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Volatile Organic Compounds in Office Buildings

2. Identification of Pollution Sources in Indoor Air

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Abstract

A great number of volatile organic compounds (VOCs) are found in the indoor air of office buildings, emitted mainly by the building materials, the consumer products used, the furnishing, office equipment, smoking, mechanical ventilation systems and outdoor air pollution. An attempt has been made to identify the strongest sources of VOCs in the indoor and outdoor air of six office buildings in Greece. Analysis of the results showed that the VOCs in the outdoor air were strongly related to the traffic in the area. Correlation of the concentrations found in both the indoor and outdoor air showed that the outdoor air contributes significantly to the chemical pollution load of the indoor air in some of the buildings. Also, a significant intercorrelation was found among the concentration patterns of aromatic and a number of aliphatic compounds, which showed that these compounds were emitted by similar sources. However, since these compounds are not emitted exclusively by car exhausts, the identification of their source is difficult. The dominant indoor sources of VOCs were permanent ones such as building materials and furniture.

Introduction

The extensive use of new building materials and consumer products has led to an immense increase in the concentrations of VOCs in buildings. The most effective way of controlling exposure to VOC levels in buildings is to reduce emissions from the various sources. This can be achieved by removing or sealing the sources that occur indoors. The main sources of VOCs in the indoor environment are building materials, furniture, consumer products and human activities [1–4]. The compounds found most frequently in buildings can be attributed to organic-based solvents used in several products [5, 6].

The contribution of the outdoor air to the indoor air pollution load differs significantly from building to building, depending on the chemical pollution load of the indoor air, the VOC concentrations in the outdoor air and the penetration of VOCs to the indoor air via the ventilation system or leakage of the building envelope [7]. Controversial findings have been reported concerning the contribution of smoking to the increase of VOC concentrations in indoor air. Some studies have shown a significant positive correlation between the VOC concentrations and the presence of smokers [5, 8], while other studies did not [9].

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Table 1. Building characteristics

Building	Situation	External pollution	Total floor area m^2	Occupants n	Age of building years	Surface materials		
						ceiling	walls	floor
A	suburb	moderate busy road	7495	250	5	mineral fibres	plasterboard	PVC tiles
B	rural	none	9540	380	3	mineral fibres	plasterboard or chipboard	carpet
C	rural	none	9190	300	2	mineral fibres	plasterboard or chipboard	carpet
D	downtown	busy road	2410	120	4	mineral fibres	plasterboard	ceramic tiles
E	suburb	parking	2492	120	21	aluminium	plasterboard	carpet
F	downtown	busy road	4170	140	30	plasterboard	plasterboard	ceramic tiles

Because of the uncertainties, it is important to identify the most dominant sources that occur in buildings and determine their contribution to the overall chemical pollution load. In this paper an attempt has been made to identify the potential sources of VOCs in 6 office buildings in Greece. This was performed by evaluating of the data collected in an investigation of the indoor air quality in these buildings [10].

Methods

The sources of VOCs found in 6 office buildings were deduced from the data concerning building characteristics and the chemical and physical measurements made, including measurements of the VOC concentrations in the indoor and outdoor air [11].

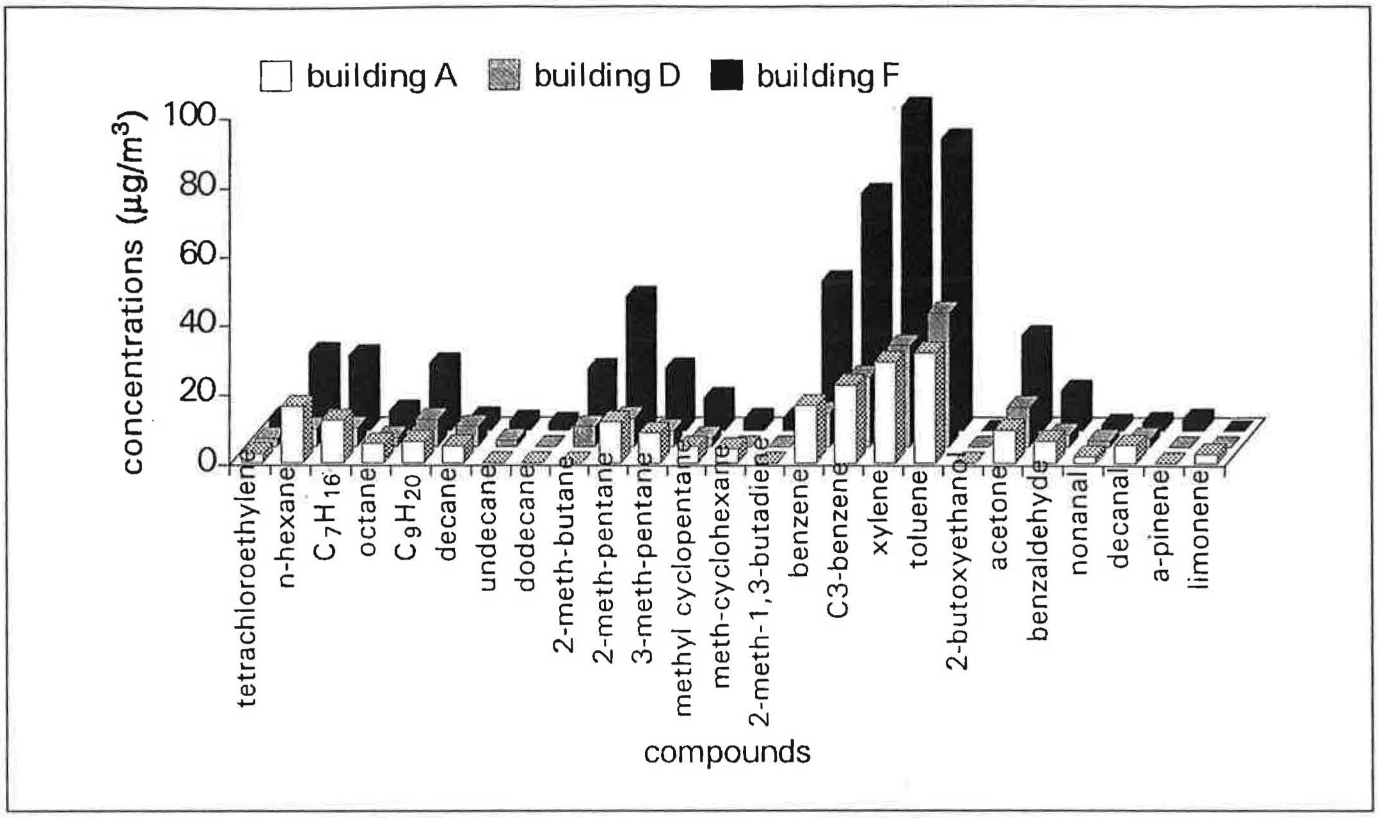
The main building characteristics obtained from the inspection of the buildings are shown in table 1. Details of the buildings are given in the preceding paper (Part 1)

The data detailing the VOCs were analysed to identify their sources. Potential VOC sources were identified from a literature survey. Correlation matrices were used in order to examine the relationship between the concentration patterns found in the air outside the office buildings, the indoor air of the various buildings and between the indoor air and the outdoor air around the same building. The indoor/outdoor (I/O) ratios were calculated for each compound in order to specify the origin of each compound together with the contribution of the outdoor air to the indoor air pollution. VOCs for which the I/O ratio was higher than 1.3 for approximately half of the rooms were classified as coming from both indoor and outdoor sources, while for compounds with an I/O ratio higher than 1.3 for more or less than half of the rooms were classified as coming from mainly indoor or mainly outdoor sources, respectively. Correlations between VOC levels and a number of other parameters were examined as well. Finally, factor analysis was used in order to determine groups of compounds that are emitted from similar sources in different buildings.

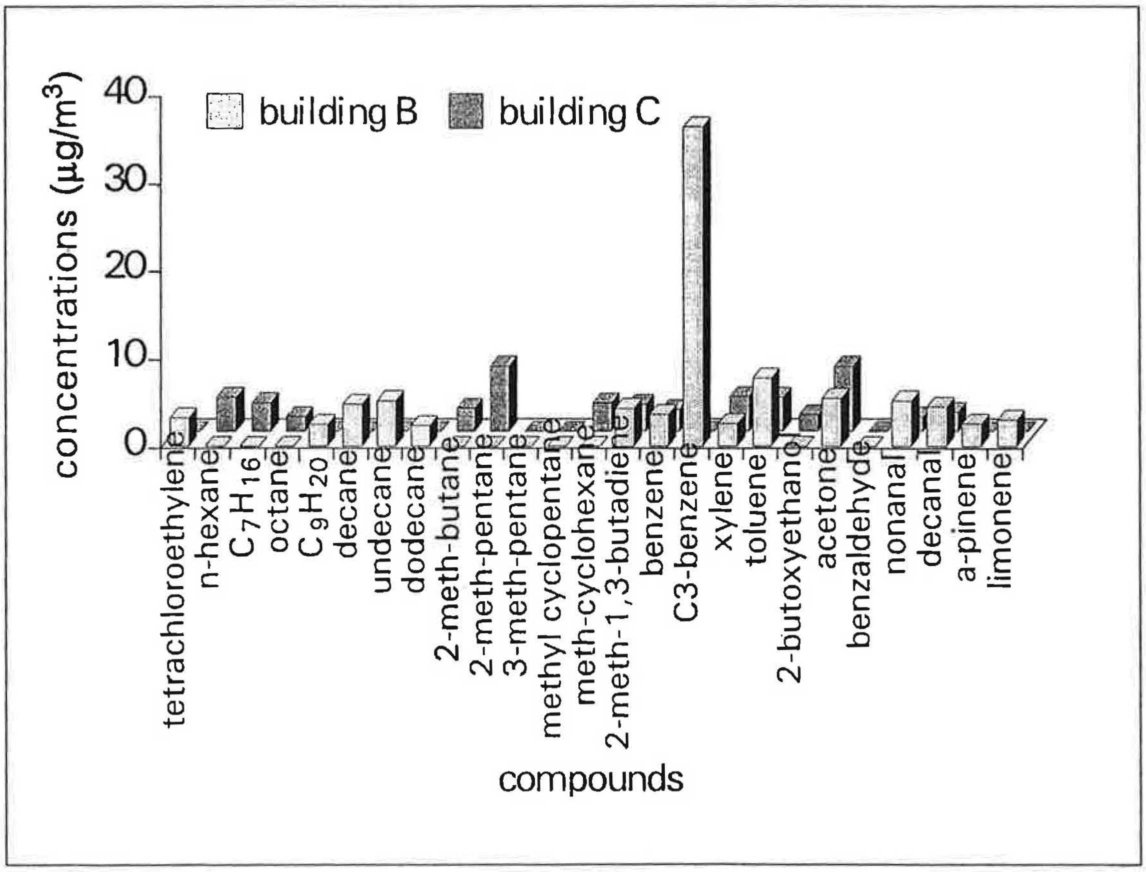
Results and Discussion

More than 60 VOCs were identified in each building. The 15 most abundant VOCs were identified for each of the 6 audited buildings. These compounds as well as their possible sources are given in table 2. The individual sources were identified from a literature survey [12–25]. As shown in table 2, the halogenated compounds are mainly emitted by consumer products. The shorter-chain aliphatic compounds such as hexane, heptane and octane are emitted by car exhausts and from solvent-based materials, while the branched-chain aliphatics: 2-methylbutane, 2-methylpentane and 3-methylpentane are mainly emitted by traffic. The aliphatic compounds C_9–C_{14} are used as solvents and they are mainly emitted by indoor sources such as building materials, furnishings and consumer products. Cyclic aliphatic compounds are found in solvent-based glues and waxes as well as in car exhausts. Aromatic compounds are emitted from a large number of sources, including car exhaust, tobacco smoke, most building materials, consumer products and furnishings. Terpenes are mainly emitted by scented consumer products such as cleaners and air fresheners. As shown in table 2, the majority of the compounds found in the buildings can come from various sources and consequently it is difficult to identify the particular sources.

Correlation matrices were used to find whether there are any relationships among the VOC concentration patterns in the outdoor air of the different buildings. The concentration patterns found in the outdoor air of buildings A, D and F had many similarities, with correlation coefficients higher than 0.75. The mixture of compounds


building A
building D
building F
concentrations (µg/m³)
100
80
60
40
20
0
tetrachloroethylene
n-hexane
C7H16
octane
C9H20
decane
undecane
dodecane
2-meth-butane
2-meth-pentane
3-meth-pentane
methyl cyclopentane
meth-cyclohexane
2-meth-1,3-butadiene
benzene
C3-benzene
xylene
toluene
2-butoxyethanol
acetone
benzaldehyde
nonanal
decanal
a-pinene
limonene
compounds

1


building B
building C
concentrations (µg/m³)
40
30
20
10
0
tetrachloroethylene
n-hexane
C7H16
octane
C9H20
decane
undecane
dodecane
2-meth-butane
2-meth-pentane
3-meth-pentane
methyl cyclopentane
meth-cyclohexane
2-meth-1,3-butadiene
benzene
C3-benzene
xylene
toluene
2-butoxyethanol
acetone
benzaldehyde
nonanal
decanal
a-pinene
limonene
compounds

2

Table 3. Correlation coefficients between the concentration patterns of VOCs in indoor air (different rooms of each building) and outdoor air

Building	Range of the correlation coefficients
A	0.76–0.96
B	0.47–0.72
C	0.32–0.52
D	0.67–0.98
E	0.38–0.89
F	0.76–0.93

Table 4. Percentage of the contribution of the outdoor air to the indoor air pollution

Building	Occurrences, %
A	58
B	17
C	29
D	25
E	66
F	68

Table 5. Classification of the most abundant VOCs according to their origin

Mainly indoor sources	n-heptane, octane, decane, undecane, benzene, acetone, 2-methyl-1,3-butadiene, naphthalene, α-pinene, limonene
Mainly outdoor sources	2-methylbutane, 2-methylpentane, 3-methylpentane, methyl-yclopentane, methyl-cyclohexane, trimethylbenzenes, *o*-xylene
Indoor and outdoor sources	n-hexane, heptane isomers, *m*-xylene, *p*-xylene, toluene, benzaldehyde

Table 6. Classification of the most abundant VOCs according to the factor loadings

Factor	Factor loadings	
1	0.98–0.72	benzene, *o*-/*m*-/*p*-xylenc, toluene, trimethylbenzenes, acetone benzaldehyde, heptane isomers, 2-methylpentane, 3-methylbutane, dimethyl-cyclopentane, 3-methylpentane, methylcyclopentane
2	0.77–0.63	n-hexane, n-heptane
3	0.79–0.59	decane, nonane, terpene, undecane
4	0.84	limonene

lation was found among the indoor air concentration patterns of the buildings A, D and F, with correlation coefficients higher than 0.8. Furthermore, there was a relationship between the rooms of the buildings B and C (correlation coefficients around 0.6).

The correlations between the concentration patterns found in the indoor air (different rooms) and the outdoor air of each building are given in table 3. It can be seen that the outdoor air significantly influenced the concentration pattern of the indoor air of the buildings that were situated in urban areas. Especially, it was shown that the correlation between the concentration patterns of the indoor and outdoor air for buildings A, D, E, and F were significant, while the correlations found for buildings B and C were weak.

The origin of each one of the compounds identified in each room was found based on the I/O ratio of the concentrations. The occurrences of the compounds that originated mainly from the outdoor air for all the rooms of each building were calculated and given as percentages in table 4. It was shown that in buildings A, E and F the outdoor air contributed significantly to the indoor air pollution, while in buildings B and C the VOCs mostly originated from indoor sources. For building D, the concentrations in the indoor air were significantly higher than the concentrations in the outdoor air, although the compounds identified in the indoor air were typical of the emissions of the cars and the concentration patterns in the indoor and outdoor air were similar, as shown in table 4. This can be explained by the fact that the measurements were done on a rainy day and outdoor pollution was low compared to other days, while the indoor pollution was high, probably due to an accumulation of pollution.

In order to specify the origin of each one of the compounds found in the audited buildings, VOCs were divided into categories based on the I/O ratio of the individual compounds in the different rooms. The most abundant compounds classified according to their origin are shown in table 5. It can be seen that from outdoor sources there are the compounds typically emitted by car exhausts, such as 2-methylpentane, 3-methylpentane, 2-methylbutane, methyl-cyclopentane, methyl-cyclohexane, while typical compounds emitted indoors come from solvent-based materials and consumer products and include naphthalene, acetone, α-pinene, limonene, octane, decane and undecane. Toluene and xylenes are emitted by various sources both indoors and outdoors.

The correlation between the concentrations of carbon dioxide and any individual VOCs was found to be very weak – similarly for the correlation between the number of persons per square meter in each room and the concentrations of the individual VOCs. This means that human activities did not give rise to sources of VOCs. Therefore, the indoor sources of VOCs must be mainly permanent sources, such as the building materials and furniture

Factor analysis was used in order to find any relationship among different compounds measured in the buildings. In this analysis, two rooms from building B were excluded (room 3 and 4), since the concentrations in these rooms were too high due to painting activities, and the proportions of the concentrations were not similar to the other rooms. It was found that the 30 most abundant compounds can be represented by 7 factors. The compounds that showed high factor loadings for the most significant factors are given in table 6. The first factor represents the most common compounds found in the outdoor and indoor air. The high loadings of these compounds mean that they were highly intercorrelated and that they were emitted from similar sources in different buildings. These compounds were mainly emitted by the exhaust fumes of cars. However, most of them were also emitted by numerous other sources, such as solvent-based materials, and therefore it is difficult to specify their origin. The other factors included compounds which have different behaviours and they were probably emitted by other sources. Nonane, decane and undecane were mainly emitted from indoor sources, such as adhesives, paints and cleaners, while limonene was emitted from consumer products or other materials.

Conclusions

In conclusion it can be stated that:

– The concentration patterns of the VOCs found in the outdoor air were influenced by the traffic in the nearby area. The concentrations of VOCs in the outdoor air were lower than the concentrations in the indoor air in all the buildings. However, the outdoor air contributed significantly to the indoor air pollution for the buildings that were situated near busy roads.

– The classification of the individual compounds according to the I/O ratio showed that many aliphatic compounds were emitted in car exhausts, while terpenes, and higher alkanes were found to be emitted mainly from indoor sources. Toluene and xylenes were found to be emitted from both indoor and outdoor sources.

– A significant intercorrelation was found among the concentration patterns of aromatic and a number of aliphatic compounds, which shows that these compounds were emitted by similar sources. Although compounds are mainly from car exhausts, they can be emitted by numerous other sources such as solvent-based materials and therefore it is difficult to specify their origin.

– A weak correlation was found between the individual VOCs and the concentrations of carbon dioxide or the number of persons per square meter in each room. This means that human activities do not result in dominant indoor sources in these buildings.

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