VOC contributions from building materials, furniture, and user equipment in low emitting and modular classrooms

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ABSTRACT

This study aimed to assess whether building materials, furniture, and user equipment are sources of pollution that would influence the need for ventilation. Between 2017-2020, measurements were taken in four regular classrooms in a low emitting school and four modular classrooms in a prefabricated school. Weekly passive sampling of volatile organic compounds (VOCs) and aldehydes were carried out in the classrooms under the following four conditions: 1) emptied, 2) furnished, 3) with furniture and user equipment, and 4) during normal use. For the first three conditions, the classrooms were measured with either no ventilation or "low" airflow rates. Total VOC (TVOC) concentrations were up to ten times higher in the unventilated classroom at the prefabricated school compared to classrooms at the low emitting school (<450 µg/m^3 for conditions 1-2). Our results show the importance of selecting low emitting building materials and proper ventilation.

INTRODUCTION

Aside from home, children spent the majority of their time at school. As a potentially vulnerable subgroup, it is essential to maintain good indoor air quality (IAQ) for children (Annesi-Maesano et al., 2013). The purpose of ventilation is to dilute indoor air pollutants. These include emissions of volatile organic compounds (VOCs) from both static sources such as building materials, furniture, equipment (Liang et al., 2014; Liang & Yang, 2013) or variable sources from the occupants and occupant-related activities (Tang et al., 2016; Weschler, 2016). In addition to ventilation, another approach is to choose construction practices and building materials that are more "green" and low emitting. The Norwegian building code specifies that a lower ventilation rate due to emissions from the building can be applied if low emitting building materials are selected. However, furniture and user equipment are also contributing pollution sources and might influence ventilation needs. This is particularly relevant in a demand-controlled ventilation strategy, where a minimum ventilation rate (V_{min}) is delivered in unoccupied spaces (Mysen et al., 2005). As the ventilation is commonly switched off during nighttime, V_{min} should be set at a rate that would dilute the build-up of emissions from the materials in the room to a satisfactory sensory level for the occupants when they enter the room (Mysen et al., 2019).

Recently, prefabricated schools are taken more and more into use while schools are being renovated or built. As a temporary solution, less emphasis might be put on selecting the materials used to construct and furnish these modular classrooms in prefabricated school buildings. This study aimed to compare the differences in VOCs between modular and low emitting classrooms and to compare how much building materials, furniture, and user equipment contribute to the VOC concentrations.

METHODS

Characteristics of the schools

The study took place at two different schools. School A is a primary school and was built according to passive-house standards. The school has concrete floor slabs covered with linoleum. The walls are timber frames with 300 mm mineral wool insulation and are clad with 13 mm plasterboard with acrylic paint. There is limited use of sealants, with no sealants visible to the rooms. School A is considered low emitting as building materials and paint were low emitting and M1-certified. Emission rates from furniture were not subject to specific demands. School A was taken in use in autumn 2016, seven months before the sampling campaign. The ventilation system is demand-controlled with CO_2- and temperature sensor in each classroom. Two classrooms on the second floor and two classrooms on the third floor were selected. The low emitting classrooms had an average floor area of 60 m^2, a height of 2.8 m, and similar furnishings. More information about the school can be found in (Holøs, Yang, Thunshelle, et al., 2019; Yang et al., 2019).

School B was prefabricated and consisted of two floors. It was taken into use in spring 2019, approximately six months before the sampling campaign. The insulated timber-frame walls are covered with painted gypsum boards and particle boards. The prefabricated walls are painted with acrylic paint. Fire stopping sealants has been used in the classrooms. The floors are particle boards covered with linoleum. Two classrooms per floor were selected for sampling. The modular classrooms had an average floor area of 60 m^2, a height of 2.8 m with similar furnishings as school A. Figure 1 shows A typical classroom in the respective schools.

Figure 1 Upper: A typical classroom in school A (with furniture and user equipment). Below: a typical modular classroom in school B (taken during furnished condition)

Study design

Measurements in the classrooms were taken under the following conditions:

- ***Emptied:*** Stripped bare of all furnishing and decorations except wall-mounted cupboards, whiteboards, and technical equipment.
- ***Furnished:*** desks, chairs, and shelves were moved back into the classroom.
- ***Furnished + user equipment:*** the classroom is kept as it is except for emptying the garbage can. The user equipment varies between classrooms.
- ***During normal use:*** no changes were done to the classroom, measured during normal use.

Table 1 shows an overview of the sampling schedule at the two schools. Due to the unexpected polishing of floors during summer 2017 at school A, the measurements had to be repeated after the summer break. This resulted in a large gap between sampling time for the different sampling conditions at school A. The conditions C1-C3 are only possible during periods when the classrooms are unoccupied, i.e., during the holidays.

Table 1 Sampling schedule for school A (low emitting) and school B (prefabricated) under four different conditions (C1=empty, C2=furnished, C3=with furniture and user equipment, C4=in normal use).

Week	No. of Room	Ventilation	C1	C2	C3	C4
School A: low emitting						
11-2017	4 + supply air	CAV				X
15-2017	2/2	Off/low			X	
40-2017	4	Off			X	
52-2017	4	Off		X		
13-2018	4	Off	X			
School B: prefabricated						
27-2019	3/1	low/off	X			
28-2019	3/1	low/off		X		
40-2019	3/1	low/off			X	
41-2019	3/1	CAV				X

Ventilation system

As the schools had different ventilation systems, the sampling conditions were not identical during normal use and with "low" airflow rates. The ventilation system at school A was operational between 6:00-23:00 including the weekends during the first year it was taken into use. Instead of using the DCV strategy, the ventilation was manually set to constant air volume (CAV) mode, and the required airflow rate was calculated based on 7 l/s of air per person. This resulted in an average airflow rate between 427 – 705 m^3/h "during normal use". For classrooms with "low" ventilation, the airflow rate was manually set to 215 m^3/h. This is the projected minimum ventilation rate (V_{min}) for school A when the DCV strategy is operated.

The ventilation was operating 24/7 during the sampling week when the ventilation condition was set to "low". School A has a building management system that logged data on room temperature, CO_2, and ventilation airflow rates.

School B has mechanical ventilation with constant air volume controls. The ventilation system is operated on either step 2 which provides ~1050 m^3/h (during normal use) or step 1 which yields ~525 m^3/h ("low"). The ventilation system is usually operational on weekdays between 06:00 – 18:00, but during the ventilation conditions "CAV" and "low", the ventilation is set to operate 24/7. School B does not log any indoor parameters, thus the airflow rates manually read from the local ventilation control system in each classroom are assumed to be representative of the airflow rates during the respective measurement weeks. An overview of the airflow rates is shown in Table 2.

The air exchange rate was also calculated using CO_2 as a tracer gas and estimated to be 0.03-0.05 h^{-1} in the unventilated classroom, ~3.2 h^{-1} when the ventilation is set on step 1, and ~6.3 h^{-1} on step 2.

Table 2 Ventilation airflow rates (mean ± standard deviation) for the respective classrooms under different ventilation conditions.

School	Classroom	Ventilation condition (m^3/h)	
		CAV	Low
A: Low emitting	A-1	628±34	
	A-2	427±44	208±17
	A-3	703±56	208±27
	A-4	628±44	
B: Prefabricated	B-1	1050	525
	B-2	1050	525
	B-3	1050	525
	B-4	1050	

Sampling and analysis

The passive samplers were placed close to the exhaust vent, approximately 1.8 m above the floor.

Volatile organic compounds were measured with passive Tenax TA air samplers, then analysed for VOCs using automated thermal desorption (TD) and gas chromatography coupled to the mass spectrometer (GC-MS). The obtained chromatograms were automatically and manually checked for identification of VOCs using commercially available and in-house libraries. The concentrations of the identified individual VOCs are expressed in "Toluene Equivalents" and ranked after concentrations. The number of identified VOCs varied between 24-30. "Total VOC" was obtained for the identified VOCs (varied between 24-37 compounds) and for the total number of compounds (TVOC) with a concentration above 1.0 µg/m^3.

Formaldehyde was sampled using the UMEX100 (SKC Ultra Ltd, UK).

Data analysis

Due to the low number of samples, only descriptive statistics were performed. The identified VOCs were categorized into several VOC groups (terpenes and terpenoids, carboxylic acids, aromatic hydrocarbons, etc) and the concentrations were summed.

RESULTS

TVOC concentrations

The average TVOC concentrations measured under different conditions for the low emitting classrooms at school A (low emitting) and the modular classrooms at school B (prefabricated) are shown in Figure 2. The highest TVOC concentrations were found in the unventilated classroom at school B (furnished: 3611 µg/m^3; empty: 2626 µg/m^3). Increasing the airflow rates to low in the modular classrooms at school B decreased the TVOC concentrations to less than 400 µg/m^3 for all three measurement conditions. In comparison, the concentration in the unventilated classrooms at school A was 397±46 µg/m^3 and 441±28 µg/m^3 for furnished and emptied, respectively.

Increasing the airflow rates to low in the modular classrooms at school B decreased the TVOC concentrations to less than 400 µg/m^3 for all three measurement conditions. In comparison, the concentration in the unventilated low emitting classrooms at school A was 397±46 µg/m^3 and 441±28 µg/m^3 for furnished and emptied, respectively.

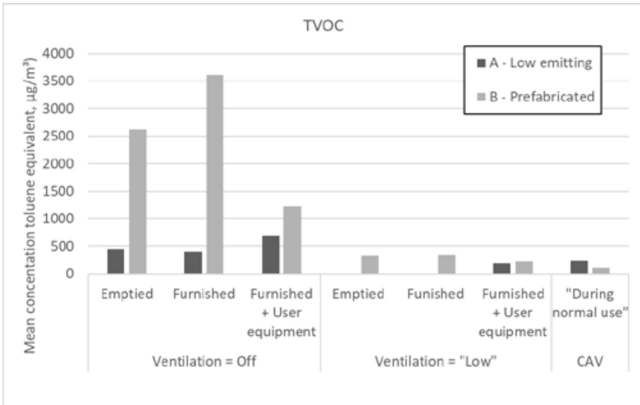

Figure 2 Average TVOC concentrations for different conditions measured in school A (low emitting) and school B (prefabricated).

During normal use, the average TVOC concentration in the low emitting classrooms at school A (230±28 µg/m^3) was twice as high as in the modular classrooms at school B (114±21 µg/m^3). The ventilation airflow

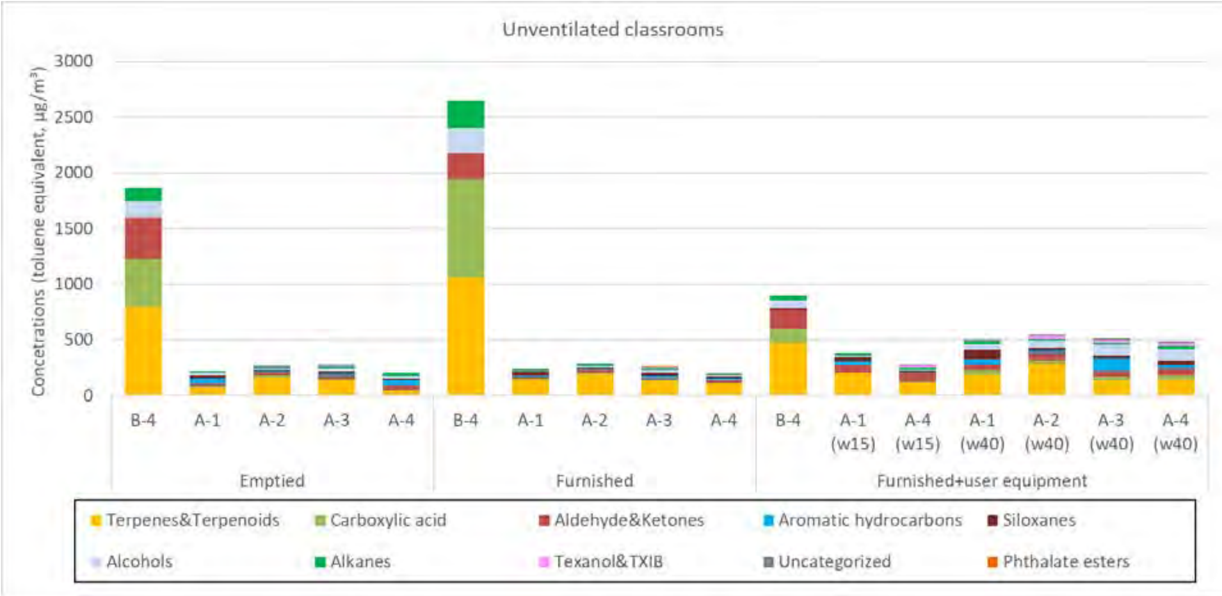

Figure 3 Distribution of VOC-groups in unventilated classrooms. Two classrooms in School A were sampled twice, in week 15 and week 40 when it was furnished and with user equipment.

rates in the modular classrooms at school B were higher than the low emitting classrooms at school A.

We observed an increase of TVOC concentrations in the unventilated classrooms at school A after adding furniture and/or user equipment, but this tendency was not seen for the modular classrooms at school B. There is a 12-week gap between the samples taken with and without user equipment in the classrooms at school B.

VOC groups in unventilated classrooms

The contributions of different VOC groups in unventilated classrooms are presented in Figure 3. At both schools, the most prevalent compound group was terpenes and terpenoids for all three measurement conditions. Alpha-pinene and 3-carene had the highest measured concentrations. Small variations in VOC groups contributing to TVOC concentrations were observed between the classrooms at school A, both when emptied and furnished. Adding user equipment into the low emitting classrooms resulted in increased concentrations of aldehydes/ketones, texanol and TXIB, and higher within-school variations in compound groups. The between-school variations in VOC groups were also more prominent. In the modular classroom at school B, carboxylic acids and aldehydes and ketones were similarly dominant VOC groups. Particularly hexanoic acid, pentanoic acid, and hexanal had high measured concentrations in the modular classrooms at school B during all three measurement conditions.

VOCs in "low" ventilated classrooms

Figure 4 presents the distribution of identified VOC groups in ventilated classrooms. Turning on the ventilation diluted the TVOC concentrations in the classrooms. In the modular classrooms at school B, carboxylic acids contributed the most to the total VOC concentrations, followed by terpenes/terpenoids, alcohols and aldehydes/ketones (with $C_{n\geq7}$).

In the low emitting classrooms at school A, in addition to aldehydes and ketones, siloxanes and TXIB contributed the most to TVOC in ventilated classrooms with furniture and user equipment.

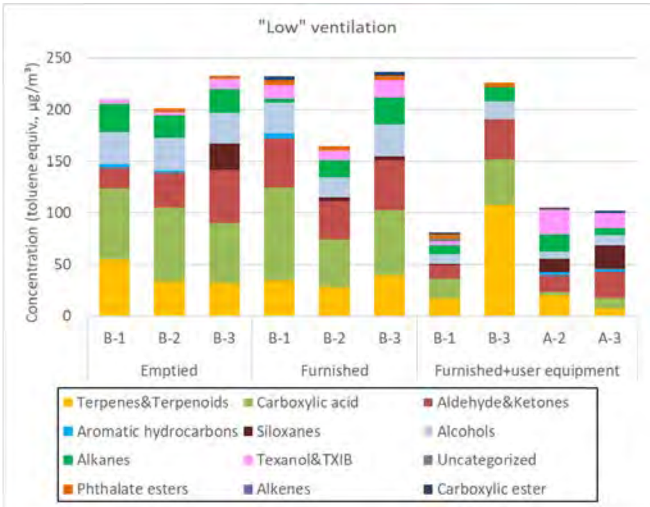

Figure 4 Distribution of VOC groups in classrooms (A: low emitting school; B: prefabricated school) ventilated with "low" airflow rates.

VOCs in classrooms during normal use

The contribution of different VOC groups in the classrooms during normal use is presented in Figure 5. Alkanes were the most prevalent VOC group in the modular classrooms at school B, followed by aldehydes and ketones. Difference in VOC-groups contributing to the total VOC concentrations are observed both within- and between-schools. In the low emitting classrooms at school A, aldehydes and ketones were the most prevent VOC group, followed by TXIB. Individual VOCs that were uncategorized also increased in the low emitting classrooms. In the supply air, aldehydes and ketones, and TXIB were the most prevalent VOC groups.

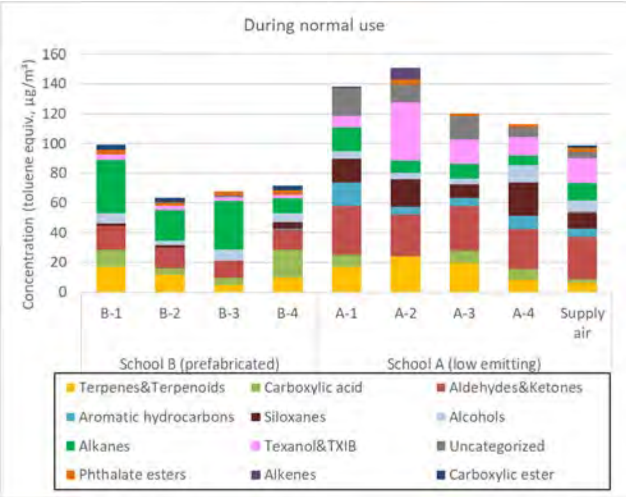

Figure 5 Distribution of VOC groups measured in classrooms (A: low emitting; B: modular) during normal usage.

Formaldehyde

The measured formaldehyde concentrations were corrected for mean concentrations measured on laboratory/field blanks, As seen in Table 3, the formaldehyde concentrations in the unventilated modular classroom exceeded the WHO guidelines for indoor air quality of 100 µg/m^3 (30-min average).

*Table 3 Overview of measured formaldehyde concentration, µg/m^3, (mean± standard deviation). * indicates not blank corrected values.*

Ventilation	Condition	School A	School B
Off	Emptied	30±13.5	129
	Furnished	48±14.6	333
	Furnished +User equipment	58±11.9	185
"Low"	Emptied		56±5.2
	Furnished		78±5.5
	Furnished +User equipment	9.6±0.8*	61±25.8
CAV	"During normal use"	15.3±1.9*	27±6.1

In the low emitting classrooms at school A, an increase in formaldehyde concentration is seen as furniture and user equipment were added. This was not observed in the modular classroom at school B.

Turning on the ventilation resulted in a substantial reduction of formaldehyde in the modular classrooms at school B. Nevertheless, the formaldehyde concentrations in the modular classrooms, ventilated and unventilated, were considerably higher than in the low emitting classrooms.

DISCUSSIONS

This study aimed to compare the differences in VOCs in classrooms at a low emitting school with those at a prefabricated school. Moreover, to assess how much building materials, furniture, and user equipment contribute to the VOC concentrations.

Low emitting versus modular classrooms

In Norway, the use of prefabricated schools has become a more common solution when schools are being renovated or built. Oftentimes, these prefabricated schools are operated for a longer period than what is usual as a temporary solution. It is thus of interest to assess whether these modular classrooms at prefabricated schools would provide equally good indoor air quality as low emitting classrooms. Our results show that both TVOC and formaldehyde concentrations measured in classrooms at the prefabricated school are substantially higher than in the classrooms at the low-emitting school. The proportion of the different contributing VOC groups in the classrooms indicate that less attention was paid to the selection of building materials, interior finishing as well as the use of solvents, sealants in the prefabricated classrooms.

Previous studies have shown that TVOC and formaldehyde concentrations are often higher in newly built or renovated buildings and the initial off-gassing phase from buildings materials can last for at least 2 years (Holøs, Yang, Lind, et al., 2019; Kang et al., 2017). A comparison of the measurements in the modular classrooms done 6 months (week 28) and 9 months (week 40) after the prefabricated school was taken into use did indeed show a rapid decline of TVOC and formaldehyde concentrations. Nevertheless, the TVOC concentration measured in the modular classroom at the prefabricated school was more than twice as high compared to the measurements done in the low emitting classrooms at approximately 9 months (Figure 3, week 15 measurements) after it was taken into use. Often, the time between these prefabricated schools to be installed till they are taken into use is short, thus the occupants of these classrooms might be exposed to high pollutant levels.

The measurements taken in unventilated classrooms over a week are not representative of the concentrations during occupancy. Nevertheless, as the ventilation is normally turned off during the night, our results might provide good indications of the concentrations the occupants are exposed to when they enter the classrooms in the morning. Ventilating with low airflow rates in the modular classrooms at the prefabricated school diluted the TVOC concentrations considerably, however, the formaldehyde concentrations (52-82 µg/m^3) were still somewhat high compared to the low emitting classrooms. This shows the importance of selecting low emitting building materials and proper ventilation strategies. To ensure that the prefabricated schools comply with requirements regarding low emitting building materials, it might be necessary to measure VOCs and aldehydes when they are taken into use. High ventilation rates, in this case, an airflow rate of 1050

m^3/h, are recommended for when the classrooms are in use. Also, to dilute the pollutant levels accumulating during the nighttime with no ventilation, it is recommended to start ventilating a few hours before the occupants enter the classrooms.

Contributions from furniture and user equipment

The measurements in the same classroom during different conditions were not taken under identical circumstances (i.e., school age, ventilation rate), making it difficult to compare results. However, considering that certain VOC groups often arise from similar sources, we can get good indications of the contributions from furniture or user equipment.

The classrooms had similar furnishings, thus adding only the furniture back into the classroom resulted in increased TVOC concentration for the unventilated modular classroom at the prefabricated school. However, when the classrooms were ventilated, the proportion of different VOC groups changed, probably due to reactions between ozone and individual compounds (Weschler & Carslaw, 2018; Wolkoff, 2020). The same tendencies can be seen when user equipment was added. Since the classrooms were occupied by pupils from different age groups, the resulting emissions from user equipment, ranging from books, art supplies, various drawings on the walls, etc, would differ accordingly.

Users and user equipment are variable emission sources and could thus influence the perceived air quality in the room. Several studies on ventilation and PAQ have been done at school A (Holand et al., 2019; Holøs, Yang, Thunshelle, et al., 2019; Mysen et al., 2019). The variations in PAQ-scores were influenced by the classroom and indicated that the minimum ventilation rates need to be adjusted according to the user groups and/or user equipment. The classrooms, where extra pollution sources were introduced into selected classrooms, required higher V_{min} (Holøs, Yang, Thunshelle, et al., 2019; Mysen et al., 2019). During the measurement week "in normal use", a study on PAQ and odor intensity in classrooms A1- A3 was done (Holand et al., 2019). The results of PAQ assessment were consistent with the VOC measurements, as the classrooms with the highest VOC-concentrations (A1 and A2) received the lowest PAQ-scores. However, the classroom with the lowest measured TVOC concentrations (A3) received the lowest average odor intensity score and there were in general complaints about unpleasant odors in this classroom. We are not certain about the causes behind these odor complaints and assessing the individual VOCs detected in each classroom is beyond the scope of this study.

In the low emitting classrooms, the pollutant levels measured in this study were generally low compared to the modular classrooms at the prefabricated school, and a low ventilation rate (218 m^3/h or 1.0 l/s per m^2) was sufficient in diluting the concentrations to an acceptable level. After the initial off-gassing phase in low emitting classrooms, the ventilation strategy, particularly for a DCV strategy, V_{min} should perhaps be controlled according to the sensory impressions of the occupants.

CONCLUSIONS

We found that the concentrations of TVOC and formaldehyde measured in modular classrooms at a prefabricated school are substantially higher than in the classrooms at a low emitting school. To ensure that the prefabricated schools comply with the requirements of low emitting building materials, it might be necessary to measure VOCs and aldehydes when they are taken into use. High ventilation rates, in this case, an airflow rate of 1050 m^3/h are recommended for when prefabricated schools are in use and the ventilation in the classrooms should be turned on a few hours before occupancy.

ACKNOWLEDGEMENTS

This study was carried out within the BEST VENT project funded by the Research Council of Norway EnergiX program under Grant 255375/E20 together with the industry partners: Undervisningsbygg Oslo KF, GK Inneklima AS, DNB Næringseiendom AS, Erichsen & Horgen AS, Multiconsult AS, Interfil AS, Camfil Norge AS, Swegon AS, Belimo Automasjon Norge AS, Toma Eiendomsdrift AS, Norsk VVS Energi- og Miljøteknisk Forenings Stiftelse for forskning.

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