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Estimation of Outdoor PM_{2.5} Infiltration into Multifamily Homes Depending on Building Characteristics Using Regression Models

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Abstract: The purpose of this study was to evaluate outdoor PM_{2.5} infiltration into multifamily homes according to the building characteristics using regression models. Field test results from 23 multifamily homes were analyzed to investigate the infiltration factor and building characteristics including floor area, volume, outer surface area, building age, and airtightness. Correlation and regression analysis were then conducted to identify the building factor that is most strongly associated with the infiltration of outdoor PM_{2.5}. The field tests revealed that the average PM_{2.5} infiltration factor was 0.71 (±0.19). The correlation analysis of the building characteristics and PM_{2.5} infiltration factor revealed that building airtightness metrics (ACH₅₀, ELA/FA, and NL) had a statistically significant ($p < 0.05$) positive correlation ($r = 0.70, 0.69, \text{ and } 0.68$, respectively) with the infiltration factor. Following the correlation analysis, a regression model for predicting PM_{2.5} infiltration based on the ACH₅₀ airtightness index was proposed. The study confirmed that the outdoor-origin PM_{2.5} concentration in sufficiently leaky units could be up to 1.59 times higher than that in airtight units.

Keywords: PM_{2.5} infiltration; infiltration factor; multifamily homes; blower door test; regression model



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1. Introduction

Outdoor PM_{2.5} is known to cause respiratory and cardiovascular diseases when the human body is exposed to it for long periods [1,2], and it is classified as a Group 1 carcinogen by the International Agency for Research on Cancer (IARC) under the World Health Organization (WHO). Accordingly, many countries have proposed national countermeasures against outdoor PM_{2.5} and have established standards intended to reduce the damage caused by exposure to PM_{2.5}. The U.S. Environmental Protection Agency (EPA) established the National Ambient Air Quality Standards for PM_{2.5} in 1997 and then in 2012 reinforced the standards at a mean level of 35 µg/m³ per 24 h. The State Council of the People's Republic of China suggested the Air Pollution Prevention and Control Action Plan in 2013 [3]. The Ministry of Environment (MOE) in Korea presented the High Concentration Fine Particle Response Manual for vulnerable groups in 2017. Action levels for outdoor PM_{2.5}, which is known to have a large impact on the human body, have been in force in Korea since 2015.

Nevertheless, outdoor PM_{2.5} can infiltrate the indoors through cracks in buildings, even under non-ventilated conditions, thereby affecting indoor PM_{2.5} concentrations [4,5]. As outdoor- and indoor-origin PM_{2.5} differ in composition, formation, and toxicity [6,7], it is necessary to evaluate their concentrations separately in order to establish management strategies for reducing indoor PM_{2.5} concentrations. Moreover, since outdoor-origin PM_{2.5} consists of air pollutants such as nitrates, sulfates, and carbon compounds, it is known

to have higher health risks than indoor-origin PM_{2.5} [8]. Accordingly, it is important to evaluate the infiltration of outdoor PM_{2.5} when managing indoor PM_{2.5}.

Several studies have evaluated the infiltration of outdoor PM_{2.5} into indoors. Existing studies have suggested a relationship between indoor and outdoor PM_{2.5} concentrations through the calculation of the indoor–outdoor concentration ratio (I/O ratio) in residential buildings [9–12]. In the measurements for occupied buildings, the average I/O ratio was found to be in the range of 0.61 to 1.00, which indicates that the outdoor PM_{2.5} concentration affects the indoor PM_{2.5} concentration. Several studies have been conducted to assess the infiltration of outdoor PM_{2.5} with infiltration factors [13–18]. The PM_{2.5} infiltration factor is an indicator of the equilibrium fraction of outdoor PM_{2.5} that penetrates and becomes suspended indoors. In these studies, the infiltration factor ranged from 0.35 to 0.66, from which it can be estimated that the indoor PM_{2.5} concentration in residential buildings is 35–66% of the outdoor PM_{2.5} concentration. The results show that the impact of outdoor-origin PM_{2.5} on indoor concentrations may vary according to the building characteristics.

Infiltration of outdoor PM_{2.5} depends on building characteristics such as the building size (floor area and volume of room), year of construction, and airtightness [18–20]. In addition, environmental conditions such as temperature and pressure differences between the indoors and outdoors can affect the amount of outdoor-origin PM_{2.5} reaching the indoors [18–21]. Stephens and Siegel [22] conducted infiltration tests of ultrafine particles (20–1000 nm in diameter) in 18 detached homes in the U.S. to analyze the correlation between various building characteristics and the outdoor source of ultrafine particles. In their study, environmental conditions, including indoor–outdoor pressure differences, differed by testing unit when conducting the infiltration test. They found a limit at which the impact of the environmental conditions was reflected in the assessment of the infiltration according to the building characteristics. Unlike the detached houses studied in previous research, according to the 2015 Population and Housing Census of Korea [23], 77.2% of residential buildings in Korea are multifamily homes, most of which are high-rise buildings of 15 or more stories. Accordingly, the PM_{2.5} infiltration is expected to vary due to the differences in building characteristics. To establish targeted management strategies for reducing indoor PM_{2.5} in diverse multifamily housing units in Korea, it is necessary to identify the impact of the dominant building factors on the infiltration of outdoor PM_{2.5}.

This study aimed to estimate the outdoor PM_{2.5} infiltration of multifamily homes depending on the building characteristics. Field test results for 23 multifamily homes were analyzed to investigate the infiltration factor and building characteristics including the floor area, volume, outer surface area, building age, and airtightness. Subsequently, regression analysis was conducted to identify the dominant building factors influencing infiltration of outdoor PM_{2.5}. To minimize the impact of environmental disturbances, the blower-door depressurization procedure [18,24], which enables the maintenance of an identical indoor–outdoor pressure difference for each test housing unit, was utilized to conduct the PM_{2.5} infiltration test. Based on the correlation analysis results, a regression model for predicting PM_{2.5} infiltration according to the ACH₅₀ airtightness index is proposed.

2. Methods

2.1. Analysis Units

The analysis units consisted of a total of 23 domestic homes. These homes had reinforced concrete structures with layouts including living rooms, kitchens, and toilets and had various building characteristics. They included 12 units being tested for the first time and 11 units that had been previously investigated in a study by Choi and Kang [18]. Among the building characteristics of the analysis units, the construction year, floor area, and window area were obtained through on-site investigation and are listed in Table 1. The average building age was 13.6 years, with a minimum of 1 year and a maximum of 38 years. The floor area ranged from 14 m² to a maximum of 212 m², with an average of 57.4 m². In terms of floor area, both small and large units were thus included in the experiment. To analyze the correlation between building factors and outdoor PM_{2.5}

infiltration, field tests were conducted to measure the airtightness of the buildings and the PM_{2.5} infiltration factor.

Table 1. Descriptive statistics of the building factors.

Building Factor	Mean	Standard Deviation	Median	Min.	Max.
Construction year	13.6	10.8	10.0	1.0	38.0
Floor area (m ²)	57.4	48.3	36.0	14.0	212.0
Volume (m ³)	131.4	111.2	83.0	32.0	488.0
Exterior wall area (m ²)	30.4	20.2	21.7	7.7	68.5
Window area (m ²)	16.1	14.9	11.8	1.8	51.6
EWA/FA ⁽¹⁾ (-)	0.62	0.27	0.54	0.25	1.19
WA/FA ⁽²⁾ (-)	0.27	0.11	0.26	0.10	0.51

⁽¹⁾ EWA/FA: Exterior wall area per floor area. ⁽²⁾ WA/FA: Window area per floor area.

2.2. Airtightness Test

To measure the airtightness of the test homes, the fan pressurization method was applied in compliance with ISO 9972 [25]. The airtightness of the buildings was calculated using the fan pressurization method based on the air flow rate generated by the fan to determine the indoor–outdoor pressure difference for five points between 10 and 60 Pa. The indoor–outdoor pressure difference and the resulting air flow rate can be explained by the power law in Equation (1), and the trend line, which is found by interpolating the measured values with a straight line, can be used to obtain the air leakage coefficient (C) and the pressure exponent. C depends on the leakage characteristics of the building; n is a value between 0.5 and 1: it is close to 0.5 when the inflow air is turbulent and close to 1.0 when it is laminar. The power law is

$$Q = C \cdot (\Delta P)^n, \quad (1)$$

where Q is the air leakage rate through the building envelope (m³ · h⁻¹), C is the air leakage coefficient (m³ · h⁻¹ · Pa⁻ⁿ), ΔP is the induced pressure difference (Pa), and n is the pressure exponent (dimensionless).

ACH₅₀ (the air change rate at 50 Pa), which is used as a performance indicator of airtightness, can be calculated using the ratio of the air flow rate to the volume of the room, while maintaining the indoor–outdoor pressure difference at 50 Pa through Equation (2). The effective leakage area (ELA) of the units when the pressure difference between the indoors and outdoors is 4 Pa can be calculated using Equation (3). Since the ELA of each unit depends on the size of the unit, the specific ELA, which distributes the ELA over the floor area, was also calculated. The normalized leakage (NL), which allows for comparison of the airtightness between units by accounting for their floor area and height, is calculated by Equation (4) using the ELA, floor area, and floor height:

$$\text{ACH}_{50} = \frac{Q_{50}}{V}, \quad (2)$$

$$\text{ELA} = C \cdot \Delta P_r^{n-1/2} \sqrt{\frac{\rho}{2}}, \quad (3)$$

$$\text{NL} = 1000 \frac{\text{ELA}}{A_f} \cdot \left(\frac{H}{2.5}\right)^{0.3}, \quad (4)$$

where Q₅₀ is the air flow rate through the building envelope under a pressure difference of 50 Pa (m³ · h⁻¹), C is the air flow coefficient (m³ · h⁻¹ · Pa⁻ⁿ), ΔP_r is the reference pressure difference (Pa), n is the air flow exponent (dimensionless), ρ is the air density (kg · m⁻³), A_f is the floor area (m²), and H is the floor height (m).

In this study, Retrotec EU6101 with DM32 (USA) was used as the measurement equipment for the fan pressurization method; the measurement error of the wind volume

was $\pm 5\%$. To prevent measurement errors caused by indoor–outdoor pressure differences, the measurement conditions proposed in ISO 9972 were employed, that is, a wind speed of less than 6 m/s and natural conditions with an indoor–outdoor pressure difference of 5 Pa or more. Assuming a single-zone target unit, the interior doors were kept open during the measurement of the blower door, and the air flow rate generated by the fan was measured to create outdoor pressure difference conditions of 10, 20, 30, 40, and 50 Pa. Based on the measurement results of the blower door, the following airtightness indicators were derived: C (leakage coefficient), n (pressure exponent), ACH_{50} , ELA (effective leakage area), specific ELA, and NL (normalized leakage). To classify the analysis units by airtightness level, the leakage class was determined according to the airtightness and ventilation requirements presented by ASHRAE 119 [26], as shown in Table 2.

Table 2. Leakage class according to ASHRAE 119.

Leakage Class	Maximum NL	ACH_{50}	Ventilation Requirement	Airtightness
A	0.1	1	Full	Sufficiently tight
B	0.14	2	Yes	Quite tight
C	0.2	3	Yes	
D	0.28	5	Some	Leaky
E	0.4	7	Likely	
F	0.57	10	Possible	Sufficiently leaky
G	0.8	14	Unlikely	
H	1.13	20	None	-
I	1.6	27	Buildings in this range may be too loose	
J	-	-	and should be tightened	

2.3. PM_{2.5} Infiltration Test

To analyze the effects of building factors on the infiltration of outdoor PM_{2.5}, a PM_{2.5} infiltration test was conducted using the blower-door depressurization method [18], which enables the assessment of outdoor PM_{2.5} infiltration under controlled pressure differences. The main strategy of the blower-door depressurization method is to use a blower door to fix the indoor–outdoor pressure difference at 10 Pa and then to measure the indoor and outdoor PM_{2.5} concentrations. To obtain the indoor PM_{2.5} concentration after the infiltrated outdoor-origin PM_{2.5} had been fully mixed into the indoor air, the indoor and outdoor PM_{2.5} concentration measurements were obtained after operating the blower door for more than one time constant to entirely replace the room air under the controlled indoor–outdoor pressure difference of 10 Pa.

Under natural conditions, the difference between the indoor and outdoor pressures of a building is generally known to be 4 Pa [27]. In this study, the pressure difference was limited to 10 Pa through the blower door to enable the comparison of the building-specific infiltration factor. This is the minimum recommended pressure difference at which the flow rate is controlled during the blower-door experiment [27], and it is an indoor–outdoor pressure difference that can be found in mid- and high-rise buildings or that can be caused by external winds in winter [28,29]. Based on the living environment in Korea, where the proportion of high-rise multifamily housing units is high, a pressure difference of 10 Pa is therefore judged as suitable for simulating the natural infiltration environment in middle- and high-rise units. Although low indoor–outdoor pressure differences can cause the measured PM_{2.5} infiltration factor to be slightly higher than the actual PM_{2.5} infiltration factor, this study included an infiltration experiment under the same environmental conditions to select the dominant building factors for outdoor PM_{2.5} infiltration through comparison of the units and then evaluated the PM_{2.5} infiltration level.

In this study, the PM_{2.5} infiltration factor as an indicator of outdoor PM_{2.5} infiltration was calculated using the indoor PM_{2.5} mass balance equation. Equation (5) is the indoor PM_{2.5} mass balance equation; it is composed of the outdoor PM_{2.5} infiltration, indoor PM_{2.5} generation, and deposition, resuspension, removal, and exfiltration terms:

$$V \cdot \frac{dC_{in}(t)}{dt} = V \cdot P \cdot \lambda \cdot C_{out}(t) - V \cdot K \cdot C_{in}(t) + E + R_{resus} - R_{rem} - V \cdot \lambda \cdot C_{in}(t), \quad (5)$$

where V is the volume of the room (m^3), C_{in} is the indoor $PM_{2.5}$ concentration ($\mu g \cdot m^{-3}$), C_{out} is the outdoor $PM_{2.5}$ concentration ($\mu g \cdot m^{-3}$), P is the $PM_{2.5}$ penetration coefficient (dimensionless), λ is the air change rate (h^{-1}), K is the $PM_{2.5}$ deposition rate (h^{-1}), E is the indoor $PM_{2.5}$ emission rate ($\mu g \cdot h^{-1}$), R_{resus} is the $PM_{2.5}$ resuspension rate ($\mu g \cdot h^{-1}$), and R_{rem} is the $PM_{2.5}$ removal rate ($\mu g \cdot h^{-1}$).

The change in indoor $PM_{2.5}$ concentration is expressed by Equation (6) with the assumption that there is no indoor $PM_{2.5}$ generation source, resuspension, or removal. The indoor $PM_{2.5}$ concentration can be expressed by Equation (7) when the indoor fine dust concentration reaches a steady-state, at which point the $PM_{2.5}$ infiltration factor (F_{in}) can be obtained as the ratio of the indoor and outdoor $PM_{2.5}$ concentrations in the steady-state, as shown in Equation (8):

$$\frac{dC_{in}(t)}{dt} = P \cdot ACH_{10} \cdot C_{out} - (ACH_{10} + K) \cdot C_{in}(t) \quad (6)$$

$$C_{in}(t) = C_{in,ss} = \frac{P \cdot ACH_{10} \cdot C_{out,ss}}{ACH_{10} + K} \quad (7)$$

$$F_{in} = \frac{P \cdot ACH_{10}}{ACH_{10} + K} = \frac{C_{in,ss}}{C_{out,ss}}, \quad (8)$$

where V is the volume of the room (m^3), C_{in} is the indoor $PM_{2.5}$ concentration ($\mu g \cdot m^{-3}$), C_{out} is the outdoor $PM_{2.5}$ concentration ($\mu g \cdot m^{-3}$), P is the $PM_{2.5}$ penetration coefficient (dimensionless), ACH_{10} is the air change rate at 10 Pa (h^{-1}), K is the $PM_{2.5}$ deposition rate (h^{-1}), $C_{in,ss}$ is the indoor $PM_{2.5}$ concentration at steady-state ($\mu g \cdot m^{-3}$), and $C_{out,ss}$ is the outdoor $PM_{2.5}$ concentration at steady-state ($\mu g \cdot m^{-3}$).

To conduct the $PM_{2.5}$ infiltration test using the fan pressurization method, Retrotec EU6101 with DM32 (USA) was used for the blower door, and a light-scattering-type AM510 (TSI, Shoreview, MN, USA), which has been used for continuous measurement of $PM_{2.5}$ concentration in previous studies [30,31], was used for the measurements. The measurement error of the $PM_{2.5}$ concentration was $1 \mu g/m^3$ over 24 h. At a measurement interval of 3 min, the indoor and outdoor $PM_{2.5}$ concentrations were measured at one point in the center of the unit and at one point in the outdoor area close to the unit. To prevent the resuspension of indoor $PM_{2.5}$ caused by air flow through the blower door, cleaning was carried out to remove indoor $PM_{2.5}$ sources before the measurements, and the measurements were conducted in the absence of indoor $PM_{2.5}$ sources or resuspension activities in the room. The $PM_{2.5}$ concentration was obtained after one time constant at a 10 Pa pressure difference at the steady-state of the indoor $PM_{2.5}$ concentration, and the infiltration factor of $PM_{2.5}$ was calculated using Equation (8).

The $PM_{2.5}$ infiltration test with the blower-door depressurization procedure was conducted to minimize the impact of environmental factors on the outdoor $PM_{2.5}$ infiltration when comparing the $PM_{2.5}$ infiltration factors of multifamily homes according to their building characteristics. Nevertheless, as the factors affecting the outdoor $PM_{2.5}$ infiltration, the outdoor $PM_{2.5}$ concentration conditions varied at the time of the measurements. When the outdoor $PM_{2.5}$ concentration is low, the margin of error in the calculation of the $PM_{2.5}$ infiltration factor may even increase to the level of the device measurement error ($1 \mu g/m^3$) due to the small difference between the indoor and outdoor $PM_{2.5}$ concentrations. When the outdoor $PM_{2.5}$ concentration changes drastically, the infiltration factor may be overestimated or underestimated depending on the pattern of change. The analysis was thus performed by classifying the outdoor $PM_{2.5}$ concentration and its fluctuations as they are expected to affect the outdoor $PM_{2.5}$ infiltration (Table 3). OPC-1 denotes the combination of concentrations that exceed the "bad" level of a daily average of $35 \mu g/m^3$

presented by the MOE in Korea and the U.S. EPA with low fluctuation, i.e., measurements with a deviation of less than 10% of the average outdoor PM_{2.5} concentration, and this case was adopted for statistical analysis. Moreover, based on the measurement results for OPC-2, which includes average outdoor PM_{2.5} concentrations below 35 µg/m³, and OPC-3, which includes outdoor PM_{2.5} concentration deviations of 10% or more than the average, trends in the measurement results were investigated according to the outdoor PM_{2.5} concentration conditions.

Table 3. Measurements classification according to the outdoor PM_{2.5} concentration (C_{out}) conditions.

Outdoor PM _{2.5} Concentration Conditions	C _{out} (µg/m ³)		Case
	Average	Standard Deviation	
High level and low fluctuation	≥35	<10% of C _{out, average}	OPC-1
Low level and low fluctuation	<35	<10% of C _{out, average}	OPC-2
High level and high fluctuation	≥35	>10% of C _{out, average}	OPC-3

2.4. Regression Analysis

To determine the building factors that have a dominant influence on outdoor PM_{2.5} infiltration, an analysis of the correlation between the building factors and PM_{2.5} infiltration factor was performed. Prior to the correlation analysis, tests of normality (the Kolmogorov–Smirnov test and Shapiro–Wilk test) were applied to the measurement data to test the validity of normal distribution between the continuous variables. Subsequently, the Pearson correlation coefficient (*r*) was calculated to determine the strength of the linear relationship between the variables, and *p*-values were calculated to evaluate the statistical significance of the relationship between the building factors and outdoor PM_{2.5} infiltration. For the statistical analysis, we utilized the Statistics and Machine Learning Toolbox in MATLAB. Linear regression analysis was performed with the PM_{2.5} infiltration factor as the dependent variable to produce an equation that describes the PM_{2.5} infiltration factor in terms of the dominant building factor that was derived from the correlation results.

2.4.1. Pearson’s Correlation Coefficient

The Pearson’s correlation coefficient is a statistic that quantifies the linear relationship between two variables; the coefficient of correlation (*r*_{xy}) between variables *x* and *y* can be calculated using Equation (9). *r*_{xy} is in the range [−1, 1]: the closer its absolute value is to 1, the stronger the correlation is; if it is greater than 0.7 in absolute value, the correlation is said to be strong. The statistical significance of the correlation can be tested by a *t*-test, and the correlation can be considered statistically significant when the *p*-value is less than 0.05.

$$r_{xy} = \frac{\sum(x_i - \bar{x}) \cdot \sum(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2} \cdot \sqrt{\sum(y_i - \bar{y})^2}} \quad (9)$$

where \bar{x} is the mean of *x*, and \bar{y} is the mean of *y*.

2.4.2. Regression Model

Regression analysis is a method for numerically modeling the relationship between independent and dependent variables and is based on the method of least squares. A model is selected when the sum of the squared residuals between the linear model and the observations is minimized. Regression models have the advantage of being able to quantify the relationship between the independent variables and the dependent variable and facilitate the intuitive interpretation of relationships among factors, making them widely used for the evaluation of explanatory objective variables in existing studies [32,33].

In this study, a regression model was used to evaluate outdoor PM_{2.5} infiltration based on the selected building factors. To select a suitable model to describe the relationships between the variables, four types of linear regression (linear, log-linear, linear–log, and

log–log regression), including log-transformation models that can explain nonlinear relationships between variables based on their log transformation, were conducted. The coefficient of determination (R^2) (Equation (9)) was used as an indicator to evaluate the ability of each regression model to explain the measured values. R^2 falls in the range [0, 1]; and the closer it is to 1, the better the regression model describes the measurements:

$$R^2 = 1 - \frac{\sum_{i=1}^n (\hat{Y}_i - \bar{Y})^2}{\sum_{i=1}^n (Y_i - \bar{Y})^2} \quad (10)$$

where Y_i is the i -th measured value, \bar{Y} is the mean of the measured values, and \hat{Y}_i is the i -th predicted value in the regression model.

3. Results and discussion

3.1. Airtightness of Analysis Units

Table 4 presents the airtightness measurements obtained for the analysis units. The ELA was found to range from 8 cm² to 435 cm². The PM_{2.5} infiltration was expected to vary depending on the leakage area, which serves as the infiltration path for PM_{2.5} under the reference differential pressure condition (4 Pa). The ratio of ELA to the floor area (ELA/FA) was calculated to control for the difference in ELA due to the varying size of the analysis units: it had a range of 0.47 cm²/m² to 7.65 cm²/m². The average ACH₅₀ was found to be 7.0 (±3.9) h⁻¹, with a minimum of 1.4 h⁻¹ and a maximum of 15.0 h⁻¹, which are similar to the results of previous studies (1.9 and 12.9 h⁻¹, respectively) [34–38] that investigated the ACH₅₀ of Korean multifamily homes. We found that the leakage classes of the multifamily homes, calculated based on the ACH₅₀ and NL in the analysis units, include a wide range of airtightness: from A (sufficiently tight) to G (highly leaky).

Table 4. Airtightness of the analysis units.

Unit	C (m ³ ·h ⁻¹ ·Pa ⁻ⁿ)	N (–)	ELA (cm ²)	Specific ELA (cm ² /m ²)			ACH ₅₀ (h ⁻¹)	NL (–)	Leakage Class
				ELA/EWA	ELA/WA	ELA/FA			
1	49.11	0.65	131	2.63	3.00	1.54	3.1	0.15	C
2	99.31	0.60	247	4.51	5.62	1.90	3.4	0.19	C
3	159.63	0.67	435	6.35	8.43	2.05	4.0	0.20	D
4	136.02	0.69	381	N. A.	N. A.	6.69	12.4	0.64	G
5	58.31	0.60	144	7.84	14.15	4.01	7.5	0.39	E
6	47.24	0.63	121	13.49	23.19	3.36	6.6	0.33	E
7	70.82	0.66	191	4.20	8.94	2.25	4.2	0.22	D
8	81.94	0.59	200	10.86	27.94	5.55	9.8	0.54	F
9	2.53	0.82	8	0.63	4.69	0.47	1.4	0.05	A
10	149.88	0.62	379	6.24	14.06	2.65	4.9	0.26	D
11	144.13	0.57	343	12.42	25.59	6.85	11.7	0.67	G
12	38.24	0.63	98	5.06	36.24	4.89	10.3	0.47	F
13	89.15	0.57	212	4.21	11.92	3.26	5.5	0.32	E
14	14.60	0.74	44	1.38	3.13	1.21	3.1	0.12	B
15	13.82	0.77	43	1.35	3.08	1.19	3.4	0.12	B
16	124.86	0.60	310	12.91	21.91	7.01	13.0	0.68	G
17	8.45	0.77	26	2.65	4.40	0.76	2.1	0.07	A
18	100.91	0.67	273	4.01	7.74	3.25	7.0	0.32	E
19	68.92	0.70	194	13.52	36.33	5.87	13.7	0.57	G
20	32.78	0.58	79	4.45	15.26	4.91	7.4	0.48	E
21	18.71	0.67	51	2.66	8.59	3.17	6.9	0.31	D
22	13.31	0.65	35	4.56	14.03	2.51	5.3	0.24	D
23	85.95	0.62	220	27.29	30.94	7.65	15.0	0.75	G

3.2. PM_{2.5} Infiltration Factor

Table 5 presents the results of the infiltration tests in the multifamily homes. The outdoor PM_{2.5} concentration at steady-state ($C_{out,ss}$) and indoor PM_{2.5} concentration at steady-state ($C_{in,ss}$) were measured to calculate the PM_{2.5} infiltration factor. The deviation of $C_{out,ss}$ and $C_{in,ss}$ was within 5% of the measured mean value, indicating that the steady-state assumption was satisfied in the calculation of the infiltration factor. The PM_{2.5} infiltration factor was shown to range from 0.31 to 1.12, with an average of 0.71 (± 0.19), under an indoor–outdoor pressure difference of 10 Pa. This suggests that when there is no indoor generating source, the indoor PM_{2.5} concentration is about 71% of the outdoor PM_{2.5} concentration. The PM_{2.5} infiltration factors (0.31 to 1.12) measured in this study were similar to or higher than those found in previous studies [13,16,17], which had an average of 0.55 to 0.66 for residential buildings.

Table 5. Infiltration test results for multifamily homes.

Unit	$C_{out}(\mu\text{g}/\text{m}^3)$		$C_{out,ss}(\mu\text{g}/\text{m}^3)$		$C_{in,ss}(\mu\text{g}/\text{m}^3)$		$F_{in}(-)$		Outdoor PM _{2.5} Condition
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	
1	142	14	169	2	62	0	0.36	0.00	OPC-1
2	27	1	26	0	20	0	0.78	0.01	OPC-2
3	159	4	160	4	104	1	0.65	0.01	OPC-1
4	77	2	78	4	58	1	0.74	0.02	OPC-1
5	35	1	34	1	26	1	0.76	0.04	OPC-1
6	66	7	63	1	68	1	1.08	0.04	OPC-3
7	132	3	133	1	79	1	0.60	0.00	OPC-1
8	53	2	53	1	37	0	0.70	0.01	OPC-1
9	34	1	35	0	21	0	0.62	0.01	OPC-2
10	102	11	86	2	76	2	0.89	0.03	OPC-3
11	189	10	192	2	135	1	0.71	0.01	OPC-1
12	35	2	35	1	32	0	0.90	0.01	OPC-1
13	75	4	70	2	46	1	0.66	0.02	OPC-1
14	130	2	133	0	70	1	0.52	0.01	OPC-1
15	266	25	296	1	152	1	0.51	0.00	OPC-1
16	30	1	30	1	20	0	0.65	0.02	OPC-2
17	41	3	43	1	25	0	0.57	0.03	OPC-1
18	74	2	76	1	49	1	0.64	0.02	OPC-1
19	82	9	94	2	30	1	0.31	0.01	OPC-3
20	91	1	90	1	76	0	0.85	0.01	OPC-1
21	51	3	52	1	47	0	0.91	0.01	OPC-1
22	44	4	41	0	46	0	1.12	0.01	OPC-3
23	70	3	73	2	64	1	0.88	0.01	OPC-1

When analyzing the correlation between F_{in} and the building factors, the measurement results were classified as OPC-1, OPC-2, or OPC-3 to reflect the level and variability of the outdoor PM_{2.5} concentration. Three units (Unit 2, 9, 16) were categorized as OPC-2, four units (Unit 6, 10, 19, 22) as OPC-3, and sixteen units (Unit 1, 3, 4, 5, 7, 8, 11, 12, 13, 14, 15, 17, 18, 20, 21, 23) as OPC-1. To avoid the margin of error factor caused by the condition of outdoor PM_{2.5} concentration when calculating the PM_{2.5} infiltration factor and to increase the accuracy of the analysis, the measurement results for OPC-1 were used to analyze the correlation between the outdoor PM_{2.5} infiltration factor and building factors.

Figure 1 shows the distribution of the PM_{2.5} infiltration factor measurements for the OPC-1 units. The PM_{2.5} infiltration factor averaged $0.68 \pm 0.15 \text{ h}^{-1}$, with a range of 0.36 h^{-1} to 0.91 h^{-1} . To determine whether the PM_{2.5} infiltration factor measurements are suitable for the analysis of the Pearson's correlation with the building characteristics, the distribution of the measurements for the units in the OPC-1 category was plotted: the measurements exhibited a roughly linear relationship with the quantiles of the normal distribution (Figure 1b). Tests of normality, namely the Kolmogorov–Smirnov test and

Shapiro–Wilk test, were applied to measurements, the results of which are listed in Table 6: both test results confirm that the t -values are within the significance level ($p > 0.05$) and that there is not sufficient evidence that the infiltration factor measurements of the OPC-1 group do not follow a normal distribution. Accordingly, the measured $PM_{2.5}$ infiltration factors for the OPC-1 group are judged to be suitable for linear correlation analysis.

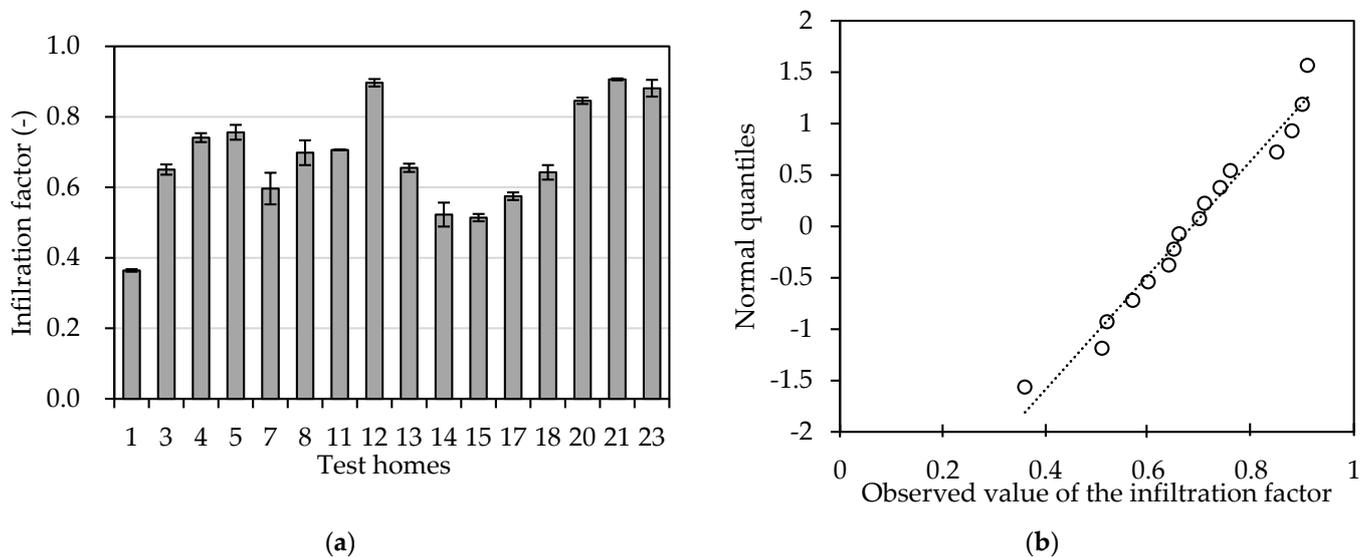


Figure 1. Distribution of $PM_{2.5}$ infiltration factor in test homes: (a) $PM_{2.5}$ infiltration factor for OPC-1 group; (b) Normal Q–Q plot of $PM_{2.5}$ infiltration factor of the analysis set.

Table 6. Tests of normality of the $PM_{2.5}$ infiltration factor.

Normality Test	Degrees of Freedom	t	p-Value
Kolmogorov–Smirnov	16	0.107	0.200 *
Shapiro–Wilk	16	0.965	0.755 *

* p -value > 0.05 .

3.3. Correlation between the $PM_{2.5}$ Infiltration Factor and Building Factors

Table 7 lists the correlations between the $PM_{2.5}$ infiltration factor and the building characteristics, and Table 8 ranks the dominant building factors in terms of correlation and statistical significance. The correlation coefficients (r) of the airtightness metrics (ACH_{50} , NL, and ELA/FA) and the $PM_{2.5}$ infiltration factor were 0.701, 0.685, and 0.684, respectively, with p -values of less than 0.01; that is, there was a strong, positive correlation that is statistically significant. The outdoor $PM_{2.5}$ infiltration is thus proportional to the airtightness of the building, and the relationship between the two can be explained through a linear model. In addition to airtightness, in the order of decreasing strength, the building characteristics found to be highly correlated with the $PM_{2.5}$ infiltration factor are WA/FA, volume, floor area, construction year, and EWA/FA. WA/FA, volume, and floor area are related to the size of the building and were found to be negatively correlated with the $PM_{2.5}$ infiltration factor, with coefficients of -0.489 , -0.366 , and -0.362 , respectively. Although the $PM_{2.5}$ infiltration factor tended to be higher in smaller units, the correlations were not statistically significant (p -value ≥ 0.05). We thus conclude that the negative correlation between building size and $PM_{2.5}$ infiltration factor is less descriptive of their relationship and that additional data are needed. The year of construction and EWA/FA had low positive correlations with the $PM_{2.5}$ infiltration factor, and the correlations were not statistically significant. ELA/FA showed a strong, positive correlation with the $PM_{2.5}$ infiltration factor within statistical significance rather than EWA/FA and WA/FA. This result implies that outdoor $PM_{2.5}$ infiltration could depend on the leakage area of the

building facade which may differ with the materials or construction of the building, rather than the size of the building facades.

Table 7. Correlation coefficient (r) between the building factors and PM_{2.5} infiltration.

	Year of Construction	Floor Area	Volume	EWA/FA	WA/FA	ELA/FA	ACH ₅₀	NL	F _{in}
Construction year	1.000	0.122	0.112	−0.473	−0.300	0.604 *	0.561 *	0.598 *	0.341
Floor area	0.122	1	0.999 **	−0.433	0.052	−0.287	−0.311	−0.287	−0.362
Volume	0.112	0.999 **	1.000	−0.434	0.057	−0.295	−0.319	−0.295	−0.366
EWA/FA	−0.473	−0.433	−0.434	1.000	0.369	−0.083	−0.082	−0.082	0.257
WA/FA	−0.300	0.052	0.057	0.369	1.000	−0.362	−0.354	−0.353	−0.489
ELA/FA	0.604 *	−0.287	−0.295	−0.083	−0.362	1.000	0.979 **	0.999 **	0.685 **
ACH ₅₀	0.561 *	−0.311	−0.319	−0.082	−0.354	0.979 **	1.000	0.978 **	0.701 **
NL	0.598 *	−0.287	−0.295	−0.082	−0.353	0.999 **	0.978 **	1.000	0.684 **
F _{in}	0.341	−0.362	−0.366	0.257	−0.489	0.685 **	0.701 **	0.684 **	1.000

* p -value < 0.05, ** p -value < 0.01.

Table 8. Ranking of the correlations between the building characteristics and PM_{2.5} infiltration.

Building Characteristic	Correlation Coefficient (r)	p -Value	Rank
ACH ₅₀	0.701	0.002 **	1
ELA/FA	0.685	0.003 **	2
NL	0.684	0.003 **	3
WA/FA	−0.489	0.064	4
Volume	−0.366	0.163	5
Floor area	−0.362	0.168	6
Construction year	0.341	0.196	7
EWA/FA	0.257	0.354	8

** p -value < 0.01.

The correlation between the building factors was also calculated: the correlations between the year of construction and the airtightness metrics (ELA/FA, ACH₅₀, and NL) were 0.604, 0.561, and 0.598, respectively, i.e., a moderate positive correlation that was statistically significant (p -value < 0.05). This may be attributable to increased airtightness in newly built multifamily homes for the purpose of saving energy. Based on the relationship between airtightness and the year of construction, the correlation between the outdoor PM_{2.5} infiltration factor and year of construction can be derived without any field tests and can be further investigated through more data collection.

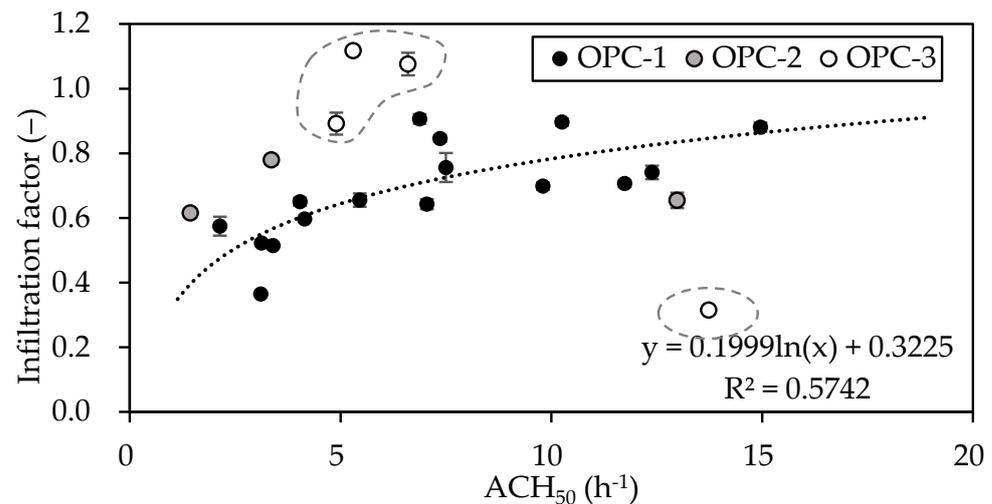
The airtightness metrics (ACH₅₀, NL, EL, and ELA/FA) were selected as the dominant factors based on the ranking of the correlations of the building factors with the PM_{2.5} infiltration factor. To avoid the problem of multicollinearity between the independent variables, ACH₅₀, which was found to have the highest correlation among the performance indicators of airtightness with the PM_{2.5} infiltration factor, was selected as the independent variable for the simple regression model.

3.4. PM 2.5 Infiltration According to ACH₅₀

Table 9 shows the results for four kinds of bivariate linear regression of ACH₅₀ and the PM_{2.5} infiltration factor. The coefficient of determination (R^2) of the linear-log regression model was found to be 0.57, indicating that this model has the highest explanatory power for the measured values. The linear-log model reflects a decreasing trend in the PM_{2.5} infiltration factor as the airtightness increases; this may explain the upper bound on the infiltration factor ($F_{in} < 1.0$) within the range of ACH₅₀ observed here. Figure 2 graphically illustrates the linear-log regression model of the PM_{2.5} infiltration factor according to ACH₅₀, utilizing ACH₅₀ and the PM_{2.5} infiltration factor for case OPC-1.

Table 9. Results of regressing the PM_{2.5} infiltration factor (F_{in}) on ACH₅₀.

Regression Model	Equation	α	β	R ²
Linear	$Y_i = \alpha + \beta \cdot X_i + \epsilon_i$	0.485 **	0.028 **	0.50
Log-Linear	$Y_i = \alpha + \beta \cdot \ln(X_i) + \epsilon_i$	0.322 **	0.200 **	0.57
Linear-Log	$\ln(Y_i) = \alpha + \beta \cdot X_i + \epsilon_i$	-0.715 **	0.044 **	0.48
Log-Log	$\ln(Y_i) = \alpha + \beta \cdot \ln(X_i) + \epsilon_i$	-0.972 **	0.314 **	0.56

** *p*-value < 0.01.**Figure 2.** Results of regressing the PM_{2.5} infiltration factor on ACH₅₀.

To assess the outdoor PM_{2.5} infiltration of a building according to its airtightness, the airtightness was categorized by leakage class (tight (ACH₅₀: 0~5 h⁻¹), leaky (ACH₅₀: 5~10 h⁻¹), sufficiently leaky (ACH₅₀: 10~15 h⁻¹)), as defined in ASHRAE 119. Figure 3 shows the mean and standard deviation of the PM_{2.5} infiltration factor according to airtightness level. In the tight units (*n* = 6), the PM_{2.5} infiltration factor averaged 0.54 (±0.09), and the value estimated by the regression model was 0.56 (±0.04). In leaky units (*n* = 6), the PM_{2.5} infiltration factor measurements averaged 0.75 (±0.09), and the estimated value was 0.72 (±0.03). In sufficiently leaky units (*n* = 4), the PM_{2.5} infiltration factor averaged 0.81 (±0.08), and the regression model estimate was 0.82 (±0.03). These results indicate that without indoor PM_{2.5}-generating sources, the PM_{2.5} concentration in tight multifamily homes may be half the outdoor PM_{2.5} and that sufficiently leaky units may be vulnerable to outdoor PM_{2.5}: the indoor PM_{2.5} concentration due to outdoor PM_{2.5} infiltration was up to 1.59 times higher in sufficiently leaky homes than in tight homes, suggesting that the indoor exposure risks of outdoor PM_{2.5} varies depending on the airtightness of the multifamily home.

Analysis of the data that were acquired under the OPC-2 and OPC-3 measurement conditions (seven units) was performed to compare the effects of the outdoor PM_{2.5} conditions. The multifamily homes in OPC-2 (*C*_{out,avg} < 35 µg/m³) with a low concentration of outdoor PM_{2.5} had ACH₅₀ values of 1.4 h⁻¹ to 13.0 h⁻¹ and PM_{2.5} infiltration factors of 0.62 to 0.78. Unlike the differences in the airtightness, there was no significant difference between the PM_{2.5} infiltration factors in the OPC-2 group. This may be due to the low outdoor PM_{2.5} concentration and low outdoor-origin indoor PM_{2.5} concentration: even a small measurement deviation can thus cause relatively large errors when calculating the infiltration factor. The OPC-3 group exhibited a large deviation in the outdoor PM_{2.5} concentration (*C*_{out,std} > 10% of *C*_{out,avg}); units in this group had ACH₅₀ values between 4.9 h⁻¹ and 13.7 h⁻¹ and PM_{2.5} infiltration factors between 0.31 and 1.12. We checked the difference in the estimated PM_{2.5} infiltration factor according to changes in the outdoor PM_{2.5} concentration. Reductions in the concentration (*C*_{out,avg} > *C*_{out,ss}) tended to be asso-

ciated with a higher PM_{2.5} infiltration factor compared to the regression model, while the opposite was true for increasing concentrations ($C_{out,avg} < C_{out,ss}$). When the concentration of the outdoor PM_{2.5} changed significantly, it was found that there was a lag time in the accumulation of the outdoor-origin indoor PM_{2.5} concentration. The lag time that occurs when outdoor pollutants infiltrate the indoors has been identified through a cross-case analysis in a previous study [39]. Based on the results of this study, additional study on the method to compensate for the impact of outdoor fine dust conditions when conducting infiltration experiments using a blower door is needed.

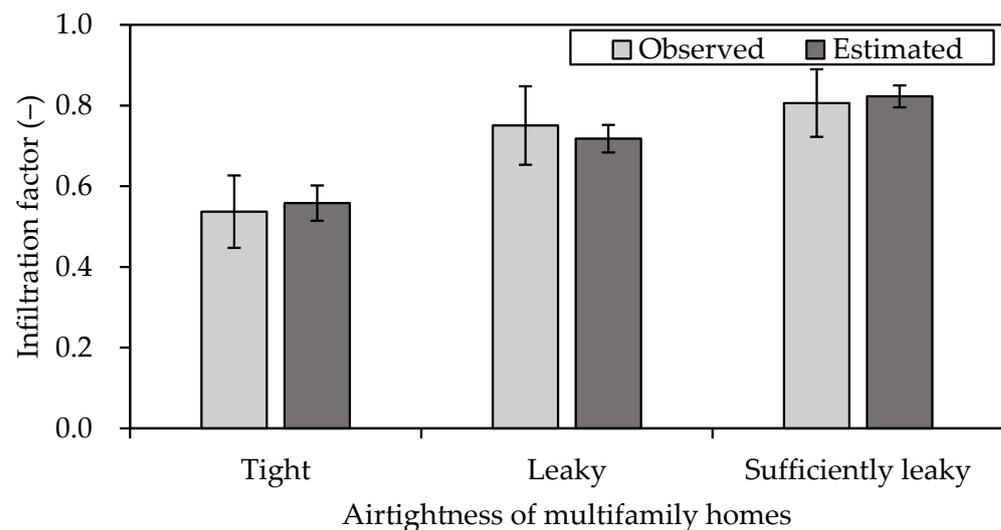


Figure 3. PM_{2.5} infiltration factor by airtightness of multifamily homes.

4. Conclusions

The purpose of this study was to evaluate outdoor PM_{2.5} infiltration into multifamily homes in Korea according to the building characteristics utilizing a field test and a regression model. The PM_{2.5} infiltration test was conducted using the blower-door depressurization procedure, and correlation analysis was used to identify the dominant building factors associated with the infiltration of outdoor PM_{2.5}. A regression model for estimating the PM_{2.5} infiltration factor based on the ACH₅₀ airtightness index was proposed. The key results of this study are as follows:

- The PM_{2.5} infiltration analysis was conducted for 23 target units in Korea, and the effective measurement of the PM_{2.5} infiltration factor for 23 homes was 0.71 (± 0.19).
- Analysis of the correlation between building characteristics and the PM_{2.5} infiltration factor showed that ACH₅₀, ELA/FA, and NL had a statistically significant ($p < 0.05$), strong positive correlation ($r = 0.701, 0.685, 0.684$) with the PM_{2.5} infiltration factor.
- Based on the correlation analysis, ACH₅₀ was selected as the dominant predictor for PM_{2.5} infiltration, and a regression model ($R^2 = 0.57$) was developed to explain the PM_{2.5} infiltration rate by the ACH₅₀ index: $F_{in} = 0.1999 \cdot \ln(ACH_{50}) + 0.3225$.
- The analysis of the PM_{2.5} infiltration rate according to the leakage class confirmed that the concentration of outdoor-origin PM_{2.5} in sufficiently leaky units can be up to 1.59 times higher than that in tight units.

We presented the PM_{2.5} infiltration factor for the estimation of the outdoor PM_{2.5} infiltration in multifamily homes in Korea and selected ACH₅₀ as the dominant building factor for predicting the infiltration of outdoor PM_{2.5}. These results are potentially useful for indoor exposure assessments and control measures against outdoor PM_{2.5} infiltration based on the airtightness performance of domestic multifamily homes. Although this study targets Korean multifamily homes, the results could be used to estimate the outdoor PM_{2.5} infiltration into homes with reinforced concrete structures which have similar characteristics. The results are also expected to be used for the calculation of dust removal loads to

establish system operating strategies aimed at maintaining proper indoor air quality. As the behavior of the particles differs according to the size fraction [40,41], fine and ultrafine particles could interact differently with building characteristics. Accordingly, the study on the relationship between size-resolved particles and building factors can be conducted in future research based on the results of this study.

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