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Volatile Organic Compounds in Office Buildings

1. Presence of Volatile Organic Compounds in the Indoor Air

Key Words
Indoor air
Volatile organic compounds
Toxic volatile organic compounds
Offices

Abstract
There is growing awareness concerning the variety of VOCs as well as their level in the indoor air. Measurements of VOCs were carried out in both the indoor and the outdoor air of six office buildings in Greece together with the measurements of other physical and chemical parameters. The experimental results showed that the toxic VOC (TVOC) concentrations in 65% of the rooms were higher than the recommended level of 200 $\mu g \cdot m^{-3}$ and that the concentrations of TVOCs in the outdoor air were lower than the concentrations in the indoor air in all the buildings examined. More than 60 compounds were identified from the TVOCs in each building among which the aromatic and aliphatic compounds were the most abundant. Although a number of other compounds were found, including terpenes, ketones, alcohols, aldehydes, esters and halogenated compounds, most of them did not exceed the level of 20 $\mu g \cdot m^{-3}$ in most of the rooms.

Introduction

Volatile organic compounds (VOCs) are considered to be an important category of compounds found in indoor air. This is due to the extremely wide variety of VOCs that have been found in the indoor air at concentrations that significantly exceed the values found in the outdoor air [1]. In most of the cases, the levels of VOCs found in the indoor air are not responsible for toxic health effects, although several VOCs have been classified as carcinogenic while others are hazardous for human health [2–5]. Moreover, it has been found that high levels of VOCs in the air can influence human comfort and can cause sensory effects [6–8], which means that the presence of noticeable levels of VOCs is one of the reasons for the perception of a poor indoor air quality by the occupants of the buildings and may be responsible for building-related symptoms. According to the guidelines proposed by Mølhave [9], the level of toxic VOCs (TVOCs) should not exceed 200 $\mu g \cdot m^{-3}$, in order to ensure human comfort, while Seifert [10] suggested a target guideline value of 300 $\mu g \cdot m^{-3}$ for TVOCs.

The concentrations of TVOCs in the indoor air can show a variance of two or more orders of magnitude depending mainly on building characteristics. According to a review study performed by Brown et al. [11] and Brown [12], the geometric mean of the TVOC concentrations in 60 established office buildings was 180 $\mu g \cdot m^{-3}$. A study [13] performed in Italy showed that the median of TVOC concentrations in 5 buildings was 298 $\mu g \cdot m^{-3}$,

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while another study [14] showed that the mean TVOC concentration in 12 randomly selected buildings in California was 470 µg·m^{-3}. The mean TVOC concentrations found in 2 buildings in Finland [15] were 236 and 247 µg·m^{-3}. However, the concentrations found in new, renovated or sick buildings can be several times higher than those found in these studies depending on the particular sources that emit VOCs, the ventilation rate, etc. Measurements in 51 sick buildings [11] showed that the geometric mean of TVOC concentrations was 490 µg·m^{-3}, while the maximum levels in particular buildings were too high for comfort. The TVOC concentrations found in two buildings in Canada [16], where complaints had been reported, ranged between 0.9 and 65 mg·m^{-3} and the values found in another 3-year-old office building in Ontario [17] showed a range of 5,200–11,000 µg·m^{-3}. In a new building in Finland [18] the mean concentration found during the week, when the mechanical ventilation was open, was 131 µg·m^{-3}, while the concentrations found during the weekend when the ventilation was closed reached values up to 1,739 µg·m^{-3}.

The indoor environment in office buildings all over Europe was investigated in the frame of a European Audit project. In particular, the estimation of VOCs was carried out in nine European countries (England, France, The Netherlands, Germany, Switzerland, Belgium, Portugal, Norway, Finland, Denmark and Greece) with the aim of developing a European database for indoor air quality [19]. In Greece, VOCs were evaluated in six office buildings in the Athens area [20] and the results are presented in this study.

Methods

Six office buildings (A–F) around the Athens area were investigated following a procedure that was developed by the participants of a European Audit project [21]. One day measurements during working hours were carried out in each building in March 1994. The investigation of each building included standard questionnaires that investigated human comfort and symptoms, an inspection of the buildings in order to observe their characteristics using a standard checklist and one-day measurements of chemical, sensory and physical parameters. The physical parameters measured were air temperature, radiant temperature, relative humidity, air velocity and noise. The chemical parameters were total suspended particulates, TVOCs, CO and CO_2. Also the perceived air quality was evaluated using trained panels.

The measurements of the VOCs were carried out in the occupied zone of five selected rooms, their adjacent spaces, the outdoor air and the supply air. In buildings A and B, VOCs were measured in six rooms instead of five. The VOCs were collected in Tenax-TA tubes spiked with ^{2}[H]$_8$-toluene as internal standard, using low-flow sampling pumps (SKC 222-4 Series). The sampling duration was approximately 2 h with an air flow of 40 ml·min^{-1}. The analysis of the VOCs was performed using Thermal Desorption (Perkin Elmer – ATD 400), Gas Chromatography (Hewlett Packard 5890) equipped with J&W DB5 MS capillary column, Flame Ionisation Detection and Mass Spectrometry (HP MSD 5970). The GC separation was performed using He as the carrier gas with temperature programme from 40 to 250 °C at a rate of 8 °C·min^{-1}. The concentration of TVOCs was calculated from the sum of the individual VOCs as toluene equivalents (µg·m^{-3}). The detection limit of the method was about 1 µg·m^{-3}.

Table 1. TVOC concentrations in buildings A–F (in toluen equivalents)

		TVOC concentrations, µg·m^{-3}					
		A	B	C	D	E	F
Room	R1	35	310	190	420	14	83(
	R2	36	350	150	620	11	51(
	R3	96	2810	170	610	13	45(
	R4	33	1370	180	700	22	76(
	R5	41	100	540	240	13	51(
	R6	11	130				
Corridors	C1	15	170	140	770	66	52(
	C2	34	200				40(
Supply		8			240	7	
Outdoor air		22	50	40	200	12	630

Results and Discussion

Six representative office buildings were selected from the Greek building stock, of which two were situated near the centre of Athens (buildings D and F), two in suburbs (buildings A and E) and two in rural areas (B and C). The age of all the buildings was greater than two years, and ranged between 2 and 30 years. The number of occupants in the audited buildings ranged between 120 and 380. Smoking was allowed in all the buildings. There were a lot of similarities between the surface coating materials used in the buildings audited. The ceiling materials used were acoustic tiles (mineral fibres) and plasterboard, while the floor materials were PVC tiles, carpets and ceramic tiles. All the buildings except F had a mechanical ventilation system.

The experimental results of the TVOCs measured in the buildings are given in table 1. The TVOC levels in the outdoor air were in the range 40–630 µg·m^{-3} and the values found were dependent on the area where the buildings

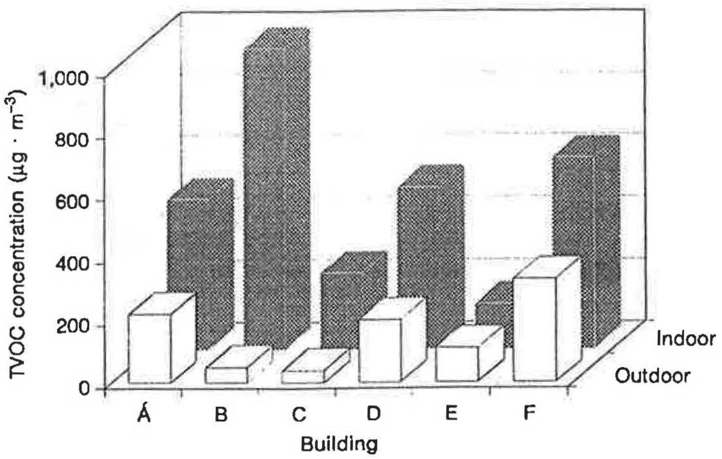

Fig. 1. Mean TVOC concentrations in the indoor and outdoor air of buildings A–F.

were located (centre, suburbs, rural). Buildings B and C were located in rural areas and the TVOC levels in the air outside these buildings were low (40–50 $\mu g \cdot m^{-3}$), buildings A and E were located in suburbs and the outdoor air concentrations for these buildings were 110 and 220 $\mu g \cdot m^{-3}$, respectively. Buildings D and F were located in the centre of the town and the outdoor air concentrations were 200 and 630 $\mu g \cdot m^{-3}$. The TVOC levels obtained in the indoor air of the buildings were appreciably different between the different buildings, being in the range 146–968 $\mu g \cdot m^{-3}$. The mean indoor air concentrations for all the buildings were higher than the outdoor air concentrations, as shown in figure 1, which indicates that the VOCs found in the indoor air originate mainly from indoor sources. The concentrations in the supply air were measured in 3 buildings, where the mechanical ventilation system was open during the auditing days. The VOC concentrations found in the supply air were low compared to the values measured in the indoor and the outdoor air, which shows that the mechanical ventilation system does not seem to contribute to the increase of VOCs found in the indoor air.

There were appreciable differences in the levels of TVOCs in the different rooms of each building (table 1). The greatest variance within a building was found in building B, where the concentrations ranged from 100 to 2,810 $\mu g \cdot m^{-3}$.

The values found in the indoor air of the audited buildings were not surprisingly high compared to those found in other office buildings, as mentioned earlier. It was found that 65% of the rooms showed concentrations higher than the recommended level of 200 $\mu g \cdot m^{-3}$ given by Mølhave [9], which represent the limit of comfort range, and 55% of the rooms showed concentrations higher than the guideline of 300 $\mu g \cdot m^{-3}$ given by Seifert [10]. However, none of the buildings showed values in the discomfort range (>3,000 $\mu g \cdot m^{-3}$). The TVOC concentrations in most of the rooms was in the multifactorial exposure range between 200 and 3,000 $\mu g \cdot m^{-3}$, which means that people can experience building-related symptoms if the other environmental parameters that prevail in the buildings contribute to the experience of symptoms. It must be noticed that the comparison of TVOC values must be performed with caution, since the definition of TVOC index differs according to the computational method used.

The number of VOCs observed in each room was higher than sixty. The compounds that were detected in all the rooms of the six buildings studied were: benzene, toluene, *o-/m-/p*-xylene, trimethylbenzenes, heptane, octane, nonane and acetone, while compounds that were detected in all the samples of outdoor air were: benzene, toluene, *m*-xylene, nonanal, decanal and acetone, as shown in table 2. Most of the compounds found in all the buildings are very common in the indoor and outdoor air and they represent the major part of the TVOCs, since they originate from various sources such as car exhausts, solvent-based materials and consumer products. However, the number of compounds found in the indoor air for the majority of the

Table 2. VOCs found in the buildings and the outdoor air

	Compounds in indoor air	Compounds in outdoor air
100% of the samples	benzene, toluene, *o*-/*m*-/*p*-xylene, trimethylbenzenes, heptane, octane, nonane and acetone	benzene, toluene, *m*-xylene, nonanal, decane, acetone
90% of the samples	all compounds mentioned above plus n-hexane, limonene, nonanal, decane and 2-methyl-1,3-butadiene	
80% of the samples	all compounds mentioned above plus naphthalene, tetrachloroethylene, 1,1,1-trichloroethane, decane, dodecane, methyl-cyclohexane, 2-methylpentane	all compounds mentioned above plus trimethylbenzenes, *p*-xylene, hexane, n-heptane, octane, nonane, 2-methylpentane, tetrachloroethylene

Table 3. Percentages of the most abundant VOC concentrations found in all the rooms

	Percentages of VOC concentrations $\mu g \cdot m^{-3}$			
	30%	50%	75%	95%
n-Hexane	7	8	16	23
n-Heptane	4	6	10	78
Heptane isomers	1	4	7	19
Octane	3	5	9	44
Nonane	2	3	7	42
Decane	2	4	8	59
2-Methylbutane	0	1	8	25
2-Methyl-1,3-butadiene	6	9	13	20
2-Methylpentane	4	5	16	45
3-Methylpentane	0	3	9	24
Methylcyclohexane	0	3	5	24
1,1,1-Trichloroethane	4	6	9	19
Benzene	7	13	24	54
Toluene	15	32	54	93
p-Xylene	2	6	10	36
m-Xylene	5	19	27	117
o-Xylene	3	7	12	29
Trimethylbenzenes	8	21	38	110
Limonene	2	4	7	41
α-Pinene	2	2	2	68
Naphthalene	3	4	9	13
Acetone	10	13	23	54

buildings was higher than the compounds found in the outdoor air, which shows that the sources emitting VOCs in the outdoor air are specific and they emit a characteristic mixture of compounds while in the indoor air there is a greater number of sources which emit a larger variety of compounds.

Regarding the concentrations of the individual VOCs measured in the buildings, it was found that the 15 compounds with the highest concentration in each room represented 70% of the total concentration of VOCs measured. Classification of the compounds according to their concentrations in the buildings showed that toluene had the highest concentration in 61% of the indoor air samples, while acetone had the highest concentration in the 30% of the indoor air samples. Moreover *m*-xylene and benzene had high concentrations in several buildings. In the outdoor air, toluene was the most abundant compound, *m*-xylene was the second most abundant and acetone was the third.

The concentrations of most of the 60 compounds detected in each sample were very low and the average concentration of the individual compounds found in each room did not exceed 10 $\mu g \cdot m^{-3}$ in most of the cases for the indoor and the outdoor air, as shown in figure 2. However, a number of compounds had high values in several rooms such as toluene and xylene, while other compounds showed high concentrations in a small number of rooms due to a particular source. These compounds were 2-butoxyethanol, benzaldehyde and others. Table 3 shows the percentages of VOC concentrations in all the rooms for the compounds that had mean concentrations higher than 5 $\mu g \cdot m^{-3}$. The mean concentrations of each category of compounds in the rooms, the outdoor air and the supply air are given in figure 3.

Aromatic compounds were present in the highest concentrations in most of the rooms, as shown in figure 4. The mean concentration of the sum of the aromatic compounds in the indoor and the outdoor air was higher than the guideline value given by Seifert (50 $\mu g \cdot m^{-3}$) [10]. The concentrations of toluene were higher than 20 $\mu g \cdot m^{-3}$ for

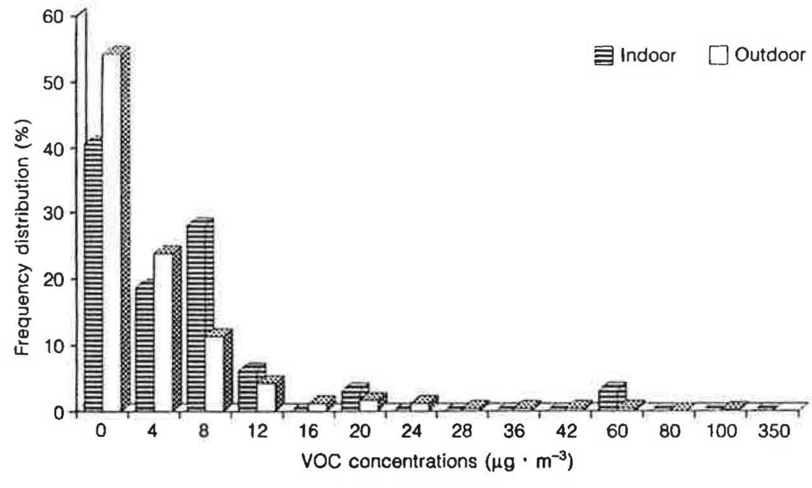

Fig. 2. Mean frequency distribution of the concentrations of all the compounds in the indoor and outdoor air.

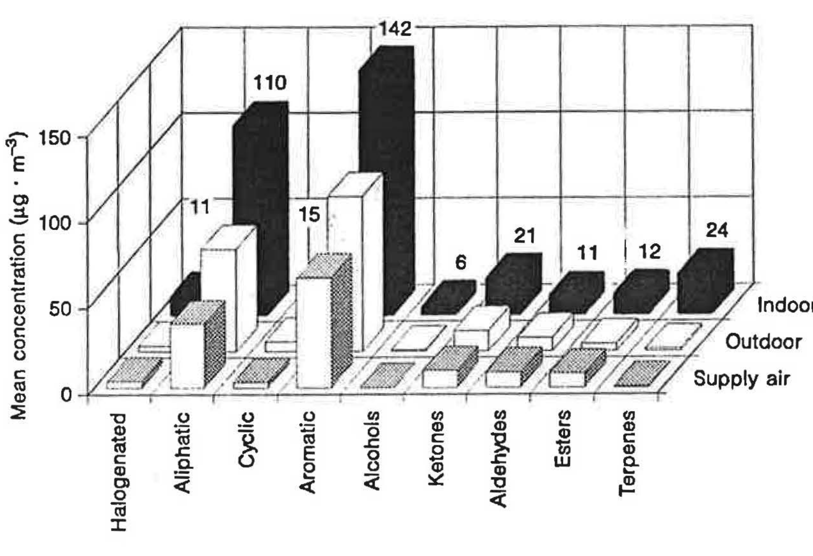

Fig. 3. Mean concentration of each category of compounds in the rooms, the outdoor air and the supply air.

55% of the audited rooms, the concentration of *m*-xylene and benzene were higher than 20 $\mu g \cdot m^{-3}$ in 45% of the rooms, while the concentrations of *o*- and *p*-xylenes and the trimethylbenzenes were lower than 20 $\mu g \cdot m^{-3}$ in most of the rooms.

Aliphatic compounds were the second most abundant with high concentrations in several rooms. The mean value of the sum of the aliphatic compounds was higher than the guideline level given by Seifert (100 $\mu g \cdot m^{-3}$). Among the aliphatic compounds, hexane and 2-methylpentane had concentrations below 12 $\mu g \cdot m^{-3}$ in 63% and 56% of the rooms respectively, while octane, heptanes, decane, 2-methylbutane and 3-methylpentane showed concentrations lower than 12 $\mu g \cdot m^{-3}$ in 80% of the rooms. All the other aliphatic compounds (C_9, C_{11}–C_{15}) had concentrations below 12 $\mu g \cdot m^{-3}$ in most of the rooms. Some cyclic aliphatic compounds found in the buildings were identified as mainly dimethylcyclopentane, methylcyclopentane, and methylcyclohexane. These compounds had concentrations below 12 $\mu g \cdot m^{-3}$ in more than 90% of the rooms.

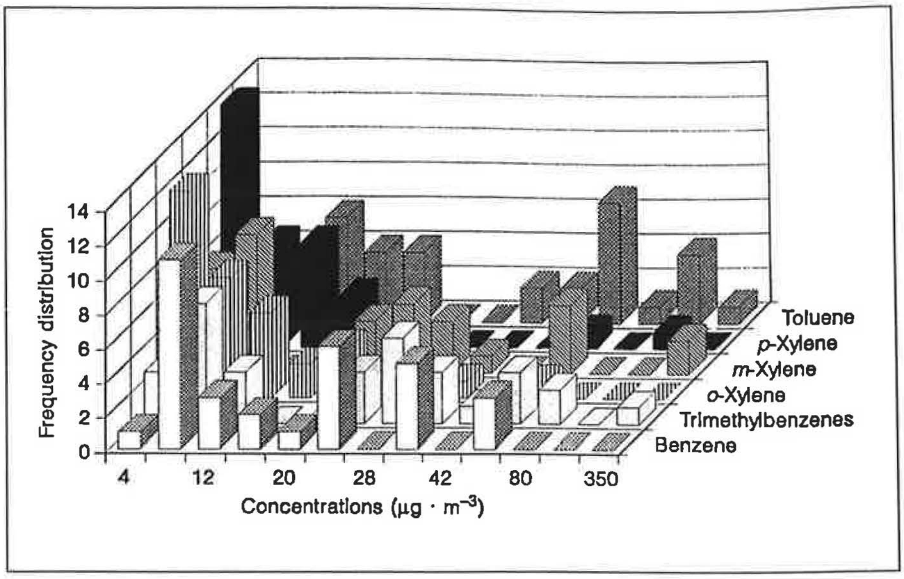

Fig 4. Frequency distribution of aromatic compounds in 32 rooms.

The remaining compounds (terpenes, alcohols, aldehydes, acids, etc.) had low concentrations in most of the rooms except where there was a source of a compound in a room. The mean concentrations of the sum of the terpenes, alcohols, acids, halogenated and other compounds for all the rooms did not exceed the guidelines given by Seifert (fig. 3). Limonene and α-pinene had concentrations higher than 12 $\mu g \cdot m^{-3}$ in 10% of the rooms. We were interested to find that naphthalene was present in most of the rooms, although mostly at concentrations lower than 12 $\mu g \cdot m^{-3}$.

Conclusions

The experimental results showed that the TVOC concentrations in 65% of the rooms were higher than the recommended level of 200 $\mu g \cdot m^{-3}$. At this level people can experience building-related symptoms, if the other environmental parameters prevailing in the buildings contribute to the symptoms. Concentrations of the TVOCs showed a great variation between the buildings and between the rooms in a building depending on the building characteristics and the VOC sources in each room. The concentrations of TVOCs in the outdoor air were lower than the concentrations in the indoor air in all the buildings, suggesting that the VOCs originate mainly from indoor sources.

Of the 60 compounds found those which were ubiquitous and found in the highest concentrations were the aromatic compounds toluene, benzene, xylenes and trimethylbenzenes, as well as some aliphatic compounds such as heptane and octane. These compounds are emitted predominately by cars and a number of sources such as solvent-based materials. Apart from these compounds, most of the others did not exceed a level of 20 $\mu g \cdot m^{-3}$ in most of the rooms.

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