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Application of Sorptive Passive Panels for Reducing Indoor Formaldehyde Level: Effect of Environmental Conditions

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***Abstract*—**Reducing formaldehyde concentration in residential buildings is an important challenge, especially during the summer. In this study, a ceiling tile was used as a sorptive passive panel for formaldehyde removal. The performance of this passive panel was evaluated under different environmental conditions. The results demonstrated that the removal efficiency is comprised between 40% and 71%. Change in the level of relative humidity (30%, 50%, and 75%) had a slight positive effect on the sorption capacity. However, increase in temperature from 21 °C to 26 °C led to approximately 7% decrease in the average formaldehyde removal performance. GC/MS and HPLC analysis revealed the formation of different by-products at low concentrations under extreme environmental conditions. These findings suggest that the passive panel selected for this study holds the potential to be used for formaldehyde removal under various conditions.

***Keywords*—**Formaldehyde, indoor air quality, passive panel, removal efficiency, sorption.

I. Introduction

INDOOR air contains a variety of airborne pollutants emitted from different sources in which their presence can directly affect the health and wellbeing of occupants [1]. Among those pollutants, formaldehyde is one of the most abundant. The main indoor sources of formaldehyde are off-gassing from wooden products, resins containing urea–formaldehyde or phenol–formaldehyde, which are used for the treatment of textiles [2]-[4]. Formaldehyde also exists in latex paints, varnishes, wood smoke and oil-based paints which are used on MDF and HDF [5]-[7]. The formation of formaldehyde is as well attributed to photo-catalytically decomposed paint binders [8].

According to Health Canada's Guideline [9], the maximum level for eight-hour exposure to formaldehyde is 50 μg/m^3; nevertheless, the concentration considerably exceeds this amount in some residential buildings. For instance, a previous study done in 96 homes in Quebec City showed that the maximum concentration of formaldehyde could reach 90 μg/m^3 between January and April, when windows were usually kept closed [10]. A similar study in 59 homes in Prince Edward Island reported a maximum formaldehyde level of 87.5 μg/m^3 in the same period of time [5]. The same study also showed that formaldehyde concentration exceeded 60 μg/m^3 in 20% of inspected houses [5].

Formaldehyde not only increases the risk of allergenic reactions such as eye and airway irritations [11], but is also linked to several chronic and carcinogenic health effects [1], [12], [13]. Long term exposure to formaldehyde at concentrations exceeding 60 μg/m^3 increases the risk of respiratory symptoms (i.e. asthma) in children between 6-36 months [14].

So far, several active (flow through) methods have been proposed for the removal of indoor air pollutants including formaldehyde. Among those, mechanical ventilation, filtration, adsorption, and catalytic oxidation are the most frequently studied [15]-[17]. However, using these active methods requires additional mechanical force which is associated with an increase in energy consumption [18]. To circumvent this dilemma, the application of indoor passive panel technology (IPPT) has been proposed as an alternative method [19], [20]. Passive removal materials (PRMs), also known as passive panels (PPs), are emerging materials designed for the removal of indoor pollutants without the requirement of any additional energy [21]. These materials can be designed in different features such as ceiling tiles, wallboards, wallpapers, paint, flooring, etc. PPs are generally categorized based on the removal mechanism, in two different classes: sorptive-based passive panels (S-PPs) and photocatalytic oxidative-based passive panels (PCO-PPs).

Although IPPT has a demonstrated potential for the removal of airborne contaminant, the removal performance of PPs is affected by the environmental/operational conditions, i.e. temperature, relative humidity (RH), concentration of air pollutants, air velocity, and loading factor. Furthermore, the formation of by-products in the presence of PCO-PPs has been frequently reported in several studies [22]. In the case of S-PPs, on the other hand, the formation of by-products is still under investigation. Moreover, the effects of change in the environmental parameters are required to be addressed when a S-PP is utilized in indoor environment.

The aim of this study is to evaluate the performance of S-PPs for the removal of formaldehyde. Sorption Capacity and re-emission of captured formaldehyde from the S-PP were evaluated under different environmental conditions (temperature, RH). In addition, the possibility of by-product

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formation from the S-PP was investigated.

The test method used for this project was adapted from a protocol previously developed at the National Research Council of Canada (NRC), Construction Research Center [23].

II. EXPERIMENTAL

A. Experimental Setup and Measurement Apparatus

Fig. 1 illustrates the schematic diagram of the setup utilized to evaluate the formaldehyde removal performance of PPs.

In this continuous system, a compressed air source was fed to a Pure Air Generator (Aadco 737) which provided dry air to the system. Mass flow controllers in a Data Acquisition System (DAS) were used to regulate the directed flow into the chamber. Two water bubblers were utilized upstream of the chamber to supply the required RH, and a portable gas generator, (PGG #11, NCR, In House), was used to generate the desired rate of the formaldehyde emission during the test. The formaldehyde flow rate was controlled by means of mass flow controllers (MKS, Made in USA). The chamber consisted of an inner chamber (0.55 m×0.6 m×0.8 m), which was installed in the middle of a 0.4 m^3 outer chamber (1 m×0.8 m×0.5 m). All parts of the outer and inner chambers were electro-polished stainless steel. The inner chamber constituted of a perforated plate and several screens upstream. A buffer plate and several screens were also placed downstream of the inner chamber. These plates and screens were used to settle and control the turbulence level and provide a uniform air flow on the surface of the installed specimen.

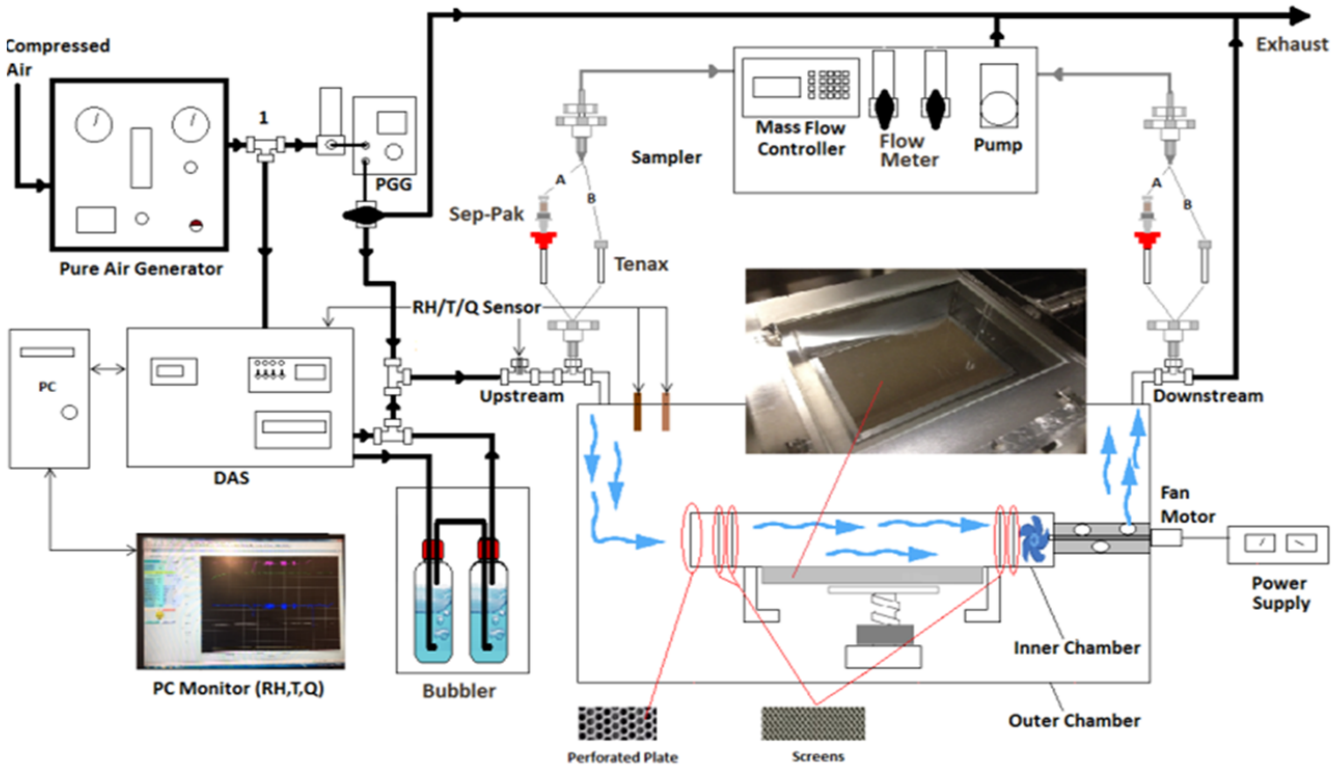

Fig. 1 Schematic diagram of the IPPT test chamber

A stainless steel tube-axial fan was placed downstream in front of the buffer plate to discharge the air to the outer chamber. This fan was located in the outer chamber and was driven using a DC motor. To avoid any influence from the laboratory atmosphere, the chamber operated slightly above atmospheric pressure.

The chamber was airtight and environmental conditions including temperature, RH, air flow rate and turbulence were under control. For this purpose, temperature and humidity sensors (Honeywell RH/T sensor HIH-4602) were located inside and outside the chamber. A differential pressure sensor was also used to measure the pressure difference between the outer chamber and the room. The signals were sent to the DAS, and data were sampled in one minute intervals to automatically record all test parameters.

To evaluate formaldehyde removal performance of the PP, a high-performance liquid chromatography (HPLC) sampling was conducted upstream and downstream of the chamber. The airflow rate and duration of HPLC sampling were 30 L/h and one hour, respectively. To qualify the formation of any other by-product, a gas chromatography/mass spectrometry (GC/MS) sampling was also performed upstream and downstream of the chamber. Air samples were collected on sorbent Tenax tubes with the airflow rate of 3 L/h for 20 minutes.

B. Materials and Challenge Compound

The tested specimen was a commercial ceiling tile (CT) constituted of mineral fiber. This S-PP demonstrated a high sorption capacity in the previously reported study by Zuraimi et al. [22]. The sample was purchased directly from the manufacturer and was stored in its original packaging.

Formaldehyde permeation tubes (VICI Metronics Dynacal; emission rate: 122 ng/min at 70 °C) were used in the PGG to provide the desired formaldehyde concentration during the experiment.

C. Test Procedure

For each test the specimen was cut in the size of 0.405 m×0.273 m. Prior to each test, the specimen was preconditioned for 48 hours in a 50 L electro-polished stainless steel chamber maintained at experiment condition (e.g. T=21±2 °C RH=50%±5%). Then, the edges of the specimen were sealed with 2 inches of a low VOC emitting aluminum tape. This provided an exposed surface area of 0.089 m^2 for the specimen. The prepared sample was then installed in the electro-polished stainless steel sample holder, inside the inner chamber. Two different temperatures (21±2 °C and 26±2 °C), and three different levels of RH (30%±5%, 50%±5%, and 75%±5%) were used for the experiments. The duration of all tests was 7 days (4 days of sorption followed by 3 days of desorption).

During the experiment, clean air was passed though the chamber for one hour. At t=0, a constant concentration of formaldehyde (100 $\mu g/m^3$) was introduced to the chamber as a challenge pollutant for 96 hours. Afterwards, at t=96 h, formaldehyde injection was stopped and the test was continued by introducing clean air into the chamber. Upstream and downstream HPLC and/or GC/MS samplings were performed at t= -1 h, 2 h, 6 h, 24 h, 48 h, 72 h, 96 h, 98 h, 102 h, 120 h, 144 h, and 168 h.

An electro-polished stainless steel (SS) plate was used as a reference to achieve the standard test condition and measure any probable sink effect in the chamber (standard ASTM) [24]. During the test, the total flow rate of the air inside the chamber was set to 0.2 m^3/h, which resulted in an air exchange rate of the 0.5 h^{-1} and a loading ratio of 0.23 m^2/m^3.

D. Performance Evaluation for VOCs Adsorption

Formaldehyde removal performance (η_F) of the S-PP was calculated as:

$$\eta_F = \frac{\int_0^t (C_{Up}(t) - C_{Down}(t))}{C_{Up}(t)} \times 100 \qquad (1)$$

where, $C_{up}(t)$ and $C_{Down}(t)$ are concentrations of formaldehyde ($\mu g/m^3$), at upstream and downstream of the chamber as a function of time.

III. Results and Discussion

A. Effect of RH

To investigate the impact of humidity on the performance of the CT, three different levels of RH (30%±5%, 50%±5%, and 75%±5%) were tested under a constant temperature of 21±2 °C. Fig. 2 illustrates the formaldehyde sorption/desorption behavior over CT during the seven-day-tests in these conditions. Results were compared to a SS specimen, as a reference, at T=21±2 °C and RH=50%±5%. The same environmental conditions were also applied to study the removal efficiency of the CT. Results are depicted in Fig. 3.

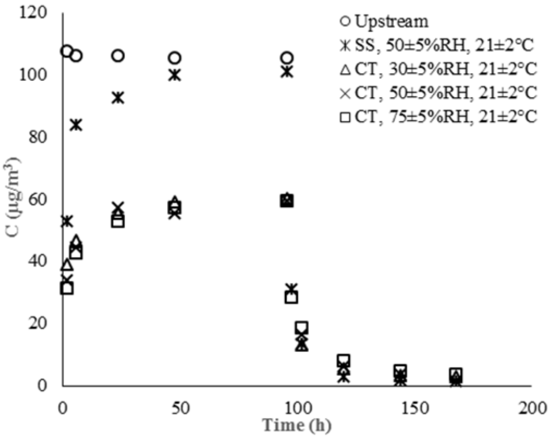

Fig. 2 Seven-day formaldehyde sorption/desorption pattern for CT and SS under various RH levels; T= 21±2 °C; RH= 30%±5%, 50%±5%, and 75%±5%

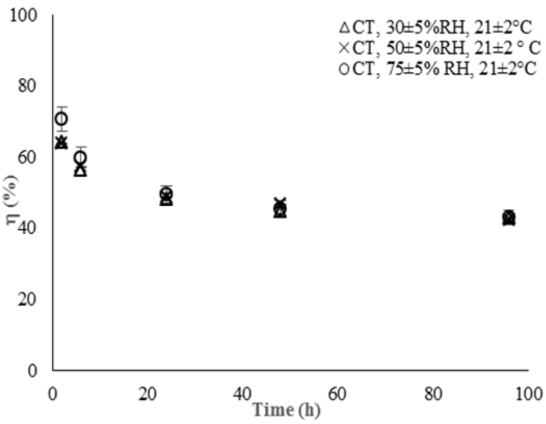

Fig. 3 Formaldehyde removal efficiency for CT under various RH levels; T= 21± 2 °C; RH= 30%± 5%, 50%± 5%, and 75%± 5%

Fig. 2 shows that in the presence of SS, the formaldehyde concentration is converged to the upstream concentration swiftly during the sorption/desorption. This indicates the inability of SS for formaldehyde removal, as it was expected. On the other hand, sorption capacity of the CT is evident, as the concentration of formaldehyde roughly halved during the course of sorption in the first four days. When formaldehyde injection was stopped, the level of detected formaldehyde was very low, indicating the capacity of the CT to maintain the trapped formaldehyde on its structure.

From Fig. 3, it can be seen that increase in the level of RH has a slight positive effect on the removal efficiency of the CT. However, this difference was observed mostly during the first 24 hours.

It has been demonstrated that in the presence of humidity, H_2O molecules can form clusters on the surface of the substrate when the sorbent media has hydrophilic characteristics and prevent target molecules to reach the active sites [15]. Since formaldehyde is readily soluble in water (solubility: 400 kg/m^3), the formed water clusters on the surface can act as a bridge between formaldehyde and the sorbent media and lead to a higher removal efficiency as observed in these experiments. However, for insoluble/ non polar compounds, the opposite result is expected. More studies on the characteristics of the sorbent are required to confirm such interpretation.

B. Effect of Temperature

To study the effect of temperature on the removal performance of the CT, temperature was raised from 21±2 °C to 26±2 °C. The highest humidity level (75%±5%) was used for these series of tests to simulate a severe air condition in indoor environment (26 °C, 75%RH). Figs. 4 and 5 show the results for the seven-day formaldehyde sorption/desorption and formaldehyde removal efficiency over CT at these conditions, respectively.

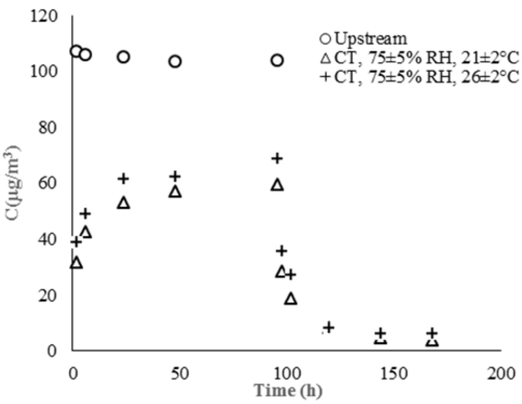

Fig. 4 Seven-day formaldehyde sorption/desorption pattern for CT under various temperatures, RH=75%±5%; T=21±2 °C and T=26±2 °C

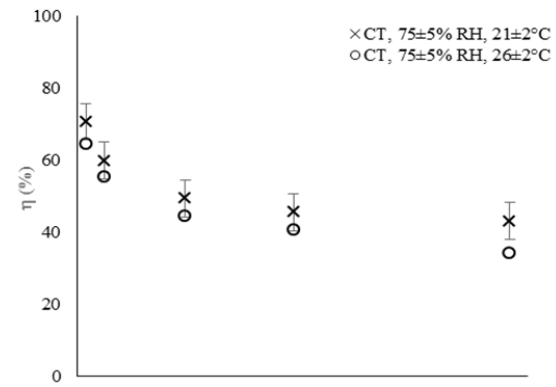

Fig. 5 Formaldehyde removal efficiency for CT under various temperatures; RH= 75%±5%; T= 21±2°C and T= 26±2°C

Results presented in Fig. 4 show a reverse correlation between the temperature and the capacity of the sorbent media to sorb formaldehyde. However, the slight deference between the desorbed amounts in two different temperatures indicates that the trapped formaldehyde has strongly bonded to the sorbent media; thus, re-emission has less dependency on the temperature.

Fig. 5 also shows a meaningful decrease in the removal performance of the CT when temperature is increased. Nevertheless, even in the worst selected conditions (RH= 75%±5%, T=26±2 °C, $C_{formaldehyde}$=100 µg/m^3), almost 40% formaldehyde removal efficiency was obtained.

C. By-Product Formation

Formation of hazardous by-products is one of the important challenges when an air purification technology is considered for indoor applications. Figs. 6 and 7 illustrate the detected organic compounds during formaldehyde removal over CT, using HPLC and GC/MS analyses.

From Fig. 6, it can be seen that in standard conditions (RH=50%, T=21 °C), the concentration of detected by-products is almost negligible. However, some by-products are formed when the most severe conditions (RH=75%, T=26 °C) are applied. However, their concentration was very low. As seen in Fig. 7, acetaldehyde can be found even in the presence of the referenced specimen (i.e. SS).

IV. Conclusion

In the present study, a CT was used as a S-PP to assess the effect of environmental conditions (RH, T) on formaldehyde removal performance. Results showed that elevated humidity has a modest effect on the removal efficiency. However, increase in the temperature level negatively impacted the performance of the sorbent. Further analyses demonstrated that re-emission of the formaldehyde did not significantly vary upon variation in temperature and RH. This indicates the reliability of the sorbent to maintain the captured pollutant.

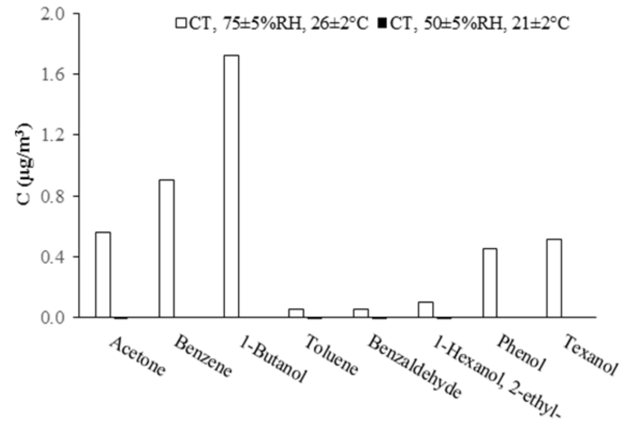

Fig. 6 Detected organic compounds during the formaldehyde removal over CT; GC/MS Analysis

Studying the possibility of by-product formation showed low levels of some organic compounds either as by-products or as emitted compounds from the specimen itself.

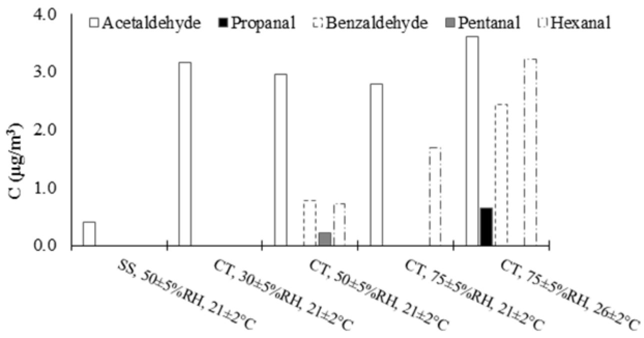

Fig. 7 Detected organic compounds during the formaldehyde removal over CT; HPLC Analysis

Given that formaldehyde concentration in residential buildings does not exceed 90 μg/m^3, and considering the removal efficiency of 40% to 71% observed under all conditions, S-PPs hold promise to reduce indoor formaldehyde concentration to safe levels.

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