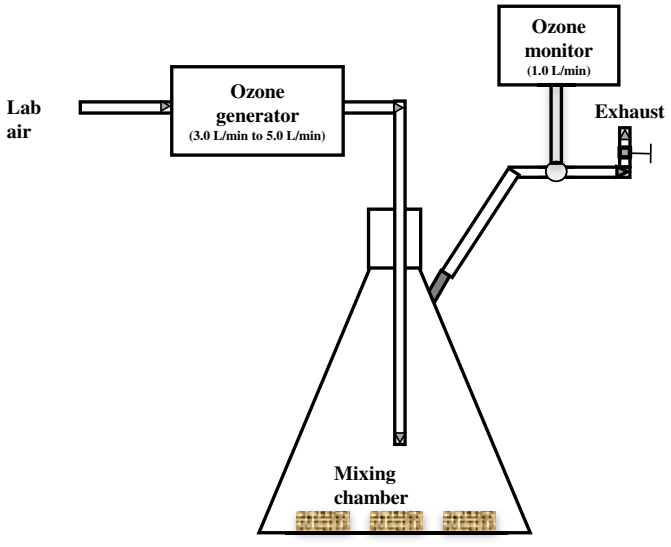

Fig. 1. Experimental apparatus for ozone treatment of bamboo and oak samples.