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Formaldehyde in High School Classrooms

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Formaldehyde in High School Classrooms

by

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Abstract

Formaldehyde in High School Classrooms

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Schools have a unique place in the fabric of America. Yet there is growing evidence that poor indoor air quality (IAQ) leads to increases in student illnesses and absenteeism, decreases in academic performance, and increased upper-respiratory problems in teachers. Past studies of IAQ in schools have been deficient in many ways. Only four of 735 published papers have involved actual measurements in high schools in North America. There has been little progress in determining the actual agents responsible for adverse effects when ventilation is inadequate. Few studies have focused on irritating oxygenated VOCs (OVOCs) and their sources. The objectives of this thesis were to better understand the levels and temporal variation of one OVOC, formaldehyde (HCHO), in 46 high school classrooms in Central Texas, to explore differences in HCHO concentrations between portable and traditional classrooms, and to compare differences between two HCHO measurement methods. Results indicate that HCHO concentrations in high school classrooms are in the range of those found in past school studies. There were statistically no differences in HCHO concentrations between portable and

traditional classrooms. Formaldehyde concentrations at night exceeded those during the occupied day as a result of mechanical systems being switched off at night to conserve energy. Finally, when HCHO concentrations were above 10 ppb, a continuous colorimetric HCHO analyzer compared favorably with a more standard DNPH-based passive sampler. This finding is important in that the continuous analyzer can provide valuable information regarding temporal variations in HCHO, which may lend knowledge regarding the role of building-related factors on HCHO concentrations and control.

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INTRODUCTION

School buildings are integral to the American education system. Every school day one in five Americans spends time in a school building [1]. This includes 55 million children and three million teachers and staff spread across 130,000 K-12 schools [1]. Yet inadequate maintenance and operation budgets at many schools lead to environmental and health challenges [2]. Connections between poor indoor air quality in schools and student illnesses, as well as decreases in academic performance, are mounting [3–6].

One important and ubiquitous indoor air pollutant is formaldehyde (HCHO). The sources of this pollutant in classrooms include pressed wood products used for cabinetry, furniture, and in wall cavities, whiteboard markers, paints, and reactions involving ozone and unsaturated organic compounds [7–9]. Formaldehyde concentrations vary spatially and over time depending on variations in air exchange rate, temperature, relative humidity, and source age [7,9].

There are multiple health concerns associated with exposure to formaldehyde in air. The acute effects are sensory irritation (eyes and upper airways), respiratory challenge (asthma and allergy), and eczema [10,11]. Formaldehyde odors can also deteriorate perceived indoor air quality; however the odor threshold has a wide and individual-specific range, i.e., 50 to 500 parts per billion (ppb) [9,10]. Formaldehyde is classified as a possible human carcinogen by the EPA and is listed as carcinogenic to humans by the International Agency for Research on Cancer (IARC), with the potential to induce tumors in the nasal region [11–15].

There have been several studies of student exposure to formaldehyde in the United States and Europe [16–19]. These studies have included measurements of the spatial variability and concentrations of formaldehyde in permanent and portable classrooms [19–21].

In this paper, results of a field study focusing on formaldehyde concentrations in portable and permanent high school classrooms over multi-day periods are presented. An important objective of the study was to better understand how formaldehyde concentrations in classrooms changes over occupied and diurnal periods. To that end, we employ a new and low-cost semi-continuous formaldehyde analyzer and compare results against passive (integrated) formaldehyde samplers.

The methods and results described in this paper are associated with one part of a larger study of indoor environmental quality in high schools entitled The Healthy High School PRIDE (Partnership in Research on InDoor Environments) study. That study involves seven high schools in Central Texas. The schools were selected for an intensive analysis of formaldehyde and a wide range of other indoor environmental quality parameters.

METHODOLOGY

Field sampling was completed in seven schools over two years, in four sequential phases (I-IV); phases I and II were completed from September through November and phases III and IV were completed from February through April. Four-day sampling events were completed in up to 30 classrooms during each phase. A total of 46 different classrooms, including eight portable classrooms across four schools, were sampled over the two-year period. The sampled classrooms were selected based on availability, teacher participation, and input from facilities personnel in conjunction with the researchers' requests. There were several types of heating, ventilating and cooling (HVAC) systems in the schools, including single zone on/off, multi-zone VAV (with and without reheat), chilled water penthouse, and wall air conditioning (AC) (for all portable classrooms).

Formaldehyde samples were collected using two methods, a four-day integrated passive sampler and a 30-minute average semi-continuous formaldehyde analyzer. At the request of teachers, HCHO samplers were typically placed on the edges of classrooms, i.e., as opposed to the middle of the classroom. A summary of the sampling matrix is presented in Table 1.

Table 1. Sampling Matrix

Sampling Event	No. School	No. Classrooms including. portables	No. Portable	Sampling DNPH	Sampling FMM
Phase I	7	29	7	29	12
Phase II	7	30	7	30	8
Phase III	5	30	6	30	2
Phase IV	5	30	6	30	15

Sampling Methodology

A summary of the sampling methodology is provided in Table 2. Four-day integrated samples were collected using passive samplers, containing tape coated with 2,4-dinitrophenylhydrazine (DNPH) (SKC UMEx 100 sampler). During each sampling event a sampler was removed from its aluminized envelope, opened, and placed on a sample stand located in each classroom. After four days the sampler was retrieved from the sample stand and closed. The sampler was placed in its aluminized envelope, the envelope sealed, and placed in cold storage (temperature < 4°C) until analysis. Samples were extracted and analyzed using high performance liquid chromatography with UV-detection (HPLC-UV). The analytical method was developed using the guidance presented in OSHA Method 1007 [22]. A duplicate sample was collected for 1/3 of the samples, and a laboratory and field blank for every 15 samples. The passive samplers where used to sample a total of 46 different classrooms across all four phases. A total of 159 passive field samples (40 of 159 samples were duplicates), 11 field blanks, and 11 laboratory blanks were collected and analyzed.

Table 2. Instrumentation

Measurement	Time Resolution	Instrument	Detection Principal	Uncertainty	Detection Limit	Resolution
Formaldehyde	Integrated 4 day	DNPH	HPLC	+/-30%	200 ng	
	Continuous 30 min	FMM	UV absorption	+/- 10% at 40, 80, 160 ppb	20 ppb[a]	1 ppb

[a] Readings below 20 ppb were provided by the manufacturer. Uncertainty below 20 ppb assumed to be +/- 4ppb.

A Formaldehyde Multimode Monitor (FMM) (Shinyei Technology Co., LTD) was used to measure 30-minute average concentrations of formaldehyde continuously over the four-day sampling period in approximately 1/3 of the classrooms in the Healthy High School PRIDE study. The FMM operates via a colorimetric reaction between formaldehyde and β-diketone on a porous glass. The FMM measures the colorimetric change using a 415 nanometer (nm) light-emitting diode (LED). The FMM was used for 37 sampling events in 23 different classrooms.

The manufacturer-specified detection range for the FMM is 20 to 1000 ppb. However, due to special software provided by the manufacturer, the reported lower detection range for our devices was 11 ppb. When concentrations were below 11 ppb, 5 ppb was assumed as the concentration, unless otherwise specified. The FMM uncertainty is specified by the manufacturer (Shinyei Technology Company, LTD) as +/- 10 percent (%) above 40 ppb, and by one distributor (GrayWolf Sensing Solution, LLC) as +/-4 ppb below 40 ppb[23]. Temperature and relative humidity were measured by the FMM. The temperature detection range was 0 to 60 ºC (+/- 1.5 ºC) and the relative humidity detection range was 10 to 90% RH (+/- 3.0% RH).

Data Analysis

To analyze differences in formaldehyde concentrations between phases I-IV, the Dunnett Test was used to compare the mean formaldehyde concentration for one sampling phase to the other sampling phases. Differences between the mean for portable and permanent classrooms during each phase were tested using the Wilcoxon Rank Sum test and the t-test. Occupied and unoccupied classroom formaldehyde concentrations were compared using the t-test. All tests were performed to a 95% confidence level.

RESULTS & DISCUSSION

The passive samplers were analyzed to compare sampling phases (I-IV) (Figure1). The mean formaldehyde concentrations in classrooms for phases I-III were not statistically different from each other, while the mean concentration for phase IV was lower than the other three phases. This was likely due, at least in part, to the building managers of five high schools having increased fresh air ventilation rates between phase III and IV. In addition, a total of 16 classrooms that had not been previously included in the study were monitored during phases III and IV, and these may have simply had lower formaldehyde concentrations than previous classrooms in the study.

The sampling phases were analyzed for differences in mean formaldehyde concentrations between permanent and portable classrooms (Figure 2). A Wilcoxon Rank Sum test for independent samples was conducted for each visit to assess the difference between the mean formaldehyde concentrations for permanent and portable classrooms. The mean formaldehyde concentrations between portable and permanent classrooms were statistically different in phase II, during which the mean formaldehyde concentration in permanent classrooms was higher ($p=0.005$) than those for portable classrooms. There was not a statistically significant difference in mean formaldehyde concentrations in the two types of classrooms for other phases.

The formaldehyde concentrations determined based on passive samplers (mean = 23 +/- 8.45 ppb [standard deviation], range = 5-47 ppb) across all sampling events in this study are in the range of those cited by others for classroom environments [16, 19, 24–27].

For this study, 100% of the 4-day average formaldehyde concentrations based on passive samplers were below the World Health Organization (WHO) guidance of 80 ppb [10], 40% of the classrooms were below the National Institute for Occupational Safety and Health (NIOSH) recommended exposure limits (REL) of 16 ppb [13], while less than 8% of the classrooms were at or below the California EPA limit of 9 ppb [28].

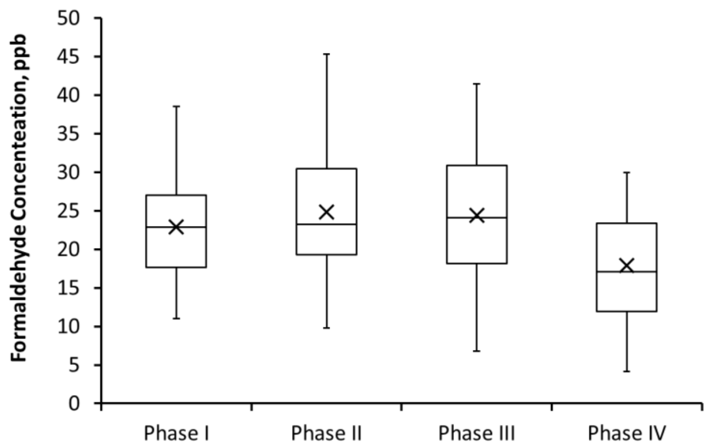

Figure 1. Quartile analysis of formaldehyde concentrations by phase of study.

The boxplot depicts maximum (upper whisker), third quartile, median (line), mean (cross), first quartile, and minimum (lower whisker) formaldehyde concentrations for each sampling phase.

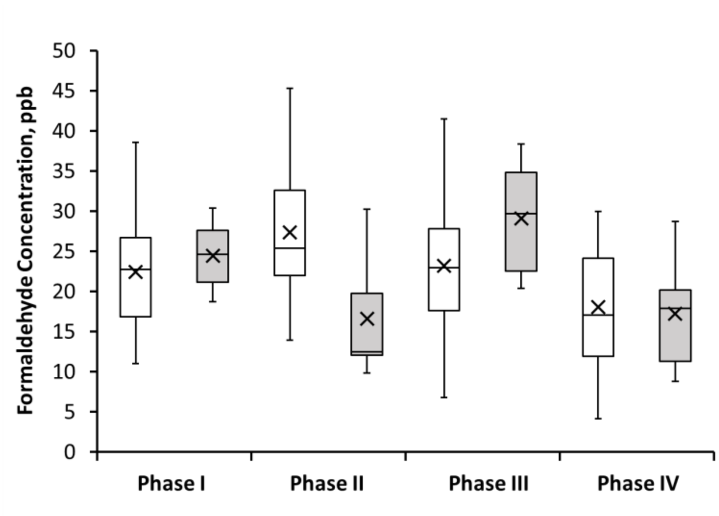

Figure 2. Boxplot Quartile Analysis of Permanent vs. Portable Classrooms

The boxplot depicts maximum (upper whisker), third quartile, median (line), mean (cross), first quartile, and minimum (lower whisker) formaldehyde concentrations for each sampling session and classroom type. The portable classroom data are shaded. The total number of permanent and portable classrooms sampled were 22 and 7 (Phase I), 23 and 7 (Phase II), 24 and 6 (Phase III), and 24 and 6 (Phase IV).

Temporal variation of formaldehyde Concentration

The FMM allowed an evaluation of time-variant formaldehyde concentrations at thirty-minute intervals. A typical pattern observed in classrooms indicates an increase in formaldehyde concentration overnight when the HVAC system is switched off, followed by a sharp decrease during the morning when the system is switched back on (Figure 3).

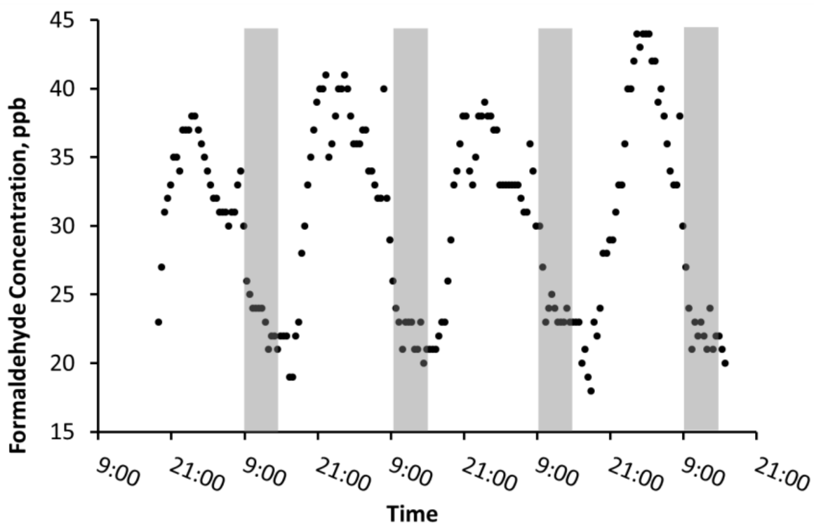

Figure 3. Example Time Series for Formaldehyde Concentration in a Classroom.

The highlighted grey area denotes the occupied day when the HVAC system is on.

Comparison of Sampling Methodologies

A comparison of four-day time-integrated formaldehyde concentrations for co-located passive samplers and FMMs is presented in Figure 4. A total of 30% of the four day average FMM values were below 10 ppb and are omitted from the comparison. The linear R^2 value for the relationship is 0.6, and the average absolute percent difference is 26% with a standard deviation of +/- 22%. While the comparison of passive sampler and time-integrated FMM results is not perfect, there is clearly a positive relationship that suggests that the FMM can be used to reasonably estimate time-variant formaldehyde concentrations.

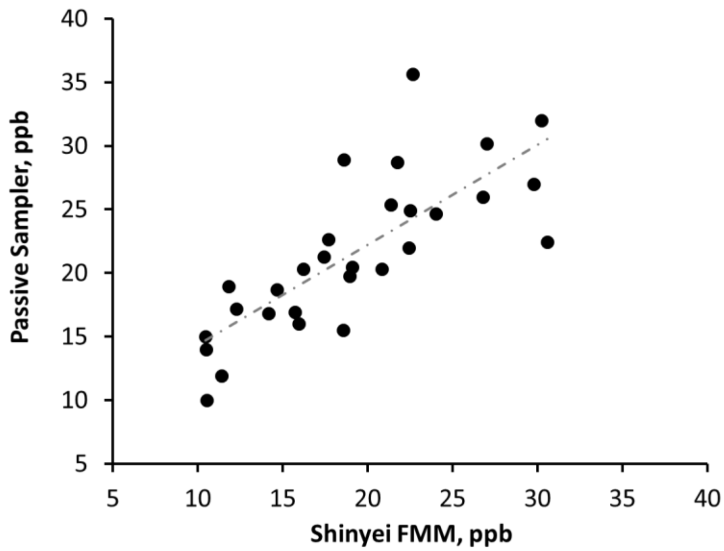

Figure 4. Parity plot of FMM vs. Passive sampler

The y axis represents the formaldehyde concentration as measured using passive samplers. The x axis represents the average formaldehyde concentration as measure using an FMM.

Analysis of Four-Day Average versus Occupied Day Average Concentrations

The passive samplers were averaged over a two-year period to obtain an average concentration for each of the 46 classrooms in which they were placed. The FMM were collocated with passive samplers in 24 of the classrooms. The classrooms were sampled at least once and at most four times. When only one sample event was available for a classroom, that point was used. These averages were then plotted against the FMM averages taken during the occupied day for the same classrooms, typically 9 a.m. to 4 p.m. on Tuesday through Friday (Figure 5).

The range of formaldehyde concentrations in classrooms with paired sample data was 6 to 38 ppb. Formaldehyde concentrations in portable classrooms were distributed throughout the data set and ranged from 15 to 31 ppb. Occupied day formaldehyde concentrations were typically below those based on passive sampler measurements in the same classroom. The four-day mean formaldehyde concentration based on passive samplers (all hours) and FMM (occupied day only) were 22.2 (standard deviation +/- 7.0) and 12.7 (standard deviation +/-5.5), respectively. The occupied day mean was significantly lower than the four day mean based on the passive sampler (p=0.00002). To control for FMM values below 10 ppb, a t-test was performed on the 15 FMM rooms with less than 10% of values below 10 ppb (p=0.001).

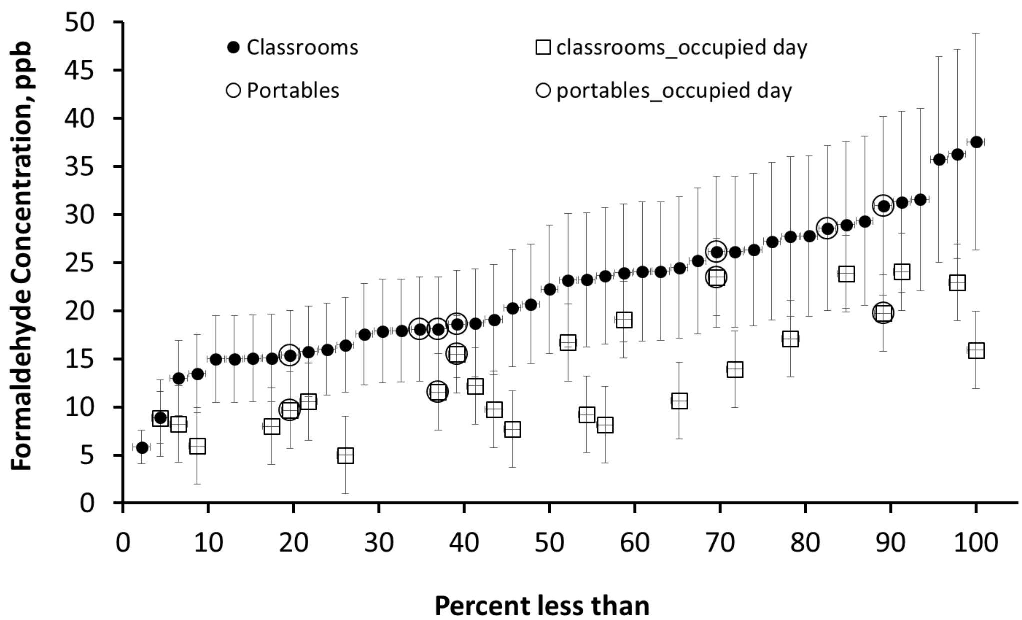

Figure 5. Cumulative distribution 4-Day Averages v. Occupied Day Averages

Open rectangles are formaldehyde concentrations based on the FMM for the occupied day only. Error bars on the FMM data represent how the formaldehyde concentration would change if readings below 11ppb were treated as 10 ppb (upper whisker) or 0 ppb (lower whisker), i.e., instead of 5ppb. Points with larger error bars had a larger percentage of data below 11 ppb. Samples collected in portable classrooms are circled. FMM data points for a particular classroom are vertically aligned with its passive sample counterpart.

Conclusions

A two-year study of formaldehyde concentrations in portable and permanent (traditional) classrooms within seven high schools was completed in Central Texas. The formaldehyde concentrations observed in these schools were consistent with those found in other studies, with generally reported mean formaldehyde concentrations below 50 ppb [16, 19 ,24–27]. In this study, no difference in formaldehyde concentrations was found between permanent (mean 23 ppb +/-8 ppb, range 8-45 ppb) and portables (mean 22 ppb +/-8 ppb, range 9-38 ppb) classrooms. However relative concentrations of formaldehyde were observed to vary based on building operations and time of the year.

Higher formaldehyde concentrations were found at night when ventilation systems were off, a finding consistent those reported by others [24,25]. As a result, occupied day concentrations were generally below unoccupied day concentrations. Importantly, for such scenarios assessments based on 24-hour or multi-day passive sampling may significantly overestimate student exposures to formaldehyde.

When concentrations were above 10 ppb the FMM and passive samplers were typically within the error of the two methods. The FMM was useful in providing time resolved formaldehyde concentrations to understand how building operation and environmental conditions might affect room concentrations.

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