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Sensory and chemical characterization of VOC emissions from building products: impact of concentration and air velocity

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Abstract

The emissions from five commonly used building products were studied in small-scale test chambers over a period of 50 days. The odor intensity was assessed by a sensory panel and the concentrations of selected volatile organic compounds (VOCs) of concern for the indoor air quality were measured. The building products were three floor coverings: PVC, floor varnish on beechwood parquet and nylon carpet on a latex foam backing; an acrylic sealant, and a waterborne wall paint on gypsum board. The impacts of the VOC concentration in the air and the air velocity over the building products on the odor intensity and on the emission rate of VOCs were studied. The emission from each building product was studied under two or three different area-specific ventilation rates, i.e. different ratios of ventilation rate of the test chamber and building product area in the test chamber. The air velocity over the building product samples was adjusted to different levels between 0.1 and 0.3 m s⁻¹. The origin of the emitted VOCs was assessed in order to distinguish between primary and secondary emissions. The results show that it is reasonable after an initial period of up to 14 days to consider the emission rate of VOCs of primary origin from most building products as being independent of the concentration and of the air velocity. However, if the building product surface is sensitive to oxidative degradation, increased air velocity may result in increased secondary emissions. The odor intensity of the emissions from the building products only decayed modestly over time. Consequently, it is recommended to use building products which have a low impact on the perceived air quality from the moment they are applied. The odor indices (i.e. concentration divided by odor threshold) of primary VOCs decayed markedly faster than the corresponding odor intensities. This indicates that the secondary emissions rather than the primary emissions, are likely to affect the perceived air quality in the long run. Some of the building products continued to affect the perceived air quality despite the concentrations of the selected VOCs resulted in odor indices less than 0.1. Therefore, odor indices less than 0.1 as an accept criterion cannot guarantee that a building product has no impact on the perceived air quality. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Building products; CLIMPAQ; Emission testing; Indoor air quality; Odor intensity; Volatile organic compounds

1. Introduction

Over the past decade it has become evident that building products are major contributors to the pollution of the indoor environment with volatile organic compounds

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(VOCs), at least during the initial period after the construction or renovation of a building (Wolkoff, 1995). Some of the emitted VOCs may affect the perception of the indoor air quality, e.g. in the form of odor nuisance, eye and airway irritation (Bluyssen et al., 1996; Nielsen et al., 1997a). Consequently, methods need to be developed to characterize the emissions from building products in sensory and chemical terms in order to understand their impact on perceived air quality and to assess potential health risks (e.g. airway irritation). This is important when developing standards for emission testing and building product labeling schemes, and when advising manufacturers on how to develop low-polluting building products.

In order to characterize a building product properly, it is important to know how various climate parameters may affect the perceived air quality and the emission rates of VOCs. Several parameters should be considered, e.g. the VOC concentration in the air, the air velocity over the building product, the age of the building product, temperature, and humidity (ECA, 1991; Guo et al., 1996; Wolkoff, 1995).

The emission rates of VOCs from building products with no internal chemical reactions generally depend on two mechanisms: (1) the diffusion of VOCs within the building product and (2) the evaporation from the building product surface to the ambient air (Clausen et al., 1991; Tichenor, 1992). Depending on the type of building product, the emission rate may be limited by one or both mechanisms. In the case of evaporation from the building product, the emission rate of VOCs may be affected by the concentration in the air, because it is the differences in partial pressures between building product surface and air which drive the mass transfer to the air. Some effects of concentration have been observed during the initial emission from liquid surface products like waterborne paints and wood finishing products (i.e. stain, polyurethane and wax) (Andersen et al., 1996; Tichenor and Guo, 1991). However, theoretical studies and measurements have indicated that the concentration effect on the emission rate especially from some building products (PVC flooring, waterborne paint, nylon carpet with latex backing, floor varnish on beechwood parquet and sealant) may be negligible (Andersen et al., 1996; Christiansson et al., 1993; Clausen et al., 1991; Jayjock, 1994; Wolkoff, 1998).

The air velocity over a building product surface may have an impact on the VOC emission rate by affecting the flow pattern in the boundary layer near the surface (Guo et al., 1996). Increased air velocity may increase the mass transfer coefficient and thereby increase the evaporation of VOCs from the surface of some building products. The largest effect of air velocity is expected for the initial emission (evaporation controlled) from liquid products (Wolkoff, 1995, 1998).

The age of a building product is an important parameter. It has been proposed to divide the emissions from

building products into primary emissions (i.e. non-bound VOCs from e.g. accelerators, additives, antioxidants, monomers, plasticizers, solvents, and unreacted raw materials) and secondary emissions, i.e. originally chemically or physically bound VOCs (VOCs that are emitted or formed by different mechanisms, e.g. decomposition, hydrolysis, oxidation, and sorption processes on the material surface) (Wolkoff, 1995). The primary emissions decay relatively fast (usually within a year) while secondary emissions for some building product types, e.g. linoleum (Jensen et al., 1996), may continue for the entire life of the building product (Wolkoff and Nielsen, 1997).

One important aspect of building product emissions is the link between VOC concentrations and perceived air quality, eye and airway irritation. An understanding of this interrelation is essential for the ability to predict the possible impact of emitted VOCs on these aspects of indoor air quality. Such information is very useful for developing better building products with a low emission and a low impact on the perceived air quality and no airway irritation. The Danish Indoor Climate Labeling scheme recommends requirements to both the concentration of selected VOCs and a sensory assessment of the emissions. For selected VOCs of concern, i.e. VOCs that are believed to have an impact on the perceived odor intensity, a concentration of 50% of the odor thresholds is used as an accept criterion for building products (Wolkoff and Nielsen, 1996). The use of 50% of the odor threshold is a pragmatic safety factor to account for the possibility of contributions of the same VOCs from other pollution sources. The labeling scheme is based on a series of assumptions. Firstly, it is assumed that the initial qualitative analysis has identified the VOCs that may affect the odor intensity. Secondly, mixtures of odorants above odor threshold are believed to be hypoadditive, i.e. the odor intensity of the mixture is less than the sum of the single odorant intensities (cf., Berglund and Olsson, 1993; Berglund and Lindvall, 1992; Cometto-Muñiz and Cain, 1991; Cometto-Muñiz et al., 1997; Laing et al., 1994; Lawless, 1977). Thirdly, the intensity of the stronger odorant alone often offers a close description of the odor intensity of the mixture (Berglund and Lindvall, 1992; Cain et al., 1995). However, below odor threshold, mixtures may show normal or hyperadditivity (Guadagni et al., 1963; Cometto-Muñiz et al., 1997; Paterson et al., 1993). Finally, the use of odor indices (see definition later) is considered a crude estimate of the relative contributions of single odorants to the odor intensity of their mixtures.

The objectives of this study were to investigate over time, in sensory and chemical terms, the impacts of: (1) the air velocity over a building product surface and (2) the concentration of the selected VOCs in the surrounding air on the odor intensity and on the emission rate, and (3) to study the interrelation between odor intensity and concentrations of selected VOCs.

2. Method

2.1. Research plan

The emissions from five different building products kept at different concentrations of VOCs and at different air velocities were studied over a 50-day period by sensory and chemical methods. The emission from each building product was studied under two or three different area-specific ventilation rates ($\mathcal{L} \text{ s}^{-1} \text{ m}^2$), i.e. different ratios of ventilation rate of the test chamber and building product area in the test chamber. The area-specific ventilation rates were within the range normally found indoors. The highest area-specific ventilation rate was five times higher than the lowest. The air velocity over the building product samples was adjusted to different levels between 0.1 and 0.3 m s^{-1} corresponding to a realistic indoor range (Girman, 1993), at constant area-specific ventilation rates. Throughout the study, the air temperature and the relative humidity in the test chambers were held constant at $23.0 \pm 0.2^\circ\text{C}$ and $50 \pm 3\%$ RH. Concurrently with measurements of the five building products, measurements of the emissions from an empty test chamber was performed as a measure of the background level. A sensory panel assessed the odor intensity on days 1, 8, 15, 29 and 50 after the building products were placed in the test chambers. For PVC flooring, assessments were performed on days 6, 13 and 29. Chemical measurements of selected VOCs were performed on days 1, 7, 21, 28 and about 40–50. The experimental conditions are listed in Table 1.

2.2. Building products

The five building products used in this study were selected to represent major groups of building products often used indoors. The building products were three floor coverings: a 1.5 mm one-layer PVC, a one component waterborne acrylic floor varnish (semi gloss, $10 \text{ m}^2 \mathcal{L}^{-1}$) applied by a paint roller onto 12 mm thick pretreated beechwood parquet and an 8 mm tufted nylon carpet on a latex foam backing. Furthermore, a water-

borne acrylic sealant for indoor use injected into a U-shaped aluminum profile, 10 mm wide and 12 mm deep, and a white pigmented waterborne acrylic wall paint ($10 \text{ m}^2 \mathcal{L}^{-1}$) applied by a paint roller onto 13 mm gypsum board were studied. The building products were wrapped in inert and diffusion-tight packing and stored at controlled conditions at 15°C immediately after receipt from the manufacturers. Test specimens were cut to size and conditioned in the main environmental chamber (see below) for 24 h before they were placed in the test chambers (time = 0 day). The sizes of the test specimens were determined so that the area-specific ventilation rate corresponded to the typical application of the building products in a real room and also accounting for the size of the test chamber. For a detailed description of the selection criteria and the handling of the building products, see Kjaer et al. (1996).

2.3. Chamber facilities

The experiments were performed in a series of CLIM-PAQ test chambers made of glass (Gunnarsen et al., 1994), see Fig. 1a. The volume of the test chamber is $50.9 \mathcal{L}$. The exhaust air from each test chamber was led through a diffuser specially designed for sensory assessments. The test specimens of the floor coverings and the wall paint on gypsum board were placed vertically, parallel to the long side of the test chamber so that the emitting surface was parallel to the direction of the air flow. Sealant in U-shaped profiles was placed on the bottom of the test chamber parallel to the long side of the test chamber. The air velocity over the building product specimens was adjusted by control of the air flow through the recirculation channel of the test chamber by a damper. The mean air velocity was measured with a hot-wire anemometer (DANTEC FLOWMASTER Precision Anemometer Type 54 N 60) in holes 5–8, see Fig. 1a. During measurements the anemometer was placed equidistant from the building product specimens and equidistant from top and bottom of the test chamber. Prior to the experiments, the test chambers were cleaned with hot water with a neutral detergent added. The test

Table 1

The ventilation rate of the test chambers, the area of the test specimens, the mean air velocity measured equidistant from the test specimens and the number of test chambers used during the study

	PVC			Varnish				Carpet			Sealant		Wall paint					
Ventilation rate ($\mathcal{L} \text{ s}^{-1}$)	0.8	1.3	1.8	1.2	0.9	1.8	1.6	0.7	1.2	1.7	0.7	1.7	0.8	1.2	1.4	1.2	1.7	1.8
Area of test specimen (m^2)	2.6	1.9	1.3	0.6	0.6	0.3	0.3	1.7	1.1	0.8	0.06	0.03	1.9	1.9	1.2	0.9	1.2	0.9
Air velocity (m s^{-1})	0.1	0.1	0.1	0.1	0.3	0.3	0.1	0.1	0.2	0.1	0.15	0.15	0.1	0.2	0.3	0.3	0.1	0.1
	0.3	0.3						0.3	0.3	0.2	0.3	0.3						
Number of CLIMPAQs	2	2	1	1	1	1	1	2	2	2	2	2	1	1	1	1	1	1

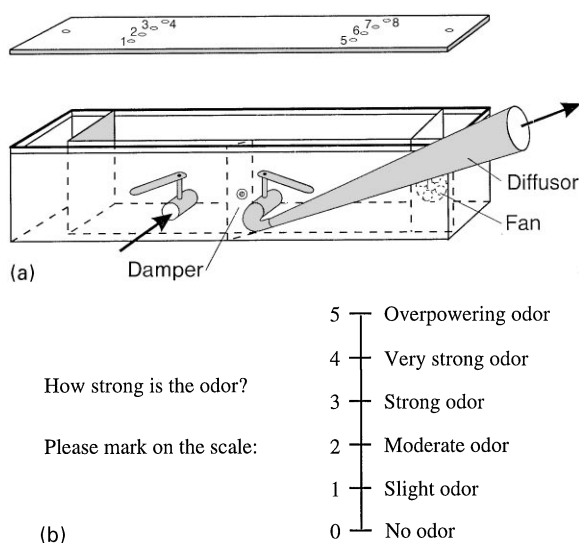


Fig. 1. (a) The CLIMPAQ test chamber. (b) Intensity scale slightly modified from Yaglou's psycho-physical scale and the accompanying question. The scale was not numbered during the assessments, but the numbers are used in Fig. 2.

chambers were then rinsed with hot water, and finally rinsed with distilled water. During the study, the test chambers were covered with aluminum sheets to hide the building products from the view of the assessors in the sensory panels. The experiments were performed in the air quality laboratory of the Danish Building Research Institute (Ekberg and Nielsen, 1995). The laboratory facilities consist of two adjacent full-scale/walk-in environmental chambers: a main chamber with a volume of 96 m³ and an antechamber with a volume of 32 m³. The test chambers were situated in the main environmental chamber, ventilated with an outdoor air exchange rate of at least 11 L h⁻¹, and at a temperature of 21.0 ± 0.5°C and at a relative humidity of 55 ± 3% RH.

2.4. Sensory panels

In the study of PVC, varnish and wall paint a sensory panel comprising 6–12 subjects (on an average 8) performed the sensory assessments. The subjects were university students and 20% of them were women. The age ranged from 21 to 45 yr with a mean age of 25 yr. In the study of sealant and carpet another panel comprising 20–25 subjects (on an average 23) performed the sensory assessments. These subjects were recruited in the neighborhood of the Danish Building Research Institute. There was an even distribution of men and women in this panel. The age ranged from 16 to 69 yr with a mean age of 39 yr. Both panels assessed the immediate odor intensity of air exhausted from the test chamber through the diffuser by marking on the scale for odor intensity

(Yaglou et al., 1936) as shown in Fig. 1b. Before the first assessment the panels were instructed on how to use the scale and the exposure equipment. Between each assessment the subjects were seated for about 2 min in a well-ventilated hall surrounding the environmental chambers. The subjects first entered the antechamber (clean air) for 1 min, and then they entered the environmental chamber with the small-scale test chambers. Here they made one assessment of the immediate perceived odor intensity before they exited to the hall again. The assessments were performed in random order. This procedure was repeated throughout a 2 h period.

2.5. Chemical measurements

Prior to the measurements in the CLIMPAQs, a screening of VOCs emitted from the building products were performed by GC/MS analysis of the air exhausted from a field and laboratory emission cell (FLEC). The measurements were done 2 days after the building products were placed in the FLEC. About 30 different VOCs were identified from each building product, for details see Wolkoff et al. (1996).

For each building product, a number of VOCs of concern were selected on the basis of low odor thresholds (Jensen and Wolkoff, 1996), abundance, and persistence, see Table 2. This selection was based on the assumption that VOCs with low odor thresholds may have an impact on the perceived air quality (Wolkoff and Nielsen, 1996). Some other VOCs were also selected. Table 2 shows whether the origin of the VOCs is considered to be from primary or secondary emissions or a combination. Finally, the airway irritation thresholds for the selected VOCs are listed.

The chemical measurements in the CLIMPAQs were performed as follows. Duplicate samples on Perkin-Elmer Tenax TA steel tubes were taken in a hole in the diffuser perpendicular to the air flow direction. The tubes were thermally desorbed and analyzed by gas chromatography and a FID detector. Each VOC was individually calibrated and the results are reported as the mean of a duplicate sample. Further details about the qualitative and quantitative analyses are described elsewhere (Wolkoff, 1998). The sum of VOCs, ΣVOC, was calculated based on individual VOC concentrations including unidentified peak areas converted to decane equivalents (equivalent to toluene).

3. Results

3.1. Sensory measurements

The mean odor intensity vs time for the five building products and an empty test chamber are shown in Fig. 2.

Table 2

Selected VOCs, an indication of whether their origin is believed to be primary or secondary emission, odor thresholds and airway irritation thresholds

Building product	VOC	Primary (P) or Secondary (S)	Odor threshold ^a ($\mu\text{g m}^{-3}$)	Airway irritation threshold ^a ($\mu\text{g m}^{-3}$)
Carpet	2-Ethyl-1-hexanol	P/S	500	7160
	4-Phenylcyclohexene	P	2	high ^b
	Nonanal	S	14	
	Decanal	S	6	
PVC	2-Butoxyethoxyethanol	P	9	high ^c
	2-Ethyl-1-hexanol	P/S	500	7160
	Phenol	P/S	427	19500
Sealant	Hexane	P	79000	high ^d
	Dimethyloctanols (isomers)	P/S	120 ^e	< 1000 ^f
Floor varnish	Butyl acetate	P	47	105000
	Butoxyethanol	P	51	417000
	Ethoxyethoxyethanol	P	< 100	high ^d
	2-Butoxyethoxyethanol	P	9	high ^e
	N-Methylpyrrolidone	P	300 ^g	20000 ^h
Wall paint	2-Butoxyethoxyethanol	P	9	high ^d
	Decanal	S	6	high ^d
	1,2-Propandiol	P	odorless	high ^d
	Texanol ⁱ	P	< 2 ^g	1000 ^j

^a From VOCBASE (Jensen and Wolkoff, 1996). ^b Expected not to cause irritation (Nitschke et al., 1991). ^c Based on high TLV.

^d Expected not to cause irritation (Sax, 1993). ^e The value for decanal is used. ^f Irritation threshold estimate based on analysis of the isomer decanal (Jensen and Wolkoff, 1996), based on analysis of homologues hexanol, heptanol, and octanol. ^g Unpublished data (Jensen and Wolkoff, 1997). ^h Tentative TLV (Danish Labor Environment Service, 1996). ⁱ Two isomers of 2,4,4-trimethyl-1,3-pentandiol mono-isobutyrate. ^j Critical indoor value from Nielsen et al. (1997a).

The assessments are shown for different area-specific ventilation rates (Q/A) and for different air velocities (V_{air}). The experimental standard deviation of the odor intensity was on average 0.7 (see Fig. 2). This corresponds to an approximate experimental standard deviation of the mean of 0.3 for PVC, varnish and wall paint and 0.2 for sealant and carpet. Generally, it was seen that after a limited decay during the first one or two weeks the odor intensity reached a nearly constant level for the rest of the period. For the liquid building products, varnish and wall paint, the sensory decay was more pronounced over the first 1–2 weeks than for the other building products. The odor intensity for the carpet did not seem to decay over the 50 day period whereas the odor intensity for sealant decreased somewhat.

3.2. Chemical measurements

The impacts of the air velocity and concentration on the emission rate for the five building products are summarized in Table 3. Figs. 3–5 show concentration vs time for different air velocities and emission rate vs time for different area-specific ventilation rates of the selected VOCs from the five building products.

3.2.1. Carpet and PVC (Fig. 3)

For carpet, the decays of 2-ethylhexanol and 4-phenylcyclohexene show no dependence of the air velocity during the 50 day period. The area-specific emission rate vs time for the same VOCs indicates a dependency of the concentration on the emission rate. At the high area-specific ventilation rate (Q/A), i.e. at the low concentration, the emission rate was highest, especially during the first 2 weeks. For PVC, the decays of 2-ethylhexanol and in particular phenol at the end of the period show some air velocity dependence. The highest concentration and thereby the highest emission rate was observed at the highest air velocity. The area-specific emission rate vs time for 2-ethylhexanol shows no effect of concentration on the emission rate.

3.2.2. Sealant (Fig. 4)

For sealant, concentrations vs time show some effect of air velocity on the emission rate for dimethyloctanols, in particular at the beginning of the period, but no effect was observed for hexane. Similarly, area-specific emission rates vs time show an impact of concentration on the emission rate for dimethyloctanols whereas there was no effect for hexane. It should be noted that

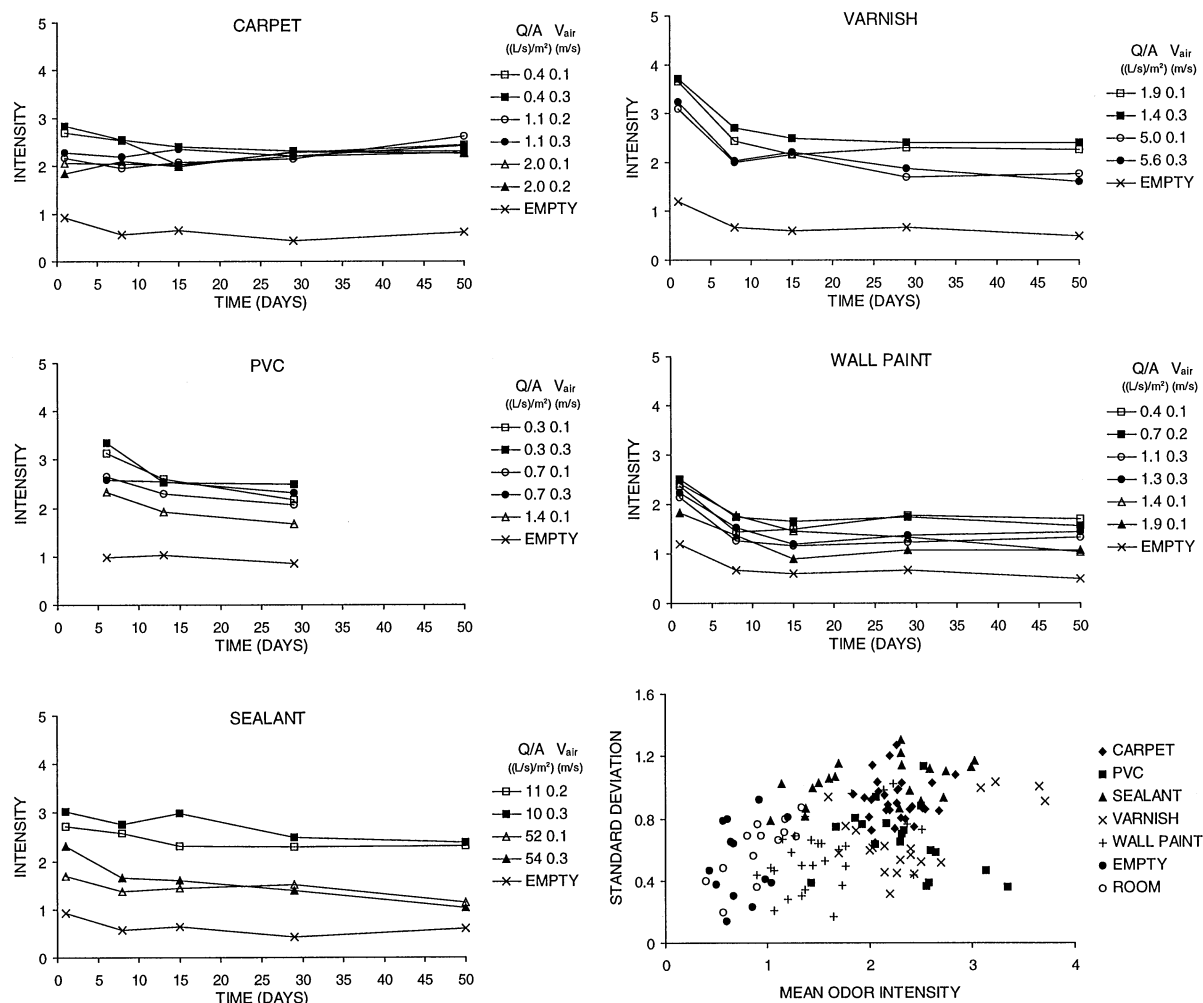


Fig. 2. Mean odor intensity vs time for three floor coverings: carpet, PVC and varnish; and for sealant, wall paint, and empty test chambers. The assessments are shown for different area-specific ventilation rates (Q/A) and for different air velocities (V_{air}). The experimental standard deviation of odor intensity votes as a function of the mean odor intensity is also shown. Each point represents the mean vote of eight persons for PVC, varnish and wall paint, and 23 persons for sealant and carpet.

dimethyloctanols may be formed during the hardening process, i.e. secondary emission.

3.2.3. Floor varnish and wall paint (Fig. 5)

The concentrations vs time and the area-specific emission rates vs time show no impact of the air velocity or the concentration on the emission rates of the VOCs from floor varnish and wall paint.

3.3. Odor index vs time

To compare the measurements of VOC concentrations with the sensory assessments, odor index vs time was

determined, see Fig. 6. The odor index (OI_i) for VOC_i is calculated as

$$OI_i = C_i / OT_i$$

where C_i is the concentration of VOC_i ($\mu\text{g m}^{-3}$) and OT_i the odor detection threshold of VOC_i ($\mu\text{g m}^{-3}$). Odor thresholds were obtained from a data compilation (Jensen and Wolkoff, 1996).

Only VOCs with an odor index greater than 1 at some point in time are considered. Since the impact of the air velocity on the emission rate is negligible or at least modest, the odor index is calculated on the basis of the

Table 3

The impact of air velocity and concentration on the emission rate of selected VOCs

Building product	VOC	Air velocity (m s ⁻¹)	Impact of air velocity	Q/A (L s ⁻¹ m ⁻²)	Impact of concentration
Carpet	2-Ethyl-1-hexanol	0.1 vs 0.3	–	0.4 vs 2.0	++
	4-Phenylcyclohexene		–		+++
PVC	2-Ethyl-1-hexanol	0.1 vs 0.3	+	0.3 vs 1.4	–
	Phenol		++		
Sealant	Hexane	0.1 vs 0.3	–	11 vs 52	–
	Dimethyloctanols		++		++
Floor varnish	Butyl acetate	0.1 vs 0.3	–	1.9 vs 5.0	–
	N-Methylpyrrolidone		–		–
Wall paint	1,2-Propandiol	0.1 vs 0.3	–	0.4 vs 1.9	–
	Texanol		–		–

The impact of differences in air velocity or impact of differences in concentration is rated in the following way: (–) the difference is less than 10% during the entire test period; (+) the difference is between 10 and 25%; (++) the difference is between 25 and 50%; (+++) the difference during the entire test period is greater than 50%.

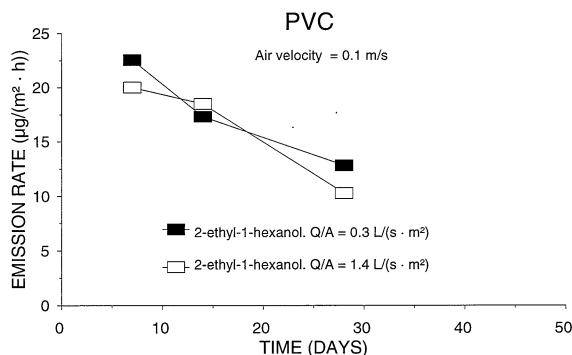
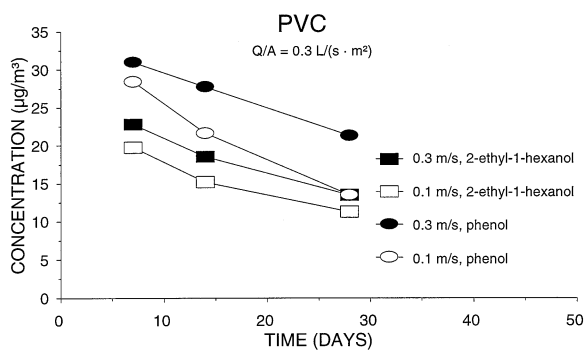
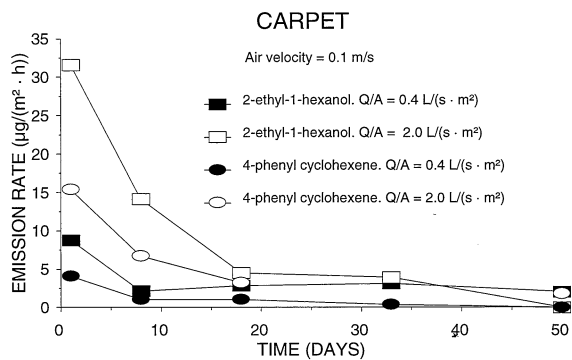
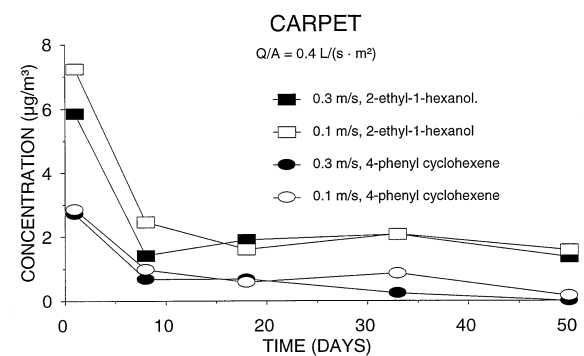


Fig. 3. Concentrations vs time at different air velocities and area-specific emission rate vs time at different area-specific ventilation rates for selected VOCs emitted from carpet and PVC.

mean concentration of measurements at the two air velocities 0.1 and 0.3 m s⁻¹, except for 3,7-dimethyloctanols from sealant.

3.3.1. Carpet

The odor index of 4-phenylcyclohexene approached 0.5 after about 1 week and 0.1 after about 7 weeks. The

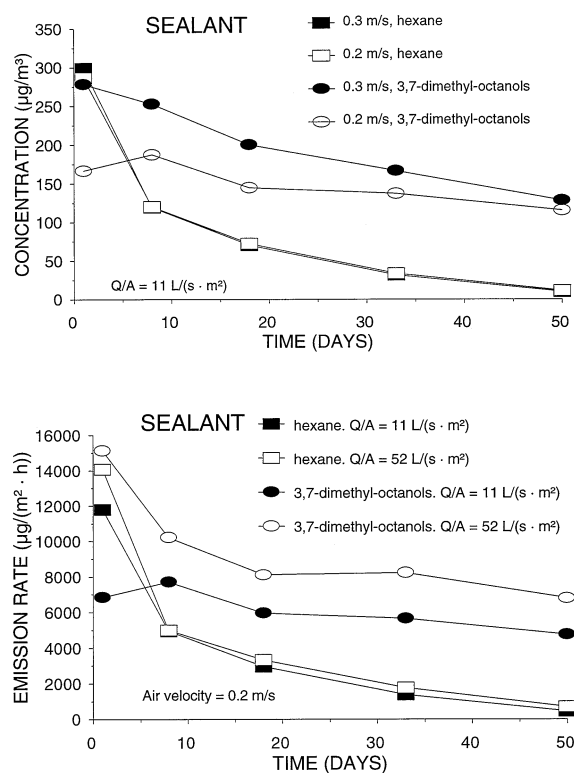


Fig. 4. Concentrations vs time at different air velocities and area-specific emission rate vs time at different area-specific ventilation rates for selected VOCs emitted from sealant.

odor indices of the two aldehydes, nonanal and decanal, fluctuated between 0.2 and 1.6 for unknown reasons. Decanal increased during the period to 1.5. The odor index of 2-ethylhexanol was about 0.01 at the start of the experiment.

3.3.2. Sealant

The odor index of dimethyloctanols was above 2 from the beginning of the measurements and approached 1 after about 7 weeks.

3.3.3. Floor varnish

The odor indices of butyl acetate and N-methylpyrrolidone both started at about 7, and approached about 1 after about 3 weeks. Both reached about 0.1 after about 5–6 weeks. The odor indices of butoxyethanol and butoxyethoxyethanol approached 0.1 within 3 weeks. Ethoxyethoxyethanol approached 0.1 after about 4 weeks.

3.3.4. Wall paint

The odor index of Texanol started at about 200, and approached 1 after about 4 weeks, 0.5 after about 6 weeks and 0.1 after around 7 weeks. The odor index of

butoxyethoxyethanol approached 0.1 after about 2 weeks. The odor index of decanal fluctuated considerable between 0.8 and 2.6, but was generally above 1.

3.3.5. PVC

The odor indices of 2-ethylhexanol and phenol were below 0.1 from the start of the experiment. For butoxyethoxyethanol the odor index was below 0.2 from the start of the experiment.

Table 4 lists the odor intensity after 50 days (for PVC after 30 days) and the approximate time to reach an odor index of 0.5 for each VOC as used in the Danish Indoor Climate Labeling scheme (Wolkoff and Nielsen, 1996). Similarly, the time to reach an odor index of 0.1 is shown. This lower index is included in an attempt to account for the more sensitive proportion of normal subjects (normosmics) that may perceive odorants down to at least one tenth of a given odor threshold. Table 4 also lists the measured sum of VOCs at the end of the experiments. The data do not indicate any correlation between the sum of VOCs and the odor intensity (see Fig. 2). For example, carpet resulted in an odor intensity of 2.4 and a sum of VOCs of $57 \mu\text{g m}^{-3}$, while the relatively high sum of VOCs from sealant or floor varnish did not result in a correspondingly higher odor intensity. Similarly, the relatively low odor intensity for wall paint did not result in a lower sum of VOCs.

4. Discussion

4.1. Air velocity

The first objective was to investigate the impact of the air velocity over the building product surface on the odor intensity and on the emission rates of selected VOCs.

4.1.1. Sensory assessment

The impact of air velocity on the odor intensity can be evaluated by comparison of odor intensities vs time in Fig. 2 at different air velocities for similar area-specific ventilation rates. These comparisons show that the air velocity has no significant impact on the odor intensity for any of the building products. This indicates that for practical purposes the impact of the air velocity on the emission rate of VOCs affecting the sensory assessments can be considered to be negligible for the investigated building products.

4.1.2. Chemical assessment

A summary of the impact of air velocity on the emission rate of VOCs is given in Table 3. For floor varnish and wall paint no impact of air velocity on the emission rate was observed. Apparently, the emission rate has become controlled by diffusion within the product

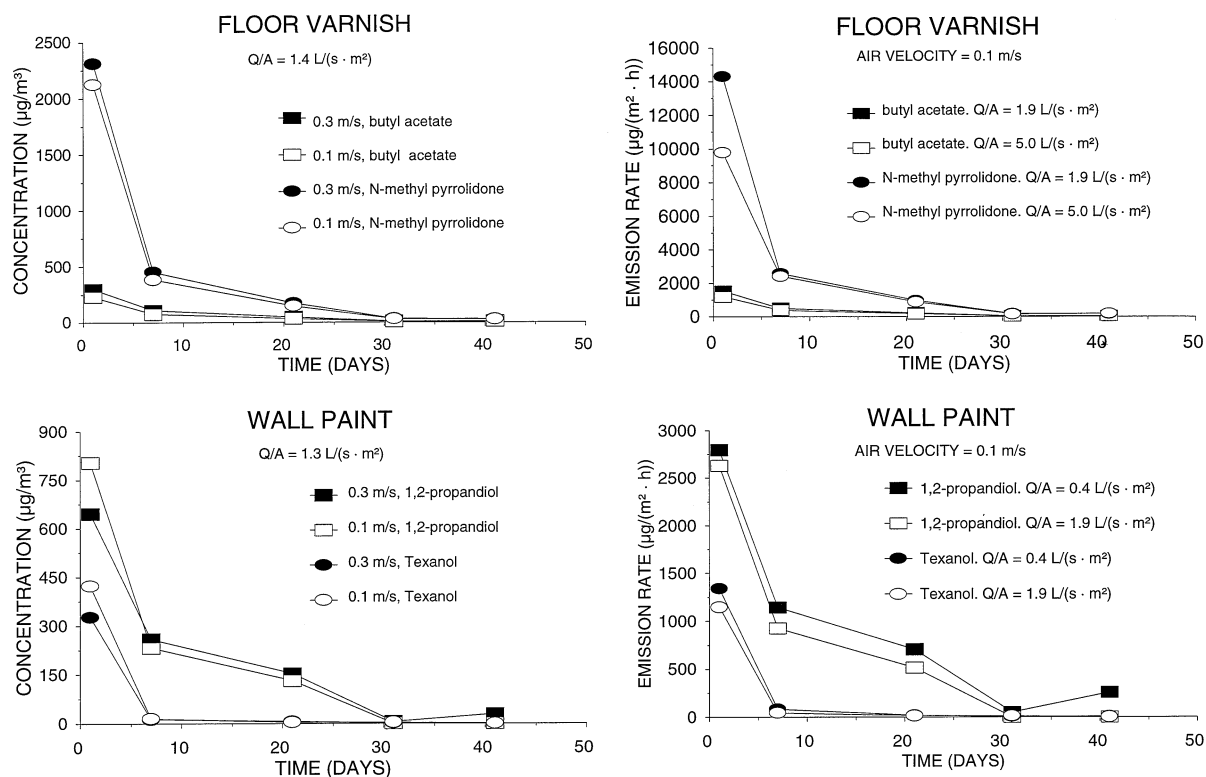


Fig. 5. Concentrations vs time at different air velocities and area-specific emission rate vs time at different area-specific ventilation rates for selected VOCs emitted from varnish and wall paint.

relatively fast (cf. Chang et al., 1997). This finding is in agreement with a study of the same building products where emissions were measured in a FLEC test chamber (Wolkoff, 1998). For carpet, the emission rates of 2-ethylhexanol and 4-phenylcyclohexene were unaffected by the air velocity. An explanation for this observation may be that the emissions of 2-ethylhexanol and 4-phenylcyclohexene from the latex backing is controlled by diffusion within the building product. For sealant the emitted dimethyloctanols showed some impact that diminished over time, whereas hexane was not affected. The reason for this observation may be that dimethyloctanols are also formed as a byproduct during the hardening process and this may lead to a composite mechanism of emissions. Hexane is a primary emission that is diffusion controlled. The emission rates of 2-ethylhexanol and in particular phenol from PVC were affected by the air velocity. This is surprising, because the emission rate would be expected to be controlled by diffusion within the product (Clausen et al., 1993). One explanation may be that high air velocity causes secondary emissions, due to chemicals susceptible to air/oxygen, e.g. plasticizers in the building product. If the air velocity increases, the thickness of the boundary layer decreases. This

may increase the effective contact of oxygen (a biradical) with the building product surface microstructure, i.e. increase of the possibility of oxidative degradation. A similar observation was found in a study of emissions from samples of the same PVC placed in the FLEC test chamber (Wolkoff, 1998). Oxidative degradation has also been shown for linoleum (Jensen et al., 1996).

4.2. Concentration

The second objective was to investigate the impact of the concentration on the emission rate.

4.2.1. Sensory assessments

It is not possible to evaluate the impact of the concentration on the emission rate of VOCs based on the sensory assessments. This would require a detailed knowledge of the exposure-response relationships on intensity votes for each of the five building products. However, it is interesting to look at the odor intensities vs time for sealant and carpet. For both building products the area-specific ventilation rate was varied by a factor of 5. For sealant, the odor intensity differed as expected for the two levels of area-specific ventilation rates during the entire

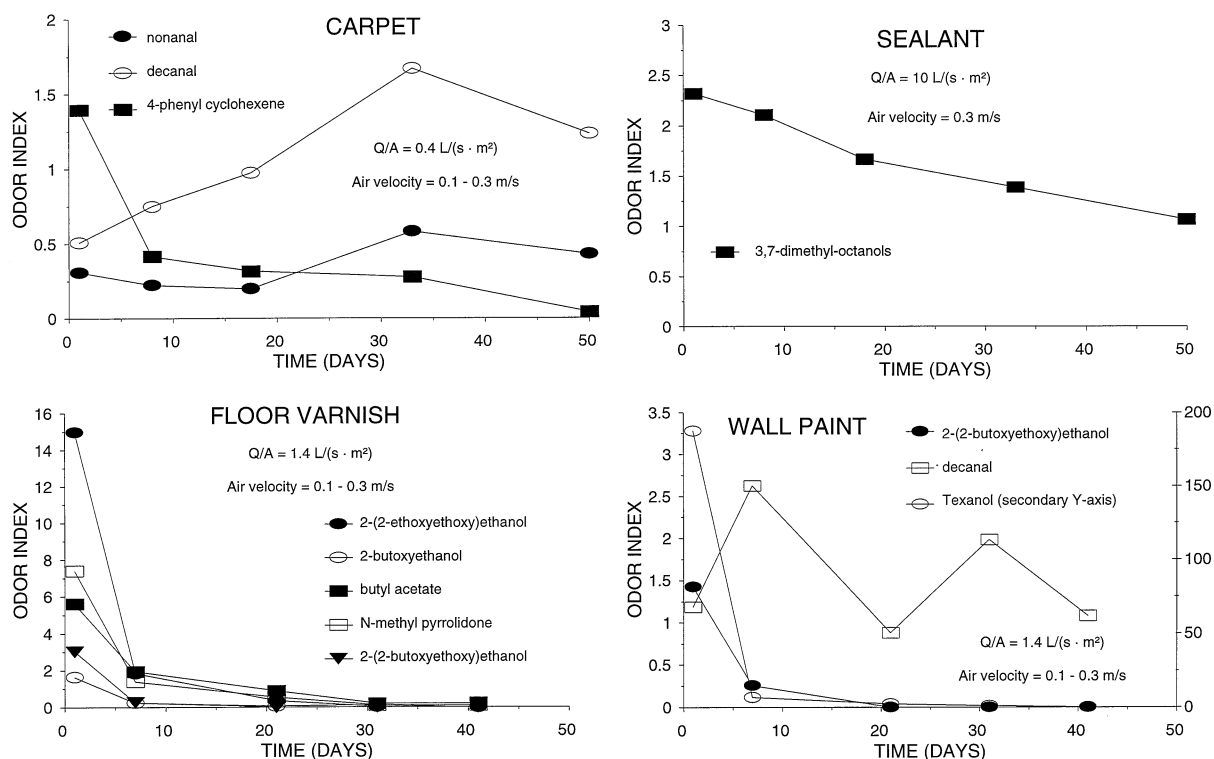


Fig. 6. Odor indices vs time at constant area-specific ventilation rate, for selected VOCs emitted from carpet, sealant, floor varnish, and wall paint.

50 day period. For carpet, however, the odor intensity only differed as expected at the beginning of the measuring period. After 30 days the odor intensity was about the same at the different levels of area-specific ventilation rate. This may be explained either by an increase in perceivable secondary emission at the lower concentration or it may simply be due to a flat slope of the exposure–response relationship for carpet compared to a steeper slope for sealant. Such differences have been seen in a parallel study of exposure–response relationships for the same and other building products (Knudsen et al., 1997, 1998).

4.2.2. Chemical assessment

The impact of concentration on the emission rate of VOCs is listed in Table 3. The impact of concentration on the emission rate of VOCs for the carpet and the sealant is difficult to explain without including a model with sink effects, in particular for the polar VOCs, i.e. 2-ethylhexanol and dimethyloctanols. A rational explanation for the relatively large difference in emission rate for carpet at different concentrations could be desorption from the fibers. Until 24 h before the carpet samples were placed in the test chambers they were stored while being wrapped in diffusion-tight packing. During this storage

period, it is possible that the fibers have adsorbed VOCs that later were desorbed, especially during the initial period of the measurements. The decay of the dimethyloctanols from the sealant is probably due to a not yet finished hardening process that releases the alcohols with the possibility of additional evaporation controlled emission.

The above results support that it is reasonable after an initial period of up to 14 days to consider the emission rate of primary VOCs from a wide range of building products to be independent of the VOC concentration in the air and of the air velocity over the product surface. Similar conclusions about the impact of the VOC concentration have been obtained for the same building products, except for wall paint (Andersen et al., 1996). For such building products it will be sufficient to quantify the emission rate of VOCs at one realistic area-specific ventilation rate, and at one air velocity to be able to model the concentration levels in a room. However, impacts of air velocity and concentration may occur for primary VOCs if the emission rate is evaporation controlled. In addition, increased air velocity may result in an increased emission rate for secondary VOCs that originate from drying, hardening, sorption, and oxidative degradation. Then, it may be necessary to quantify the

Table 4

Odor intensity after 50 days^a (for PVC after 30 days), the approximate time for reaching an odor index of 0.5 and 0.1 for the selected VOCs, and the approximate sum of VOCs from the five building products after 30–50 days

Building product: VOC	Area specific ventilation rate $\mathcal{L} \text{ s}^{-1} \text{ m}^{-2}$	Odor intensity	Time (weeks) before reaching an odor index of		ΣVOCs^b ($\mu\text{g m}^{-3}$)
			0.5	0.1	
Carpet:	0.4	2.4			57 ^c
4-Phenylcyclohexene			1	7	
Nonanal ^d			≈ 7	> 7	
Decanal ^d			> 7	> 7	
PVC:	0.3	2.3			141 ^e
2-Butoxyethoxyethanol			0	0	
2-Ethylhexanol			0	0	
Phenol			0	0	
Sealant:	11	2.4			163 ^e
Dimethyloctanols ^f			> 7	> 7	
Floor varnish:	1.4	2.4			420 ^g
Butoxyethanol			< 1	< 3	
Ethoxyethoxyethanol ^f			< 3	< 5	
2-Butoxyethoxyethanol			< 1	< 3	
Butyl acetate			< 4	> 7	
N-Methylpyrrolidone ^f			3	< 5	
Wall paint:	1.3	1.4			125 ^g
2-Butoxyethoxyethanol			< 1	< 3	
Decanal ^d			> 7	> 7	
Texanol ^f			≈ 6	> 7	

^a See Fig. 3. ^b Sum of VOCs. ^c After 7 weeks. ^d Fluctuating concentrations. ^e After 4 weeks. ^f Tentative or unpublished odor thresholds used, see Table 1. ^g After 6 weeks.

emission rate of VOCs at more than one realistic area-specific ventilation rate and at more than one air velocity to be able to model the VOC concentrations at different area-specific ventilation rates and different air velocities.

4.2.3. Airway irritation

It has recently been proposed to use threshold limit values (TLVs) for risk assessment of airway irritation due to indoor air pollutants, if no indoor air standard or guideline exist (James and Gardner, 1996; Paustenbach, 1997). For continuous exposure of VOCs and accounting for specially sensitive humans an indoor air guideline for airway irritation has been proposed to be $1/40 \cdot \text{TLV}$ (Nielsen et al., 1997a). If none of the emitted VOCs (nor their sum) exceed these levels, the building products are not believed to cause airway irritation. For the five building products of this study the levels of the selected VOCs were all below $1/40 \cdot \text{TLV}$ after 2 weeks, see Table 2. Therefore, none of the VOCs are considered to cause airway irritation after about 2 weeks. Within the first 2 weeks, the dimethyloctanols from sealant and Texanol from wall paint may be expected to cause airway irritation. However, since irritants are additive, airway irritation cannot be ruled out even after 2 weeks, but it is

considered unlikely for carpet, paint, and sealant (cf. Nielsen et al., 1997b).

4.3. Sensory assessments vs chemical measurements

The third objective was to study the interrelation between odor intensity and concentrations of selected VOCs. This interrelation was studied by comparison of odor intensities vs time with the corresponding odor indices vs time for selected VOCs believed to affect the odor intensity. The odor intensity decreased within the first 2 weeks; most for varnish and wall paint, less for PVC, and only marginally for sealant and carpet (see Fig. 2). Thereafter, the odor intensity reached a nearly constant level for the rest of the period. The odor intensity leveled out at around 2.4 for all building products except for wall paint that ended at 1.4. The odor indices of the selected VOCs for carpet, PVC, varnish, and wall paint showed a markedly faster decay (Fig. 6) than the corresponding odor intensities (Fig. 2). For all building products the odor indices reached 0.1 after 50 days for the primary VOCs, see Tables 2 and 4. Both carpet and wall paint are believed to emit some secondary VOCs (e.g. the aldehydes, nonanal and decanal) that only slowly, if at all, approach an odor index of 0.1. The

fluctuations of the aldehyde concentrations from carpet and wall paint and the dimethyloctanols from sealant are not well understood, but they are believed to be partially derived from some surface degradation (oxidation) or unknown mechanisms of secondary origin (including hardening processes).

The present data show that building products continue to affect the perceived air quality, even when the concentrations of primary VOCs are well below their respective odor thresholds. Therefore, odor indices less than 0.1 for selected VOCs cannot guarantee that a building product has no impact on the perceived air quality. A reason for this could be emissions of secondary VOCs. A better understanding of the nature of secondary emissions and their impact on the perceived air quality seems essential, because they may be responsible for the continued odor of the building products, even after known primary VOCs have decayed to far below their respective odor thresholds.

Several explanations can be suggested for the above discrepancies between the decay of VOC concentrations and corresponding odor intensity. These are: (1) We do not measure all the VOCs that are present in the air and that affect the odor intensity. (2) The building products emit VOCs with high odor indices, but in low concentrations which are not captured or analyzed by the analytical techniques available. (3) Available odor thresholds are too high, due to inadequate olfactometric techniques (Punter, 1983), uncertainties about exposure due to e.g. sniffing technique and insufficient airflow (Laing, 1982). (4) Odor thresholds are based on 50% detection of odor by a panel of judges and do not take into account inter-personal variations, i.e. some individuals may be orders of magnitude more sensitive to odors than others. (5) If a building product emits a mixture of similar odorous VOCs (e.g. aldehydes), below odor threshold, normal or hyperaddition may occur (see Introduction). This means that mixtures of VOCs may affect the perceived air quality although the individual compounds are all below their respective odor thresholds.

In the present study odor intensity was used as a measure of the perceived air quality. However, to describe “air quality” more directly, a measure of the hedonic characteristics of the air are required. At present, only a sensory panel can provide such information, e.g. assessment of the acceptability of the polluted air. Such assessments cannot be based on chemical measurements since hedonic information on individual VOCs is not available, and even if it were, it would be impossible to predict how combinations of VOCs would be perceived. However, for some building products that emit VOCs above their odor thresholds guidance may be provided, based on chemical measurements, for the development of building products with a lower sensory impact. Even so, this may not fully explain what affects the perceived air quality. At present, the use of sensory panels is the only

method sensitive enough to characterize the perceived air quality caused by low-emitting building products.

5. Conclusions

- For the investigated building products which represent a wide range of building products it seems reasonable after an initial period of up to 14 days to consider the emission rate of primary VOCs to be independent of the VOC concentration in the air and of the air velocity over the building product. However, if the building product surface is sensitive to oxidative degradation, increased air velocity may result in an increase of secondary VOC emissions.
- The odor intensity of the emissions from the building products only decayed modestly over time. Consequently, it is recommended to use building products which have a low adverse impact on the perceived air quality from the moment they are applied.
- Some of the investigated building products continued to affect the perceived air quality even when the concentrations of selected VOCs resulted in odor indices less than 0.1. Therefore, odor indices less than 0.1 as an accept criterion cannot guarantee that a building product has no impact on the perceived air quality.
- The odor indices of primary VOCs decayed markedly faster than the corresponding odor intensities. This indicates that it is the secondary emissions, rather than the primary emissions, that affect the perceived air quality in the long run.
- To be able to understand the impact of emitted VOCs on the perceived air quality, more research has to be carried out on the chemical-sensory relationship of VOC mixtures, especially at concentrations below odor threshold. This includes determination of high-quality odor thresholds for relevant indoor VOCs, a better understanding of hedonic effects of VOCs, and a general improvement of the chemical analytical performance.

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References

- Andersen, T.E., Knudsen, H.N., Tirkkonen, T., Orko, I., Saarela, K., Clausen, G., Fanger, P.O., 1996. Air pollutant concentration effects on VOC emission rates of building and furnishing materials. *Proceedings of the Indoor Air Quality and Climate '96*, Nagoya, vol 1, pp. 559–564.
- Berglund, B., Lindvall, T., 1992. Theory and method of sensory evaluation of complex gas mixtures. *Annals of the New York Academy of Sciences* 641, 277–293.
- Berglund, B., Olsson, M.J., 1993. Odor-intensity interaction in binary mixtures. *Journal of Experimental Psychology* 19, 302–314.
- Bluyssen, P.M., de Oliveira Fernandes, E., Groes, L., Clausen, G., Fanger, P.O., Valbjørn, O., Bernhard, C.A., Roulet, C.A., 1996. European indoor air quality audit project in 56 office buildings. *Indoor Air* 6, 221–238.
- Cain, W.S., Schiet, F.T., Olsson, M.J., de Wijk, R.A., 1995. Comparison of models of odor interaction. *Chemical Senses* 20, 625–637.
- Chang, J.C.S., Tichenor, B.A., Guo, Z., Krebs, K.A., 1997. Substrate effects on VOC emissions from a latex paint. *Indoor Air* 7, 241–247.
- Christiansson, J., Yu, J.-W., Neretnieks, I., 1993. Emission of VOC's from PVC-floorings – models for predicting the time dependent emission rates and resulting concentrations in the indoor air. *Proceedings of the Indoor Air Quality and Climate '93*, Helsinki, vol. 2, pp. 389–394.
- Clausen, P.A., Lauersen, B., Wolkoff, P., Rasmussen, E., Nielsen, P.A., 1993. Emission of volatile organic compounds from a vinyl floor covering. In: Nagda, N.L. (Ed.), *Modeling of Indoor Air Quality and Exposure*. American Society for Testing and Materials, Philadelphia, pp. 3–13.
- Clausen, P.A., Wolkoff, P., Holst, E., Nielsen, P.A., 1991. Long term emission of volatile organic compounds from waterborne paints – methods of comparison. *Indoor Air* 1, 562–576.
- Cometto-Muñiz, J.E., Cain, W.S., 1991. Influence of airborne contaminants on olfaction and the common chemical sense. In: Getchell, T.V. et al. (Eds.), *Smell and Taste in Health and Disease*. Raven Press, New York, pp. 765–785.
- Cometto-Muñiz, J.E., Cain, W.S., Hudnell, H.K., 1997. Agnostic sensory effects of airborne chemicals in mixtures: odor, nasal pungency, and eye irritation. *Perception and Psychophysics* 59, 665–674.
- ECA (European Collaborative Action Indoor Air Quality and its Impact on Man, COST Project 613), 1991. Guideline for the characterization of volatile organic compounds emitted from indoor materials and products using small test chambers. Office for Publication of the European Communities, Luxembourg. (Report No. 8 (EUR 13593 EN)).
- Ekberg, L.E., Nielsen, J.B., 1995. A laboratory for investigation of the air quality in simulated indoor environments. The 16th AIVC Conference, Palm Springs, USA, 19–22 September.
- Girman, J.R., 1993. Simple modeling to determine appropriate operating conditions for emission testing in small chambers. In: Nagda, N.L. (Ed.), *Modeling of Indoor Air Quality and Exposure*, ASTM STP 1205. American Society for Testing and Materials, Philadelphia, pp. 145–148.
- Guadagni, D.G., Buttery, R.G., Okano, S., Burr, H.K., 1963. Additive effect of sub-threshold concentrations of some organic compounds associated with food aromas. *Nature* 200, 1288–1289.
- Gunnarsen, L., Nielsen, P.A., Wolkoff, P., 1994. Design and characterization of the CLIMPAQ, chamber for laboratory investigations of materials, pollution and air quality. *Indoor Air* 4, 56–62.
- Guo, Z., Tichenor, B.A., Krebs, K.A., Roache, N.F., 1996. Considerations on revisions of emissions testing protocols. In: Tichenor, B.A. (Ed.), *Characterizing Sources of Indoor Air Pollution and Related Sink Effects*, ASTM STP 1287. West Conshohocken, PA, American Society for Testing and Materials, USA, pp. 225–236.
- James, J.T., Gardner, D.E., 1996. Exposure limits for airborne contaminants in spacecraft atmospheres. *Applied Occupational and Environmental Hygiene* 11, 1424–1432.
- Jayjock, M.A., 1994. Back pressure modeling of indoor air concentrations from volatilizing sources. *American Industrial Hygiene Association Journal* 55(3), 230–235.
- Jensen, B., Wolkoff, P., 1996. VOCBASE – odor thresholds, mucous membrane irritation thresholds and physico-chemical parameters of VOCs. A PC program, Version 2.1, National Institute of Occupational Health, Copenhagen.
- Jensen, B., Wolkoff, P., Wilkins, C.K., 1996. Identification of oxidative emission processes by nitrogen versus air exposure of building materials, characterizing indoor air pollution and related sinks. In: Tichenor, B.A. (Ed.), *ASTM STP 1287*. Philadelphia, pp. 145–152.
- Kjaer, U.D., Nielsen, P.A., Marcussen, L., Wolkoff, P., 1996. Characterization of emissions from building products: selection criteria, storage, and handling of indoor materials for experiments. *Proceedings of the Indoor Air Quality and Climate '96*, Nagoya, vol. 3, pp. 573–578.
- Knudsen, H.N., Clausen, G., Fanger, P.O., 1997. Sensory characterization of emissions from materials. *Indoor Air* 7, 107–115.
- Knudsen, H.N., Valbjørn, O., Nielsen, P.A., 1998. Determination of exposure–response relationships for emissions from building products, *Indoor Air*, accepted for publication.
- Laing, D.G., 1982. Characterisation of human behaviour during odour perception. *Perception* 11, 221–230.
- Laing, D.G., Eddy, A., Best, D.J., 1994. Perceptual characteristics of binary, trinary, and quaternary odor mixtures. *Physiology and Behavior* 56, 81–93.
- Lawless, H.T., 1977. The pleasantness of mixtures in taste and olfaction. *Sensory Processes* 1, 227–237.
- Nielsen, G.D., Hansen, L.F., Hammer, M., Vejrup, K.V., Wolkoff, P., 1997b. Chemical and biological evaluation of building material emissions I. A screening procedure based on a closed emission system. *Indoor Air* 7, 8–16.
- Nielsen, G.D., Hansen, L.F., Wolkoff, P., 1997a. Chemical and biological evaluation of building materials' emissions II. Approaches for setting indoor air standards or guidelines for chemicals. *Indoor Air* 7, 17–32.
- Nitschke, K.D., Mizell, M.J., Beekman, M.J., Lomax, L.G., 1991. Dermal sensitization potential and inhalation toxicological evaluation of 4-phenylcyclohexene. *American Industrial Hygiene Association Journal* 52, 192–197.

- Patterson, M.Q., Stevens, J.C., Cain, W.S., Cometto-Muñiz, J.E., 1993. Detection thresholds for an olfactory mixture and its three constituent compounds. *Chemical Senses* 18, 723–734.
- Paustenbach, D.J., 1997. Methods for setting limits for acute and chronic toxic ambient air contaminants. *Applied Occupational and Environmental Hygiene* 12, 418–428.
- Punter, P.H., 1983. Measurement of human olfactory thresholds for several groups of structurally related groups. *Chemical Senses* 7, 215–235.
- Sax, 1993. *Sax's, Dangerous Properties of Industrial Materials*, 8th ed. Van Nostrand Reinhold, New York.
- Tichenor, B.A., 1992. Characterization material sources and sinks – current approaches. *Annals of the New York Academy Sciences* 641, 63–78.
- Tichenor, B.A., Guo, Z., 1991. The effect of ventilation on emission rates of wood finishing materials. *Environmental Interaction* 17, 317–323.
- Wolkoff, P., 1995. Volatile organic compounds – sources, measurements, emissions, and the impact on indoor air quality. *Indoor Air (Suppl. 3)* 9–73.
- Wolkoff, P., 1998. Impact of air velocity, temperature, humidity, and air on long-term VOC emissions from building products. *Atmospheric Environment* 32, 3259–3268.
- Wolkoff, P., Jensen, B., Kjær, U.D., Nielsen, P.A., 1996. Characterization of emissions from building products: short-term chemical and comfort evaluation after one day. *Proceedings of Indoor Air Quality and Climate '96, Nagoya*, vol. 4, pp. 331–336.
- Wolkoff, P., Nielsen, P.A., 1996. A new approach for indoor climate labeling of building materials – emission testing, modeling, and comfort evaluation. *Atmospheric Environment* 30, 2679–2689.
- Wolkoff, P., Nielsen, P.A., 1997. How to evaluate VOC emissions from building products? A perspective. *Proceedings of Healthy Buildings/IAQ '97, Washington DC, USA*, vol. 3, pp. 491–496.
- Yaglou, C.P., Riley, E.C., Coggins, D.I., 1936. Ventilation requirements. *ASHRAE Transactions* 42, 133–162.