A Study on the Emission Characteristics and Prediction of Volatile Organic Compounds from Floor and Furniture

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ABSTRACT: In this study, indoor VOCs concentration emitted from floor and furniture was measured after the installation of floor and furniture in a real residence. With the measured data, prediction method and predication equations for indoor concentration of each VOCs and BTEX were developed. The following conclusions were drawn from this study. First, according to the predicted results of concentration decrease of BTEX (benzene, toluene, ethylbenzene, m,p,o-xylene) after the installation of floor in a real residence, prediction equation can be expressed using exponential function. Second, in case of floor, more reliable prediction equation can be obtained by using cumulative value of indoor concentration than by using just hourly measured value directly. Indoor concentration of benzene can be expressed as $y=408.52(1-e^{-0.0031\times \text{time}})$ with R^2 of 0.94 which is significantly high value. Third, toluene showed the highest concentration in case of furniture installation indoors, and it needed the longest time for concentration decrease. However, other substances except toluene showed constant concentration throughout the measurement period. Fourth, in case of furniture installation indoors, prediction equation of toluene concentration decrease is estimated to be $y=3616.3\times e^{(-0.1091\times \text{time})}+513.96\times e^{(-0.0006\times \text{time})}$ with R^2 of 0.95 which is significantly high value.

Nomenclature

A	: source area [m^2]
C, C_s	: indoor concentration and the concentration of pollutant among the incoming air [μg/m^3]
$C_{b,t}$	: blank concentration at time t [μg/m^3]
C_t	: VOCs concentration at time t [μg/m^3]
EF_a	: VOCs emission factor per unit area [μg/m$^2\cdot$h]
ER	: emission rate [μg/h]
k	: first-order decay rate constant
L	: loading factor [m^2/m^3]
N	: air change rate [N/h]
t	: time [h]
t_{max}	: the time of maximum concentration [h]
V	: interior volume [m^3]

Subscripts

0	: initial state
s	: steady state

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1. Introduction

Recently, indoor air quality (hereafter IAQ) has become one of the most significant issues for the health of occupants and the comfortable indoor environment. In particular, use of the building materials with high air-tightness has greatly improved the performance on insulation and air-tightness in newly constructed buildings. In addition, applications of various construction methods for energy conservation have also contributed to the enhancement of the insulation and air-tightness performance. However, the IAQ becomes considerably degraded when the residential and indoor pollutants from petrochemical building materials are present. The reason is because these composite materials for buildings tend to emit slowly a substantial amount of hazardous air pollutants (hereafter HAPs) such as volatile organic compounds (hereafter VOCs) over a long period of time.

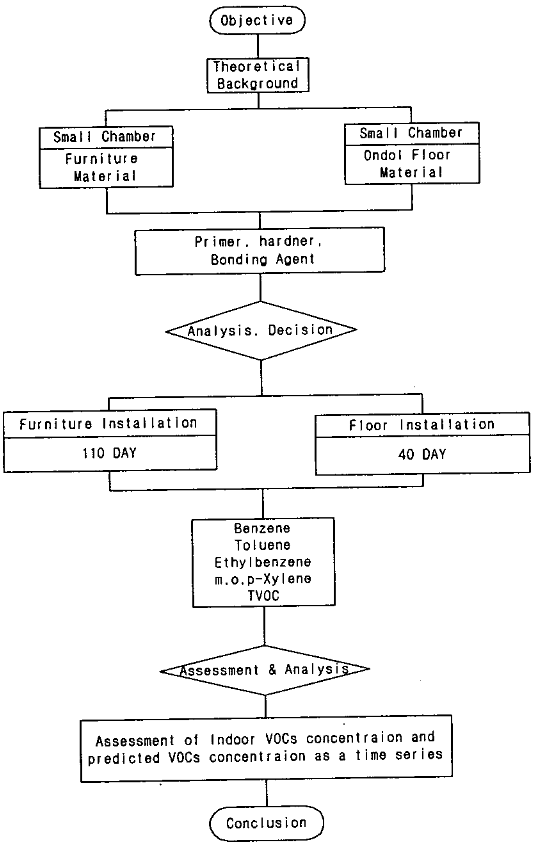

Fig. 1 Research process.

This research has been motivated by the following two academic and practical reasons. First, previous research on IAQ has focused on the effects of ventilation, particles, CO and CO_2, but not much research has been done about the issue of VOCs. In particular, a great deal of research has been recently conducted about the assessment of VOCs' concentration and there emission rates, but the topic on the prediction and assessment of the decrease in indoor concentrations has been relatively neglected.

Moreover, most houses in Korea have used Ondol heating system, wooden floor, and wooden furniture for a long time. The problem is that one of the materials for the Ondol system is petro-chemical paints, which have been also used on the surface of the furniture. The risk from the use of petro-chemicals is the slow emission of the considerable amount of indoor pollutants.

Thus, the objective of this study is to measure the indoor VOCs concentration, especially BTEX (Benzene, Toluene, Ethylbenzene, and m,p,o-xylene), from Ondol floor and large-sized indoor furniture. Moreover, the prediction method and equation are developed based on the VOCs concentration data from floor and furniture in real residence. The process of this research is presented in Fig. 1.

2. Theoretical background

VOCs emission factor refers to the emitted amount of pollutant per unit area and unit time, expressed as Eq. (1).

$$\begin{aligned} EF_a &= \frac{(C_t - C_{b,t}) \times Q}{A} \\ &= \frac{(C_t - C_{b,t}) \times NV}{A} \\ &= (C_t - C_{b,t}) \times q \\ &= (C_t - C_{b,t}) \times \frac{N}{L} \end{aligned} \tag{1}$$

Emission Factor and Emission Rate[1] are related as follows:

$$ER = A(EF) \quad (2)$$

If the emission pattern for a source can be approximated by a mathematical expression, the emission factor can be estimated by fitting a proper chamber model to the time-concentration data by means of non-linear regression.

For a constant source with emission factor EF the following mass balance equation holds:

$$\frac{dC}{dT} = L(EF) - NC \quad (3)$$

Given the initial conditions: $t=0$ and $C=0$, the solution to C is:

$$C = \frac{L(EF)(1-e^{-Nt})}{N} \quad (4)$$

The unknown parameter EF can be estimated by fitting Eq. (4) to the chamber concentration data. Moreover, the first-order decay source model is one of the most commonly used empirical models for decaying emissions:[1]

$$EF = (EF_0)e^{-kt} \quad (5)$$

The corresponding chamber model is

$$\frac{dC}{dt} = L(EF_0)e^{-kt} - NC \quad (6)$$

Which has the following solution under the condition of $t=0$ and $C=0$

$$C = \frac{L(EF_0)(e^{-kt} - e^{-NT})}{(N-k)} \quad (7)$$

A good initial estimate for k in Eq. (7) is:

$$k = (N)e^{(k-N)t_{max}} \quad (8)$$

3. Experimental methods

Two kinds of experiment were conducted in this study: material experiment for basic material of floor and furniture, and application experiment in a real residence.

Application experiment in a real residence was conducted for 100 days after the installation of furniture and for 40 days after the installation of floor. Primer, smoothener for smooth surface, painting and attachment of paints, hardener for surface finishing, and three adhesives were selected as the subjects of basic material experiment of floor.

Measurement results are expressed with concentration of each substance (benzene, toluene, ethylbenzene, m,p-xylene, and o-xylene) and TVOC emission factor. Figures 2 and 3 present the installation of floor and furniture respectively.

Table 1 and Fig. 4 present the overview and the plan of the measurement room respectively. In both cases of floor and furniture installation,

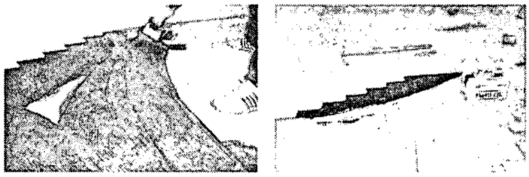

Fig. 2 The installation of floor.

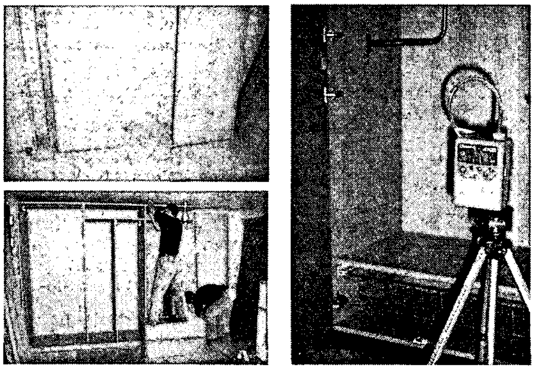

Fig. 3 The installation and measurement of furniture.

Table 1 Overview of measurement room

	Floor installation (W×D×H mm)	Furniture installation (W×D×H mm)
Size	3,000×4,500×2,150	4,200×3,600×2,300
Installed area	2,800×4,300	4,000×660×2,300
Loading factor	0.465 m^2/m^3	0.294 m^2/m^3
ACH	0.5~0.7	
Time interval and measurement period	1~10 days, 15, 20, 25, 30, 35, 40 days	1, 2, 3, 6 hours, 1~10 days, 15, 20, 25, 30, 35, 40 days
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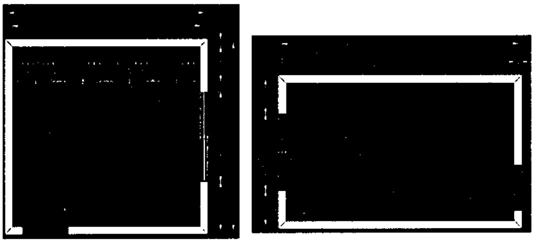

(a) Furniture installation (b) Floor installation

Fig. 4 Plan of measurement room.

mechanical heating and cooling systems were not operated. In case of floor experiment, maximum and minimum temperature were 28℃ and 17℃ respectively during the measurement period. Maximum and minimum relative humidity were 63% and 43% respectively. In case of furniture installation, maximum and minimum temperature were 29.5℃ and 14.3℃ respectively. Maximum and minimum relative humidity were 67% and 42% respectively.

4. Analysis of experimental results

4.1 Experimental results of floor

Figure 5 presents the time-dependent concentration variation of VOCs in a real residence with floor installed, and Fig. 6 presents the cumulative concentration of VOCs emitted from the floor.

As presented in Figs. 5 and 6, indoor concentration of BTEX (benzene, toluene, ethylbenzene, m,p-xylene, and o-xylene) decreases rapidly until 100 hours, but begins to decrease gradually after 100 hours. However, in case of toluene, initial trend was similar to other substances, but the concentration rose rapidly after 300 hours and then decreased again. This is considered to be

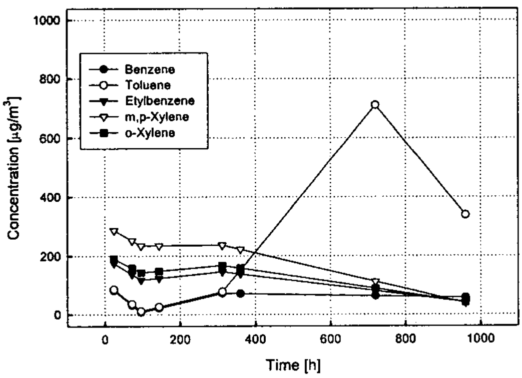

Fig. 5 Concentration variation of each substance (floor installation).

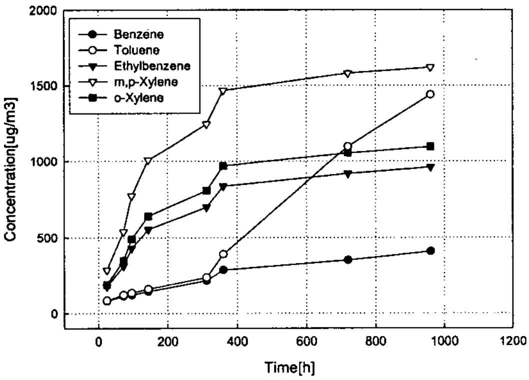

Fig. 6 Cumulative concentration variation of each substance (floor installation).

the result of the effect of adhesive used in floor installation rather than effect of the floor itself, indicating that adhesive gradually affects indoor concentration through hardening process.

4.1.1 Prediction of concentration decrease

Figure 7 presents the predicted results of ethylbenzene concentration decrease after the floor installation. According to the predicted results by converting y-axis into log value for exponential function, prediction equation for ethylbenzene concentration is estimated to be $y = 159.26 \times e^{-0.0010 \times \text{time}}$ with R^2 of 0.72 which is relatively high value. Moreover, from the prediction of m,p-xylene concentration in the similar way to ethylbenzene, prediction equation can be expressed as $y = 292.7 \times e^{-0.0013 \times \text{time}}$ with R^2 of 0.87 which is considerably high value, indicating that indoor concentration can be properly predicted in real residences.

Indoor concentration of o-xylene can also be predicted using exponential function. Prediction equation is estimated to be $y = 184.5 \times e^{-0.0010 \times \text{time}}$ with R^2 of 0.77 which is lower value than the case of m,p-xylene, but it can be used in real residences without any problems. Figure 10 presents predicted results of concentration decrease of xylene. Prediction equation can be estimated to be $y = 476 \times e^{-0.0012 \times \text{time}}$ with R^2 of 0.98 which is considerably high value. Predicted results of indoor concentration decrease are presented in Table 2.

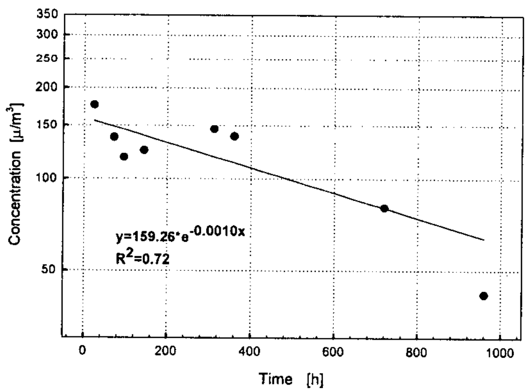

Fig. 7 Prediction of ethylbenzene concentration decrease.

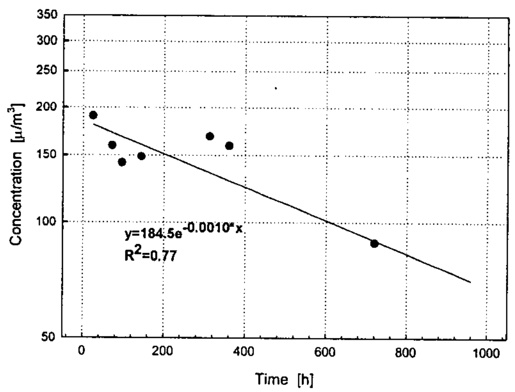

Fig. 9 Prediction of o-xylene concentration decrease.

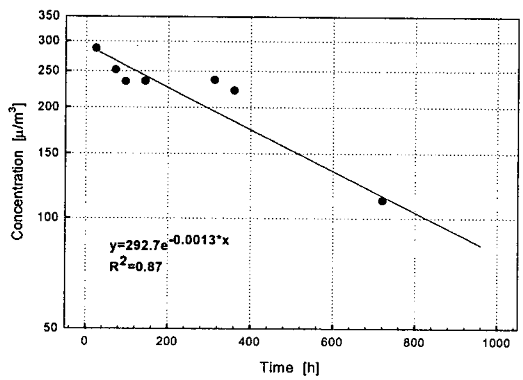

Fig. 8 Prediction of m,p-xylene concentration decrease.

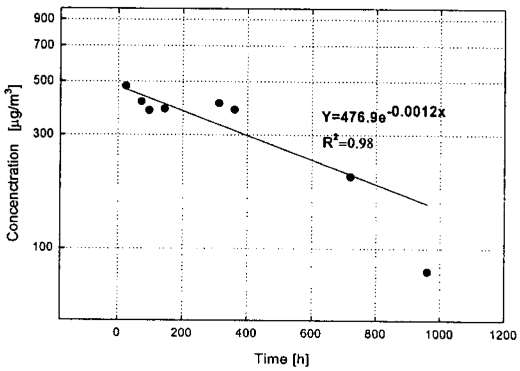

Fig. 10 Prediction of xylene concentration decrease (floor installation).

Table 2 Prediction of concentration and cumulative concentration decrease

Prediction method	Substance	Prediction equation	R^2
Concentration decrease	Ethylbenzene	$159.26e^{-0.0010\times time}$	0.72
	Xylene	$476.9e^{-0.0012\times time}$	0.98
	m,p-xylene	$292.7e^{-0.0013\times time}$	0.87
	o-xylene	$184.5e^{-0.0010\times time}$	0.77
Cumulative concentration	Benzene	$408.52(1-e^{-0.0031\times time})$	0.94
	Toluene	$1444887937(1-e^{-0.0031\times time})$	0.94
	Ethylbenzene	$933.25(1-e^{-0.0059\times time})$	0.98
	Xylene	$2661.9(1-e^{-0.0062\times time})$	0.99
	m,p-xylene	$1588.9(1-e^{-0.0064\times time})$	0.98
	o-xylene	$1073.87(1-e^{-0.0059\times time})$	0.98
	BTEX	$5433.55(1-e^{-0.0038\times time})$	0.97

4.1.2 Prediction of cumulative concentration

In order to predict indoor concentration of benzene after the floor installation, prediction form can be modified as presented in Fig. 11. benzene concentration is predicted using cumulative value not just using hourly measured data directly. As a result, time-dependent concentration variation can be expressed as $y=408.52(1-e^{-0.0031\times time})$ and chi-square was 0.94. Moreover, in case of toluene, predicted results are presented in Fig. 12 with R^2 of 0.94 which can be considered as high value. In case of ethylbenzene, predicting cumulative concentration was also available; chi-square was 0.98 which is significantly high value and prediction equation can be expressed as $y=933.28(1-e^{-0.0059\times time})$.

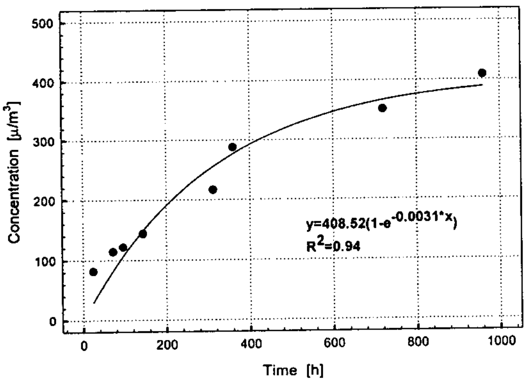

Fig. 11 Prediction of benzene cumulative concentration.

Figures 14 and 15 present the predicted results of indoor concentration of m,p-xylene and

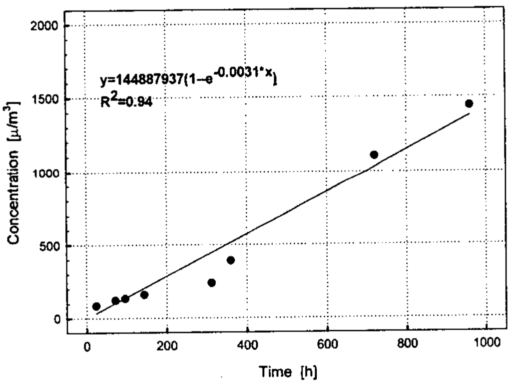

Fig. 12 Prediction of toluene cumulative concentration.

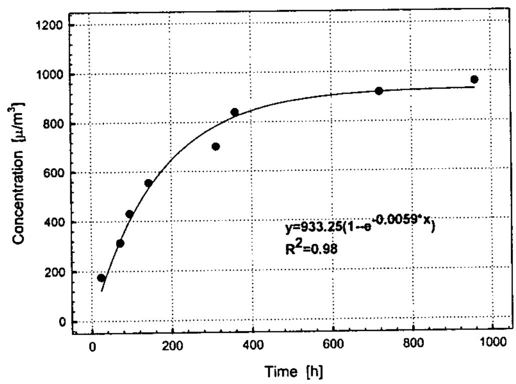

Fig. 13 Prediction of ethylbenzene cumulative concentration.

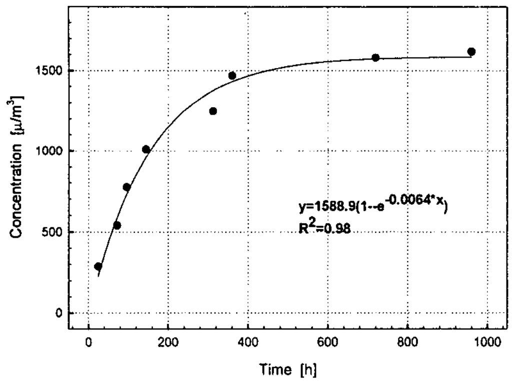

Fig. 14 Prediction of m,p-xylene cumulative concentration.

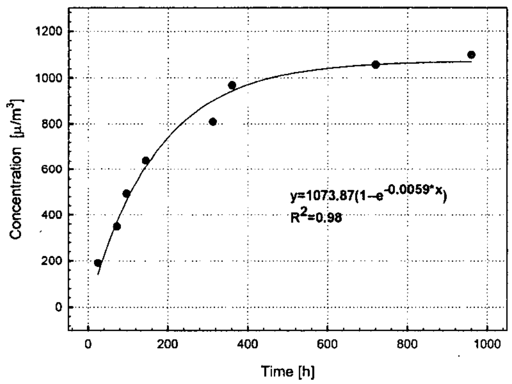

Fig. 15 Prediction of o-xylene cumulative concentration.

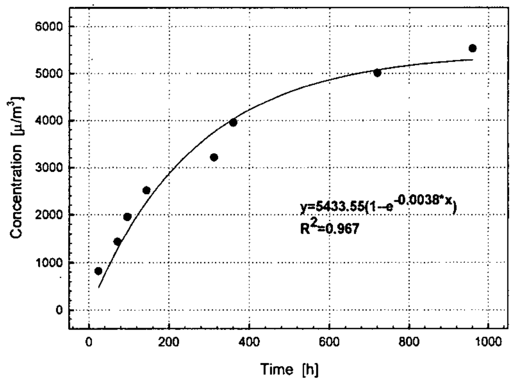

Fig. 16 Prediction of BTEX cumulative concentration.

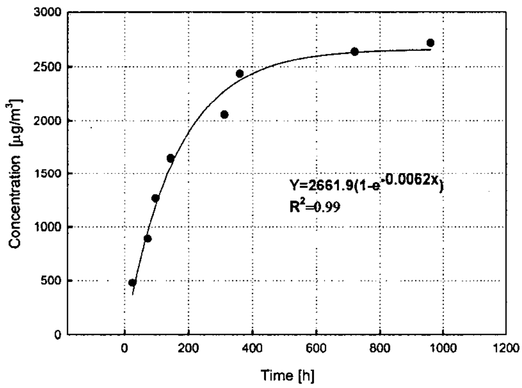

Fig. 17 Prediction of xylene cumulative concentration (floor installation).

o-xylene respectively. As presented in Fig. 14, chi-square was 0.98, indicating that this prediction equation will be properly applied to real space, and Fig. 15 also shows that this equation can also be properly used in real space after the floor installation due to the high R^2 value of 0.98. Predicted results of the total cumulative concentration of each substance are presented in Fig. 16. Prediction equation of the sum value of indoor BTEX cumulative concentration can be expressed as $y=5433.55(1-e^{-0.0038\times \text{time}})$ with R^2 of 0.967 which is significantly high value, indicating that the sum value of BTEX concentration can be properly predicted. The comparison of predicted values using just hourly measured concentration directly and those using cumulative concentration is presented in Table 2. The prediction using cumulative concentration have higher chi-square value than that using hourly data of concentration directly, indicating that more reliable prediction equation can be obtained by using cumulative value of indoor concentration.

4.2 Experimental results of furniture

Figure 18 shows indoor concentration variation of BTEX (Benzene, Toluene, Ethylbenzene, m,p,o-Xylene) with time after the installation of furniture in a real residence. In case of toluene, emission rate decreased rapidly after 500 hours, reaching steady-state. However, indoor

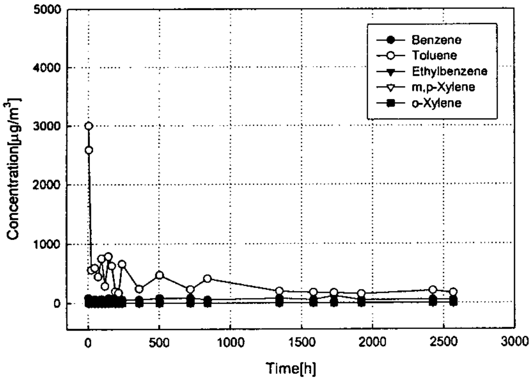

Fig. 18 BTEX concentration variation (furniture installation).

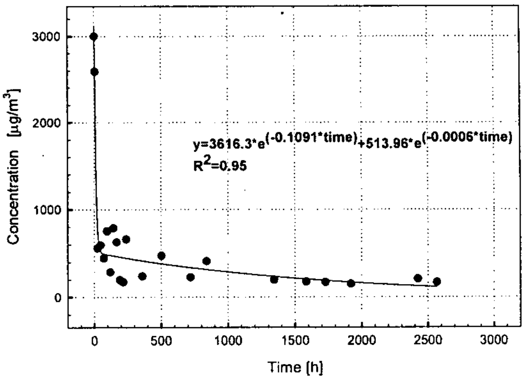

Fig. 20 Prediction of toluene concentration decrease.

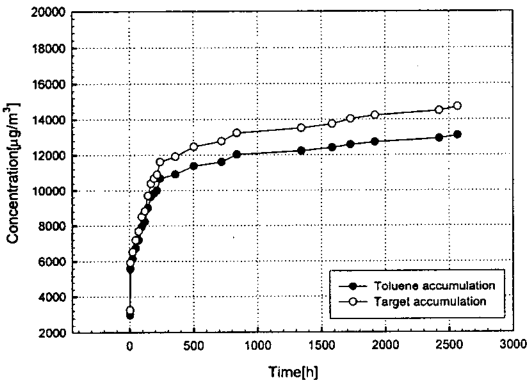

Fig. 19 Toluene and BTEX cumulative concentration (furniture installation).

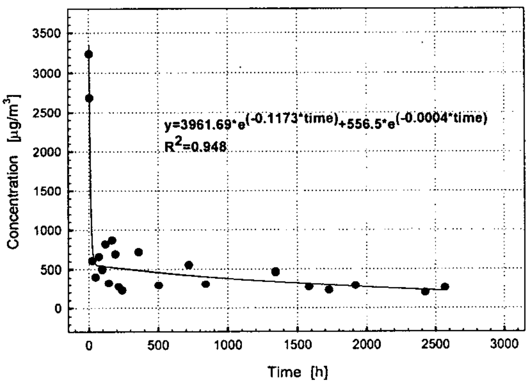

Fig. 21 Prediction of BTEX concentration decrease.

concentration of other substances except toluene was measurement period.

Figure 19 shows the cumulative concentration variation of each substance for the prediction of indoor concentration as a function of time.

4.2.1 Prediction of concentration decrease

Figure 20 presents the predicted results of indoor concentration of toluene after the installation of furniture indoors. Prediction equation is estimated to be $3616.3 \times e^{(-0.1091 \times \text{time})} + 513.96 \times e^{(-0.0006 \times \text{time})}$ with R^2 of 0.95 which is significantly high value, indicating that this equation can properly predict the time-concentration profile after the installation of furniture indoors. Figure 21 presents predicted results of the total BTEX concentration. Prediction equation can be expressed as $3961 \times e^{(-0.1173 \times \text{time})} + 556.5 \times e^{(-0.0004 \times \text{time})}$ with R^2 of 0.95 which is significantly high value like the case of toluene, indicating that this equation can also properly predict the indoor concentration of BTEX.

4.2.2 Prediction of cumulative concentration

Figure 22 shows the predicted results of indoor concentration decrease of toluene using cumulative concentration after the installation of furniture. Prediction equation is estimated to be $y = 4036.85 + (9143.6 \times \text{time})/(117.3 \times \text{time})$ with R^2 of 0.974, the highest value of prediction methods. Therefore, more reliable prediction

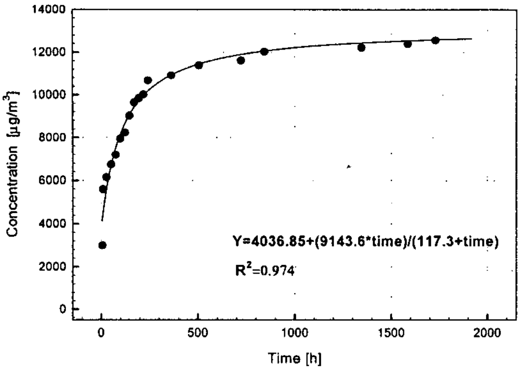

Fig. 22 Prediction of toluene cumulative concentration.

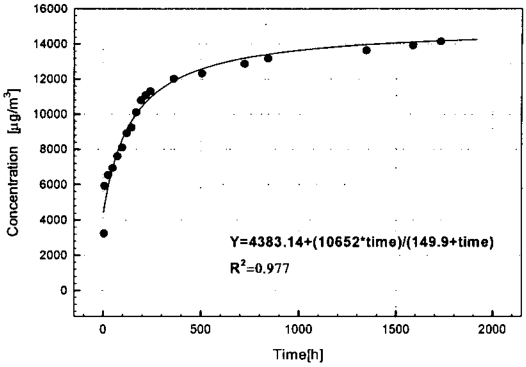

Fig. 23 Prediction of BTEX cumulative concentration.

equation can be obtained by using cumulative value of indoor concentration of toluene after the installation of furniture like the case of floor.

Figure 23 presents the predicted results of total BTEX concentration decrease using cumulative concentration of BTEX. Total BTEX concentration can be expressed as $y = 4383.14 + (10652 \times \text{time})/(149.9 + \text{time})$ with R^2 of 0.977, indicating that BTEX concentration and time are highly correlated to each other. Thus, VOCs concentration can be properly predicted after the installation of furniture with similar loading factor to this case.

5. Conclusion

In this study, indoor VOCs concentration emitted from floor and furniture was measured after the installation of floor and furniture in a real residence. With the measured data, prediction method and predication equations for indoor concentration of each VOCs and BTEX were developed. The following conclusions were drawn from this study.

(1) According to the predicted results of concentration decrease of BTEX (benzene, toluene, ethylbenzene, m,p,o-xylene) after the installation of floor in a real residence, prediction equation can be expressed using exponential function.

(2) In case of floor, more reliable prediction equation can be obtained by using cumulative value of indoor concentration than by using just hourly measured value directly. Indoor concentration of benzene is estimated to be $y = 408.52(1 - e^{-0.0031 \times \text{time}})$ with R^2 of 0.94 which is significantly high value.

(3) According to the predicted results of cumulative concentration of ethylbenzene, prediction equation can be expressed as $y = 933.25(1 - e^{-0.0059 \times \text{time}})$ with R^2 of 0.98 which is significantly high value. Thus, VOCs concentration can be properly predicted after the installation of floor in a real residence with similar loading factor.

(4) Cumulative concentration of m,p-xylene and o-xylene can also be properly predicted with R^2 of 0.98 which is also significantly high value.

(5) Toluene showed the highest concentration in case of furniture installation indoors, and it needed the longest time for concentration decrease. However, other substances except toluene showed constant concentration throughout the measurement period.

(6) In case of furniture installation indoors, prediction equation of toluene concentration decrease is estimated to be $y = 3616.3 \times e^{(-0.1091 \times \text{time})} + 513.96 \times e^{(-0.0006 \times \text{time})}$ with R^2 of 0.95 which is significantly high value.

(7) In case of floor installation indoors, prediction equation of toluene concentration decrease can be expressed as $y=4036.85+(9143.6 \times time)/(117.3 \times time)$ with R^2 of 0.974 which is significantly high value. Therefore, more reliable prediction equation can be obtained by using cumulative value of indoor concentration of toluene after the installation of furniture like the case of floor.

Further research should be conducted on the development of more precise and accurate prediction equations by simplifying and generalizing the form of prediction equation based on the experimental results of the application of various indoor materials in residences.

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