Effects of building material on levels of volatile organic compounds in Taiwan's typical office buildings

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ABSTRACT

The research emphasized on typical characteristics of interior decoration material, decorated area and relative influence factors to consider about the contaminants concentration of TVOC and formaldehyde in Taiwan. This study conducted complete diagnosis and measurement in six office buildings including 16 different types of office rooms in 2001. In this survey, the characteristic of the space, types of building materials used, properties of decorated area and the room volume were all considered. The concentrations of TVOC and formaldehyde, indoor air temperature and related humidity were all measured with air change rate and air leakage value measurements at the same time. Each objective case was measured over 1 week of working period to complete realize the indoor environment variation including common and remarkable situations.

The results of the field investigation reveal that the following materials were often used in office space. The sequences orders were wood-based material (29%), polyvinyl chloride flooring (21%), carpet (18%), gypsum board (18%), mineral fibre board (14%). Moreover, the correlation analysis on the off-working hours concentration of formaldehyde, TVOC and decorative intensity divided into air leakage value can give the equation. By the theory of mass balance and regression analysis, the correlation on correlative influence factor with concentration of TVOC and formaldehyde could be obtained. An empirical model of the formaldehyde and TVOC concentration was constructed to help the designers and architects in making a proper choice of materials in Taiwan's office buildings.

INDEX TERMS

Material emission; Formaldehyde; TVOC; Office buildings; Empirical model

INTRODUCTION

Serial studies have shown that a number of volatile organic compounds (VOCs) exist in office buildings and those are proved to be associated with many symptoms, carcinogenic and chronic non-carcinogenic health effects. The potential indoor sources of these compounds include paint, adhesives, vinyl floor, ceiling, wall coverings, carpets, insulation material, composite wood products and some equipment. Studies also indicate that high concentrations of VOCs were observed when large amount of these products are installed in buildings. Many countries such as Germany, Denmark, USA, Canada, Japan and European Union are therefore promoting material labelling programmes or guidelines to reduce VOCs exposure in indoor environments. Moreover, material emission also became an important evaluating factor that has been adopted in Green Building Evaluation Tools in several countries. Previous researches have made a lot of efforts in examining the emission compounds and emission rates of new material products from chamber study. However, there are limited data that show the relationship of VOC levels and materials used in occupied spaces where various interior

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decoration materials, such as furniture, ceiling and floor materials coexist. This study therefore aims to identify the typical characteristics of interior decoration material in office buildings and further examine the association between decorated area of certain material and exposure levels of TVOC and formaldehyde under the conditions with different influence factors. An empirical model that has been constructed based on mass balance for emission of formaldehyde and TVOC will be further proposed in our study to help the designers and architects control indoor material emissions by considering the sum of material emission rate and ventilation efficiency in Taiwan’s office buildings.

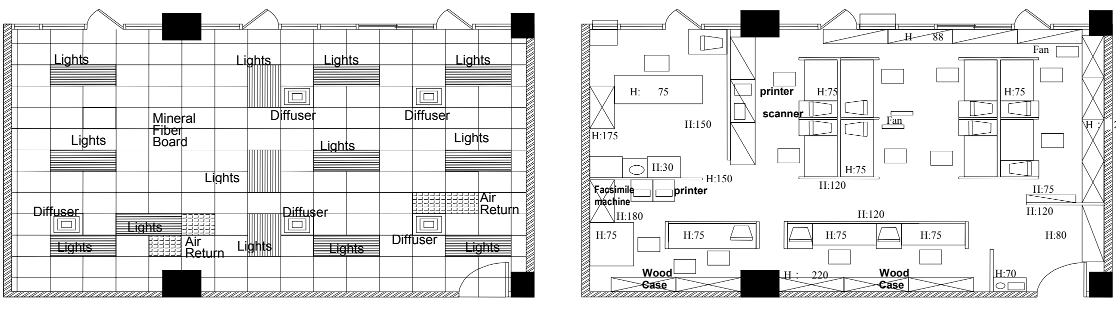
METHODS

HCHO, TVOC and Air Change Rate Measurements

Six large air-conditioned office buildings, including 16 testing spaces, were randomly selected from the records of building registration and requested for participation from their occupants after prior walk-through investigation. All these buildings were located at metropolitan cities of northern, central and southern Taiwan. HCHO and TVOC were measured using real-time monitors to document 24 h concentration variation in each testing space continuously. The concentrations variation of HCHO and TVOC during night-time without HVAC system operation was used to estimate the average emission rates in every testing space. The air change rate in each testing space was measured at the same time with 12 points samplers (Model type 1301, 1302, 1303, INNOVA Co., Denmark) using tracer gas (SF_6) decay method.

Decoration Materials Investigation

According to the material testing database from Architecture and Building Research Institute in Taiwan (ABRI, Taiwan, 2002), we highlight serial materials that should be taken into account in our field study. Decoration materials including applied material, such as carpets and ceiling boards, and unity furniture were recorded during the field investigation. Figure 1 shows the illustration of materials registration in our testing spaces. The sum of the area for the same decoration materials was estimated according to our detail field measurements and material records. The relationship between indoor HCHO and TVOC levels and the area of certain material used was examined in every testing space.

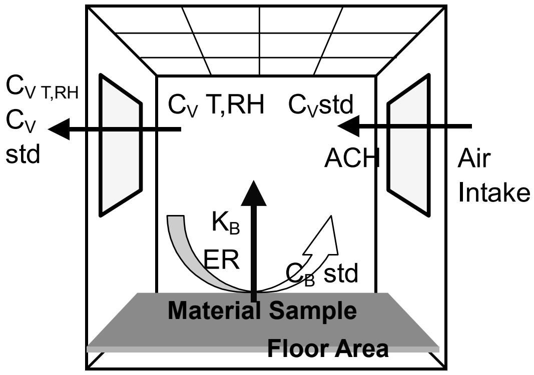


(a.) (b.)

Figure 1 The materials registrations in space A2 (a) ceiling plan; (b) indoor plan.

Theoretical Room Emission Balance Model

According to the empirical Emission Balance Model (Matthews, 1986), the indoor formaldehyde concentration of a perfect mixing system can be presented as in Figure 2 and Eqn (1). The effective factors include the emission rate (ER) at a typical temperature, relative humidity and indoor concentration, decoration area (AREA), the air change rate per hour (ACH) and the room volume (VOL).



$$C_{V,T,RH} = \frac{ER_{T,RH,Cv} \times (AREA)}{ACH \times VOL} \tag{1}$$

Where,

$C_{V\ T,RH}$ = Concentration in steady state of temperature (T) and relative humidity (RH),mg/m^3.

$ER_{T,RH,CV}$ = Emission rate in temperature (T), relative humidity (RH) and the concentration of target pollutant $C_{V\ T,RH}$, $mg/m^2/h$ AREA = Area of sample, m^2. VOL = Room Volume, m^3

Figure 2 Perfect mixing mass balance model.

When different part of the materials emitted the same kind of contaminate, such as HCHO or TVOC, the emission balance model can be revised to sum of total emission rate multiply the decoration area by different materials and divided by ACH and room volume (Eqn 2).

$$C = \frac{\sum (\mathrm{ER}_i \times \mathrm{AREA}_i)}{\mathrm{ACH} \times \mathrm{VOL}} \tag{2}$$

where, C denotes concentration of VOCs (HCHO or TVOC) in steady state (mg/m^3); ER_i is the VOCs emission rate of each material, ($mg/m^2/h$); ACH is the air change rate per hour, (h^{-1}); $AREA_i$ means total decoration area of each material (m^2) and VOL is the volume of the room (m^3).

The ER_i value of Eqn (2), based on the measurement of small-piece testing chamber, represents the emission rate in typical situation. However, there also exists an estimation difference between chamber test and the field measurement. The average emission rate for specific VOC could be obtained from field measurement. In order to clarify the effects of different material, the coefficient of emission intensity, Ea_i, was introduced to revise the equation, and then we have

$$\mathrm{ER}_i = \mathrm{ER} \times \mathrm{Ea}_i \tag{3}$$

where, Ea_i denotes the coefficient of emission intensity from different materials.

When the ER_i value of Eqn (3) is substituted into Eqn (2), we get the following equation:

$$C = \frac{\mathrm{ER}}{\mathrm{ACH} \times \mathrm{VOL}} \sum (\mathrm{Ea}_i \times \mathrm{Da}_i) \tag{4}$$

where, Da_i denotes the sum of surface area in different material (m^2).

Equation (4) is the theoretical equation used in this study. Data from field measurements including the air change rate, the volume of testing space, the average emission rate and the material area are variables that are substituted into this model.

RESULTS AND DISCUSSION

Five types of decoration materials, wood-based material (29%), polyvinyl chloride flooring (21%), carpet (18%), gypsum board (18%) and mineral fibre board (14%), were used most commonly in Taiwan's typical offices as per our field measurements. The relationships between indoor HCHO and TVOC concentrations and decoration area of these materials, which was examined by simple linear regression are shown in Table 1.

Table 1 The relationships between decorated areas of different materials and levels of HCHO and TVOC in office buildings

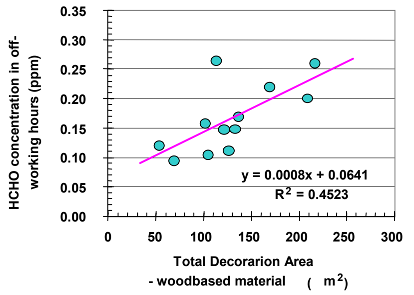
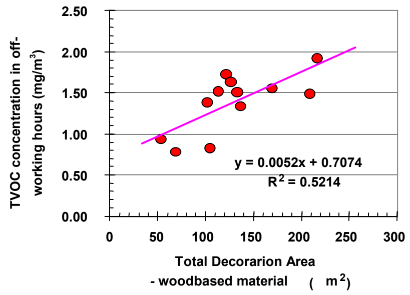
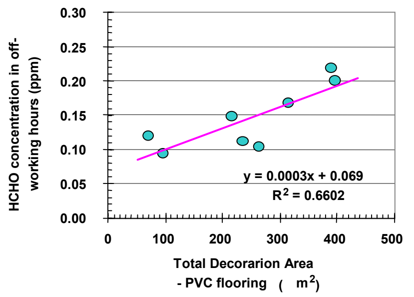
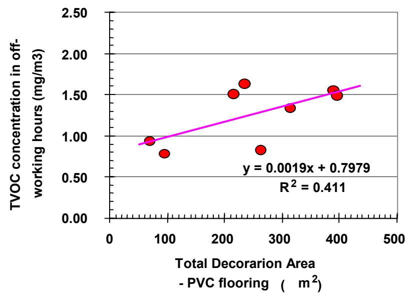
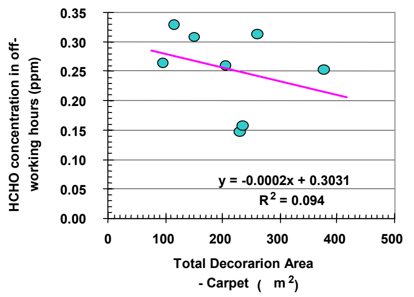
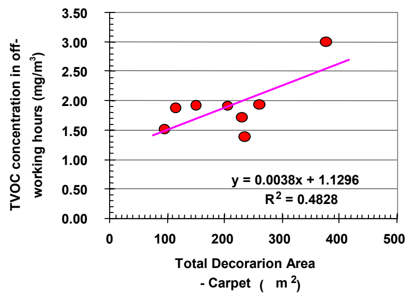
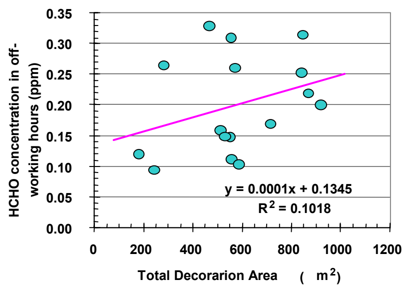
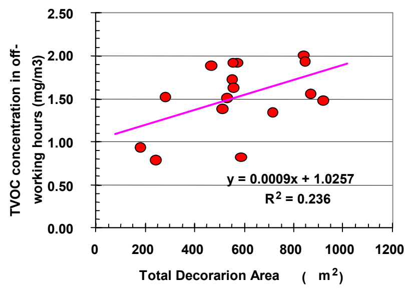
<table>
<tr><th>Pollutants / Types</th><th>HCHO (ppm)</th><th>TVOC (mg/m³)</th><th>Remarks</th></tr>
<tr><td>Wood -based material (Area, m²)</td><td>
</td><td>
</td><td>16 cases all have wood- based material including bookcases, desks and partition boards. The ages are quite different.</td></tr>
<tr><td>PVC Flooring (Area, m²)</td><td>
</td><td>
</td><td>Eight spaces are utilized the 30 cm×30 cm PVC flooring with glues between floor. All spaces are at least 5 years old.</td></tr>
<tr><td>Carpet (Area, m²)</td><td>
</td><td>
</td><td>Eight spaces are utilized the 50 cm×50 cm square carpet boards with glues between floor. All spaces are at least 6 years old.</td></tr>
<tr><td>Total decorated Material (Area, m²)</td><td>
</td><td>
</td><td>Total decorated materials means the sum of wood-based material, PVC flooring, carpet, gypsum board and mineral fibre board</td></tr>
</table>

Table 2 shows the correlation coefficients and statistical results of the relationship between HCHO and TVOC concentrations and different decoration materials. Our results show that significant relationship between indoor HCHO levels and the decorated area of wood-based material, gypsum board and PVC flooring (R^2 = 0.606–0.660). In addition, the same pattern also could be found in indoor levels of TVOC and decorated area of wood-based material (p = 0.008, R^2 = 0.521). A positive relationship, without significant association, also found between total decorated area and indoor levels of HCHO and TVOC.

Table 2 The correlation coefficients of the relationship between HCHO and TVOC concentrations and different decoration materials

Material types (%) \ Correlation coefficient	HCHO concentration (ppm)			TVOC concentration (mg/m^3)		
	R^2	*p*-value	*F*-value	R^2	*p*-value	*F*-value
Wood-based material (29%)	**0.606**	**0.001**	**18.4**	**0.521**	**0.008**	**10.896**
Gypsum board (18%)	**0.631**	**0.019**	**10.264**	0.416	0.084	4.267
PVC flooring (21%)	**0.660**	**0.014**	**11.656**	0.411	0.086	4.186
Carpet (18%)	0.094	0.460	0.622	0.483	0.0557	5.600
Mineral fibre board (14%)	0.125	0.390	0.854	0.096	0.454	0.640
Total decorated area	0.102	0.228	1.586	0.236	0.056	4.325

Quantitative control of various materials used in indoor environments seems to be an effective way to regulate indoor HCHO and TVOC emissions according to the previous relationships. Our study therefore tries to construct an empirical model and consider its utility in real building environments when applying it in quantitative materials control strategy. We measured parameters including environmental concentrations of HCHO and TVOC, air change rates, volume of testing space, average emission rate, and decorated area of different materials from field study. According to theoretical equation of material emission (Eqn 4), we take these measured parameters into the equation to calculate the coefficient of emission intensity from these five major materials. An empirical model represented by Eqn (5) was obtained.

$$C = \frac{\mathrm{ER}}{\mathrm{ACH} \times \mathrm{VOL}} (\beta + \mathrm{Ea}_1 \times \mathrm{Da}_1 + \mathrm{Ea}_2 \times \mathrm{Da}_2 + \mathrm{Ea}_3 \times \mathrm{Da}_3 + \mathrm{Ea}_4 \times \mathrm{Da}_4 + \mathrm{Ea}_5 \times \mathrm{Da}_5) \quad (5)$$

where C is the predicted concentration in typical office space by empirical model, ER is the average emission rate ($mg/m^2/h$), Da_1 is the area of wood-based material (m^2), Da_2 is the area of gypsum board (m^2), Da_3 is the area of carpet (m^2), Da4 is the area of mineral fibreboard (m^2) and Da_5 is the area of PVC flooring (m^2). β, Ea_1, Ea_2, Ea_3, Ea_4,Ea_5 represent the respective coefficients of emission intensity.

Table 3 Results of multiple regression between levels of HCHO and TVOC and coefficient of emission intensity for five major materials

Coefficient of emission intensity	Variables	HCHO		TVOC	
		Coefficient	P-value	Coefficient	P-value
B	Constant	-179.606	0.176038	19.60175	0.749568
Ea_1	Wood-based material	1.984	0.014744	1.13118	0.006096
Ea_2	Gypsum board	2.516	0.835652	1.38644	0.813435
Ea_3	Carpet	3.382	0.555493	2.34365	0.403207
Ea_4	Mineral fibreboard	0.512	0.937837	1.49270	0.640846
Ea_5	PVC flooring	0.752	0.938644	0.86269	0.855412
Annotation		**$p < 0.001$, $R^2 = 0.91$**		**$p = <0.001$, $R^2=0.96$**	

Table 3 shows the results of multiple regressions between indoor HCHO and TVOC concentrations and coefficients of emission intensity for the five major materials. Significant regression models could be observed with R^2 higher than 0.90. In HCHO model, higher partial regression coefficients (>1) could be found in wood-based material, gypsum board, and carpet. In the TVOC model, higher partial regression coefficients were observed in most materials except PVC flooring. On substituting these coefficients, which are greater than 1 into Eqn (5), we have

$$C_{\mathrm{HCHO}} = \frac{\mathrm{ER}_{\mathrm{HCHO}}}{\mathrm{ACH} \times \mathrm{VOL}} (-124.12 + 1.98 \times \mathrm{Da}_1 + 1.52 \times \mathrm{Da}_2 + 2.14 \times \mathrm{Da}_3) \quad (6)$$

$$C_{\mathrm{TVOC}} = \frac{\mathrm{ER}_{\mathrm{TVOC}}}{\mathrm{ACH} \times \mathrm{VOL}} (12.04 + 1.32 \times \mathrm{Da}_1 + 2.36 \times \mathrm{Da}_2 + 1.96 \times \mathrm{Da}_3 + 0.046 \times \mathrm{Da}_4) \quad (7)$$

These equations could be the predictive models that can be utilized in estimating the VOC emissions in office. However, the material emission rate still has a gap between results testing in chamber study and the patterns in buildings coexisting with various decorated materials. The average emission rate (ER value) also needs further clarification and examination. Our study provides an idea that an empirical model constructed according to our field investigated data might be a possible option in controlling VOC emissions in building environments. A numbers of field studies are also needed for further verifying the emission rates and other effective factors of various materials to make this predictive model more representative.

CONCLUSIONS AND IMPLICATIONS

Our results show that significant relationships between indoor HCHO and TVOC levels and the decorated area of various materials could be found at office buildings in Taiwan. An empirical predictive model is therefore conducted for considering quantitative control of various materials used in indoor environments during the design process. Further researches are needed to clarify and verify the parameters in our model.

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