Airtightness Data and Characteristics of 752 Residential Units of Reinforced Concrete Buildings in Korea

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ABSTRACT

This paper presents airtightness data measured for about 752 units of high-rise reinforced concrete buildings (apartment buildings) that have been recently constructed within five years in Korea. Target buildings were mainly constructed by using reinforced concrete walls/floors, and dry/wet walls were installed between units. Airtightness data of residential units were analysed based on values of ACH50 and air permeability. To identify the airtightness characteristics of reinforced concrete residential buildings, the measured airtightness data were analysed in terms of the dwelling unit sizes, wall types between units, and flow exponent n. The ACH50 values of the dwelling units were measured to range between 1.02 and 4.81, and the average value of the measured units was 2.39. It was found that the flow exponent of the measured units was 0.61 on average. The airtightness prediction model was derived by examining the correlation between a variable by component area and a variable by connection length, and performing regression analysis on these correlations. The ACH50 value tended to decrease as the floor area increased.

KEYWORDS

Airtightness, Reinforced concrete residential buildings, Fan pressurization method, Air leakage characteristic, Airtightness prediction

1 INTRODUCTION

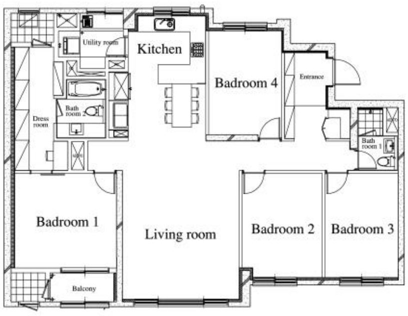
In a climatic zone similar to that in South Korea, infiltration and exfiltration in non-airtight buildings increase air-conditioning and heating energy costs and lead to problems such as condensation. For this reason, the importance of airtightness is being increasingly emphasized to reduce the energy consumption in buildings. Many countries have been proposing necessary building performance criteria regarding energy saving to make measurements in the completion step mandatory (Sherman et al. 2004, Chan 2013). Furthermore, the verification and evaluation processes on airtightness performance, which are the most crucial factors in terms of criteria for saving energy in newly constructed buildings, are being established and institutionalized. However, in Asian countries other than Japan (Yoshino 2008), an institutional base for building airtightness has either been absent or insufficient. Accordingly, studies on measuring airtightness of detached houses are being widely conducted in other countries, but it is difficult to find studies or data about the airtightness of high-rise residential buildings (i.e., apartments) of the type mainly used as residences in major Asian cities where high-density development is ongoing. This study presented the airtightness data of 752 residential units of four apartment complexes in Korea, to provide baseline data for establishing airtightness criteria for dwellings such as apartments. Airtightness of a unit was evaluated based on the ACH50 and air permeability values, and the correlation between them was analyzed. In addition, multiple regression analysis on the areas and the connection lengths, which are components of the building envelope, was performed using measurement data in order to derive an airtightness prediction model.

2 AIRTIGHTNESS MEASUREMENT SUMMARY

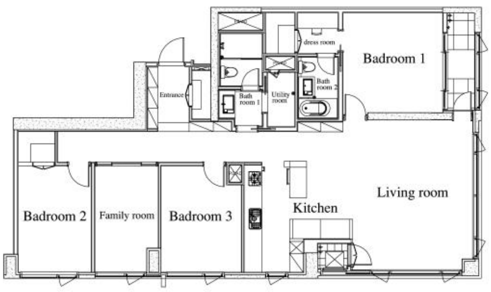
Buildings A to D, which were measurement targets, were constructed as high-rise residential buildings between 2010 and 2015 in Korea, and have a reinforced concrete structure. Airtightness of these buildings was measured based on Method B described in ISO9972 (2006) when all the main components of the envelope such as windows, doors, and facilities were installed, but before building completion. The test buildings are briefly described in Table 1. All the apartment complexes have structures of reinforced concrete. In terms of a building plan, in the tower type, there is a core mainly at the center, surrounded by units. In contrast, parts of A and D apartment complexes were of the plate-type building plan. As for the envelope, the A to D apartment complexes were considered to be of the punched window type. Regarding partition walls between units, wetwall construction (concrete wall) were used in the A and D apartment complexes and drywall construction in the B and C apartment complexes. Examples of typical floor plan in apartment complex are presented in Fig. 1.

Table 1: Test Building Summaries

Classification	Apartment A	Apartment B	Apartment C	Apartment D
Construction	Reinforced Concrete Structure, Flat Slab			
Building use	Residentials (apartment)			
Exterior wall type	Punched Window Type			
Number of stories	2 basements, 23~32 stories	2 basements, 12~28 stories	2 basements, 11~33 stories	2 basements, 25~32 stories
Height (m)	104.1 m	96.7 m	108.8 m	105.7m
Number of units	1401 units	1014 units	845 units	1861 units
Number of test units	210 units	148 units	129 units	265 units
View				



124m² type floor plan



129m² type floor plan

Figure 1: Examples of Floor Plan

Unit planning characteristics for high-rise residential buildings with structures of reinforced concrete are indicated in Table 2. The results from analyzing the envelopes of housing units based on their enclosed area, shows that the area of the ceiling and floor accounted for the largest part of the envelope, followed by that of the walls and windows. In each unit, there was one entrance door, and a louver in utility room containing the air conditioner. In terms of ventilation penetrations, a heat recovery ventilation system with 4~6 air inlets/outlets was installed in all the units, and one air exhaust vent was installed in kitchen and two installed in each bathroom. The area of the unit envelope changed significantly according to the unit size, but the number of mechanical penetrations for vents and drains was almost the same.

Table 2: Characteristics of the Target Apartment Units

Classification	Material or method	Number	Area Rate (%)	Apartment
Wall	Gypsum board	-	0	Apartment A , D
	Concrete	-	27 ~ 32	
	Gypsum board	-	4 ~ 15	Apartment B , C
	Concrete	-	13 ~ 24	
Floor/Ceiling (Slabs)	Concrete	-	30 ~ 35	All
Windows	PVC framed window	5 ~ 8	5 ~ 12	All
Entrance door	Steel door	1	0.3 ~ 0.8	All
Louver in utility room	Aluminium louver	1	0.4 ~ 0.7	All
Air/Pipe duct area	Gypsum board	3 ~7	4 ~ 11	All
Hear recovery ventilation	4~6 air inlets/outlets	1	-	All
Exhaust vents	Kitchen	1	-	All
	2 Bathrooms	2	-	All

Airtightness of the housing units was measured in accordance with measurement conditions proposed in ISO9972, as shown in Table 3. In contrast to detached houses, apartments have envelopes directly facing the exterior air, neighbouring units, and corridor, as well as floors and ceilings adjoining the upper and lower units. Thus, because adjacent units might affect the airtightness of the target units, the windows and entrance doors of the adjacent units were kept open to assume outdoor conditions. Openings such as doors and windows connected to the outside of target units were closed; whereas interior doors were kept open, to make a single zone. In addition, the various vents such as air inlets/ outlets and exhaust vents connected to the outside were all sealed.

Table 3: Test Conditions

Classification	Test Condition
Test space	To create a single zone
Zone height × indoor/outdoor air temperature difference	≤ 250 m K
Wind speed (near the ground)	≤ 6 m/s
Outdoor temperature	5 ~ 35 °C
The range of the induced pressure difference	10 ~ 60 Pa
Increments of induced pressure differences	5 ~ 10 Pa
Accuracy	± 5 %

3 AIRTIGHTNESS RESULTS

To obtain the airtightness of high-rise residential buildings with reinforced concrete structure, the airtightness of 752 units was measured. Six to twelve people were deployed in each apartment complex, including apartment A (210 units), apartment B (148 units), apartment C (129 units), and apartment D (265 units) to measure airtightness for four to six months. All the windows and doors of the adjacent units, as well as the windows of common corridors and stairway doors, were kept open to prevent negative effects on these units.

3.1 Ach50 and Air Permeability

To compare the airtightness of the target units, measurement results were analyzed based on the values of ACH50 and air permeability, which are used to represent airtightness. Fig. 2 and 4 present frequency distribution graphs (i.e., histograms), which indicate the number of relevant units by numerically classifying the values of ACH50 and air permeability measured. Figures 3 and 5 indicate measurement and mean values of each apartment complex in quartiles. It was found that the ACH50 values were between 1.02 and 4.81 (mean = 2.39). The ACH50 values were between 1.50 and 4.81 (mean = 2.85) for apartment A, between 1.41 and 3.60 (mean = 2.31) for apartment B, between 1.12 and 3.79 (mean = 2.48) for apartment C, and between 1.02 and 3.80 (mean = 2.02) for apartment D. These results indicate that apartment D was the most airtight and that apartment A was the least airtight. Given that apartments A to D all had envelopes of the punched window type, and that they were all recently constructed by the same construction company, we expected that the airtightness would also be similar. However, it seems that differences in window shapes and household partition (interior) walls affected the results. Moreover, because the value of ACH50 decreases as the floor area increases (as reported in previous studies), the ACH50 values of apartments A and D, which included relatively many small units, were higher than those of apartments B and C. It was also found that the value of air permeability was generally between 0.98 and 4.59 $m^3/h \cdot m^2$ (mean = 2.29). The value of air permeability was 1.39 and 4.59 $m^3/h \cdot m^2$ (mean = 2.70) for apartment A, 1.39 and 3.51 $m^3/h \cdot m^2$ (mean = 2.25) for apartment B, 1.11 and 3.57 $m^3/h \cdot m^2$ (mean = 2.42) for apartment C, AND 0.98 and 3.67 $m^3/h \cdot m^2$ (mean = 1.94) for apartment D.

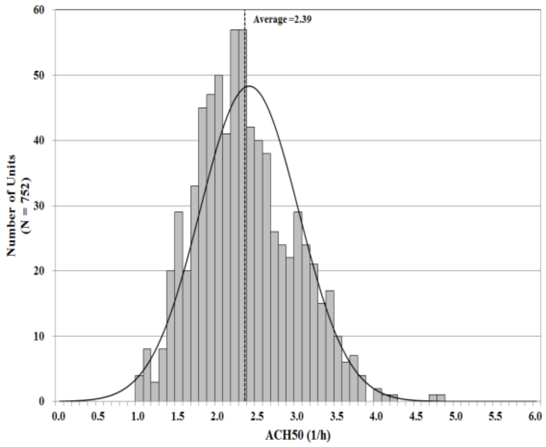


Figure 2: ACH50 Distribution

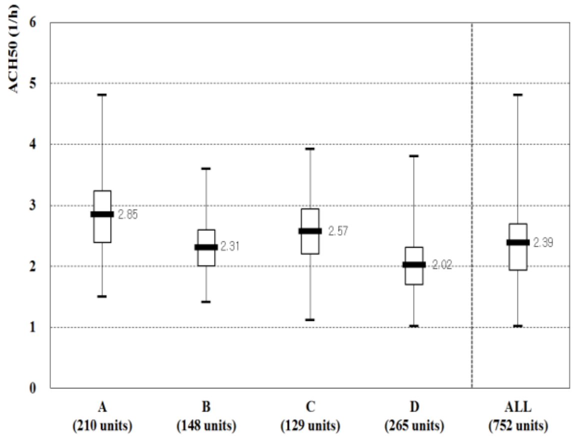


Figure 3: ACH50 Results

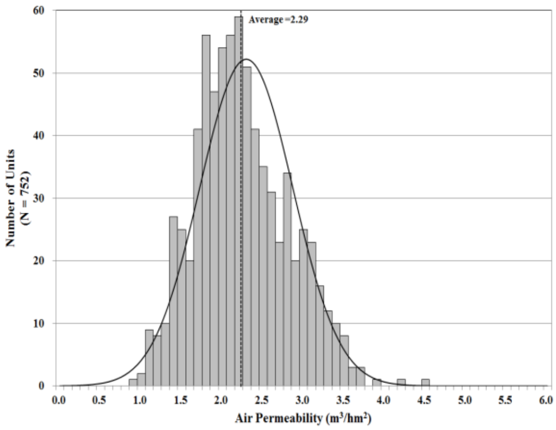


Figure 4: Air Permeability Distribution

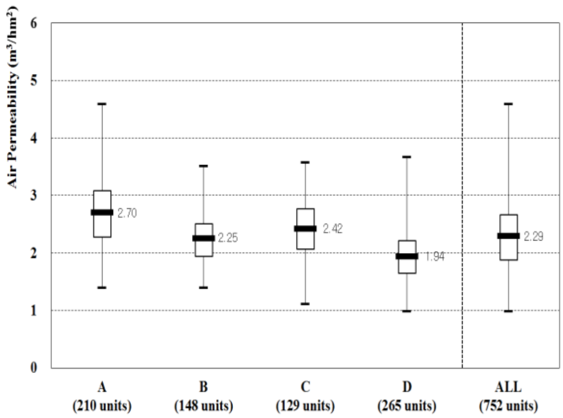


Figure 5: Air Permeability Results

To identify a correlation between ACH50 and air permeability, the two values were analyzed using a scatter diagram based on the analytic result shown above. As a result, the distribution shown in Fig. 6 was found, and the ratio of ACH50 to air permeability was close to 1.0. The volume and envelope area of the measured units are similar, and indeed, a surface to volume (S/V) ratio of the target units was verified to be between 0.965 and 1.100 (i.e., close to ‘1’).

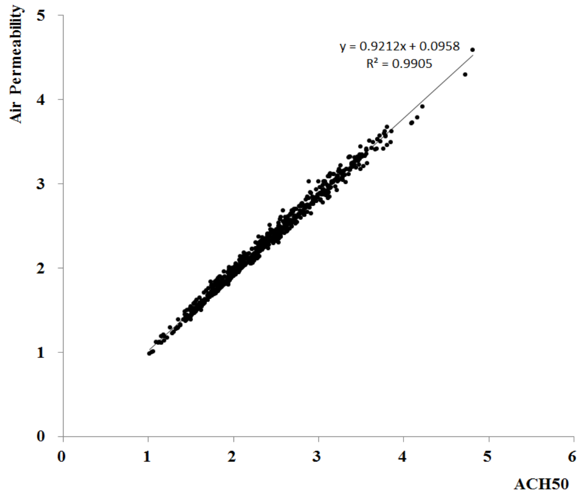


Figure 6: Relationship between ACH50 and Air Permeability

3.2 Airtightness Characteristics

To analyze the airtightness characteristics of housing units, airtightness of the target units of apartments A to D were examined according to the floor area and types of partition walls. To analyze the relationship between the floor area (size) and airtightness of a housing unit, airtightness of the target units was classified according to the floor area. ACH50 was used to represent the result of analyzing airtightness according to floor area, and the measurement data is shown in Fig. 7. The result of examining airtightness according to the area of housing units of each complex, based on one way ANOVA analysis, is indicated in Table 4. By calculating mean values of each floor plan and representing them using a trend line, it was found that the value of ACH50 tended to decrease as the floor area increased. This result indicates that the value of airtightness decreases as the floor area increases.

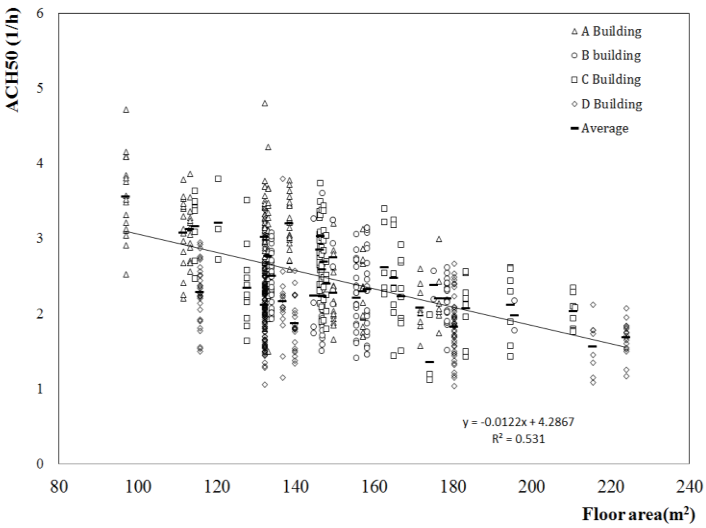


Figure 7: ACH50 According to the Floor area (Unit Sizes)

Table 4: One-way ANOVA Result for Airtightness for Each Unit Area

Apartment		Range(m^2)	Number of Units	Average of ACH50	Standard deviation	F value	Significance Probability
A	A1	80 ~ 100	17	3.55	0.546204	33.55711938	0.0000000000
	A2	100 ~ 120	29	3.09	0.425938		
	A3	120 ~ 140	114	2.95	0.502706		
	A4	140 ~ 160	34	2.28	0.433692		
	A5	160 ~ 180	16	2.13	0.348787		
	Sum	80 ~ 180	210	2.85	0.606387	-	-
B	B1	120 ~ 140	28	2.50	0.346872	2.677146627	0.0493836702
	B2	140 ~ 160	94	2.28	0.497214		
	B3	160 ~ 180	24	2.21	0.268802		
	B4	180 ~ 200	2	1.98	0.276479		
	Sum	120 ~ 200	148	2.31	0.448270	-	-
C	C1	100 ~ 120	7	3.16	0.436577	8.982701583	0.00000026811
	C2	120 ~ 140	15	2.51	0.608864		
	C3	140 ~ 160	51	2.71	0.457660		
	C4	160 ~ 180	31	2.28	0.615012		
	C5	180 ~ 200	15	2.09	0.439762		
	C6	200 ~ 220	10	2.03	0.223355		
	Sum	100 ~ 220	129	2.48	0.577864	-	-
D	D1	100 ~ 120	31	2.28	0.401743	11.48879037	0.00000001328
	D2	120 ~ 140	164	2.08	0.450523		
	D3	180 ~ 200	45	1.82	0.393204		
	D4	200 ~ 220	8	1.56	0.356926		
	D5	220 ~ 240	17	1.68	0.229318		
	Sum	100 ~ 2400	265	2.02	0.455082	-	-

To analyze the characteristics of cracks where exfiltration occurs, the flow exponent n was examined as shown in Fig. 8. The n value refers to a property value of a crack, and is irregular when the shape of the crack changes, according to the size of the pressure difference. The n value of typical buildings is between 0.6 and 0.8, and the average n value was 0.60 for apartment A, 0.62 for apartment B, 0.61 for apartment C, and 0.61 for apartment D. The mean n value of all target units was found to be 0.61, and 50% of all the n values were between 0.59 and 0.62. In the work of Chan et al. (2013) the n value was reported to be 0.65, whereas in the work of Derek Sinnott et al. (2012) it was reported to be 0.64. This means that apartments constructed with reinforced concrete walls have smaller cracks in air leakage area than wooden detached houses.

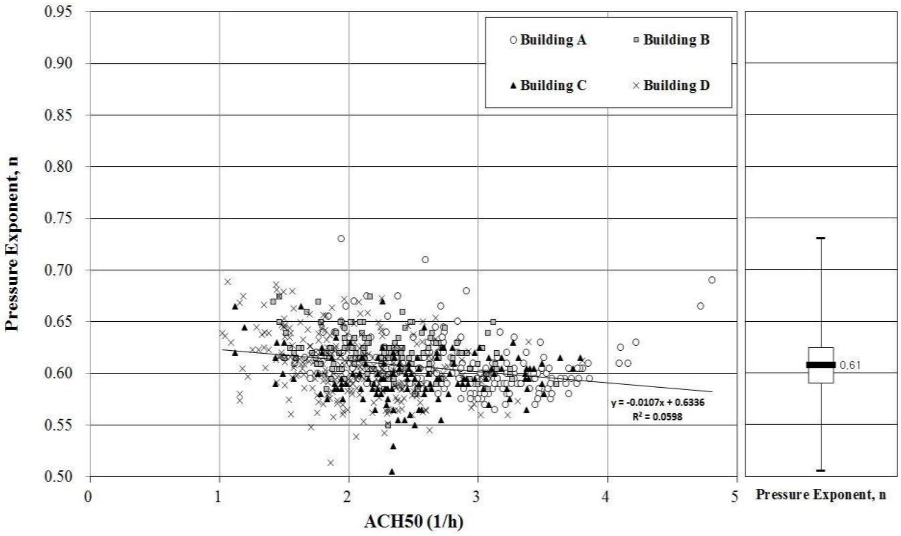


Figure 8: Distribution of Flow Exponent and ACH50 for Each Apartment

4 AIRTIGHTNESS PREDICTION MODEL

Among previous studies about predicting airtightness, Reinhold and Sonderegger (1983) presented the geometric information on buildings and the main elements of detached houses as variables to estimate airtightness. Montoya et al. (2010) derived a regression model by applying factors such as the structure type, floor area, building age, number of stories, insulation type, and heating system and Pan Wei (2010) analyzed a correlation of factors such as the building method, dwelling type, management context, and design target. In this study, we established variables regarding envelope components by classifying them into factors related to area, and factors related to joint length (connection length between the components), to derive a prediction model for airtightness of a housing unit. The airtightness prediction model was derived through regression analysis of the ACH50 value representing airtightness. Based on the analytic result of the envelope components of the housing units, variables were classified according to the area and joint length of the envelope components. Variables by area were classified into the slab, wetwall, drywall, AD/PD drywall, windows, entrance door, and louver in utility room. The variables by joint length were classified into dry and dry wall, wet and wet wall, dry and wet wall, wall and window, AD/PD room walls, wall and louver, and wall and the entrance door. Table 5 represents symbols and explanations for the variables.

Table 5: Variable Symbols According to the Area and the Joint Length Elements

Variable Symbol	Explanations
Aslab	The area of the floor and the ceiling
Asidewet	The area of wetwalls
Asidedry	The area of drywalls
Awin	The area of windows
AADPD	The area of Air Duct/Pipe Duct
Alouver	The area of louver
Adoor	The area of entrance door
Ldrydry	The length of the joint between two drywalls
Lwetwet	The length of the joint between two wetwalls
Ldrywet	The length of the joint between the drywall and wetwall
Lwin	The length of the joint between wall and window
LADPD	The length of the joint between walls for air duct/pipe duct room
Llouver	The length of the joint between wall and louver
Ldoor	The length of the joint between wall and entrance door

4.1 Multiple Regression Analysis: Area

Correlation between the variables was analyzed using a scatter diagram and the results indicated that the slab area and window area exhibited the most linear relationship and that they have a closer correlation with airtightness than do the other variables. It was also found that the slab area showed a highly negative correlation (explanation power coefficient R^2 = 0.61), followed by the window area, which showed a relatively high correlation compared to other variables. Through multiple regression analysis of the ACH50 value representing airtightness and area by factor, a regression model was derived, as shown in Eq. 1.

$$ACH50 = 4.654 - 0.007 \times Aslab + 0.004 \times Asidedry \quad (1)$$

In the regression model, the ACH50 value decreases as the slab area increases, whereas the ACH50 increases as the area of the drywall increases. As shown in the correlation analysis results above, the slab area has the most significant effect, followed by the area of drywall. Standardized path coefficients of the slab area and drywall area were found to be –0.801 and 0.180, respectively.

4.2 Multiple Regression Analysis: Joint Length

In the scatter diagram, only the joint length of windows and doors exhibited a linear relationship with airtightness, whereas other variables did not. The R^2 value of windows and doors was 0.32 and showed a negative correlation. The result of analyzing correlation coefficients also showed that only the joint length of windows and doors had a correlation within the significance probability of 5%. By analyzing the correlation based on the scatter diagram and correlation coefficients, a correlation between windows and doors and airtightness was verified. Finally, a regression model (Eq. 2) was derived by performing multiple regression analysis of the ACH50 value representing airtightness and joint length by factor

$$ACH50 = 3.136 - 0.014 \times Lwin + 0.035 \times Ldrydry + 0.121 \times Llouver + 0.007 \times LADPD \quad (2)$$

In this model, the ACH 50 value decreases as the joint length of windows and doors and AD/PD drywalls increases, whereas the ACH50 increases as the joint length of the dry and wall and that of the wall and louver increase. The standardized path coefficient between variables was found to be - 0.544 for windows and doors, 0.258 for the dry and dry wall, 0.308 for the wall and louver, and - 0.216 for the joint length of the AD/PD dry walls. The explanation coefficient R^2 value representing goodness of fit of the prediction model was 0.45 for the prediction model regarding joint length, with low explanation power. On the other hand, the R^2 value for the prediction model regarding the area was 0.64 with greater explanation power. Based on this result, it seems that Eq. 1, the prediction model based on to the component area, is more appropriate than that based on the joint length of envelope components, and that this model could be used effectively to estimate airtightness in apartments where airtightness cannot be measured.

5 CONCLUSIONS

The airtightness of 752 units was measured to provide data on the airtightness of apartment constructed with reinforced concrete, and to analyze their airtightness characteristics. Multiple regression analysis was performed on the area and the length factors, which are components of the envelope, to derive the prediction model. By measuring the airtightness of 752 apartment units with reinforced concrete structure, it was verified that the ACH50 values were between 1.02 and 4.81 and that the overall mean ACH50 was 2.39. The air permeability value was between 0.98 and 4.59 $m^3/h \cdot m^2$ and the overall mean air permeability was 2.29 $m^3/h \cdot m^2$. The result of analyzing airtightness by classifying target units by floor area (size), showed that the ACH50 value decreased as the floor area increased. This result was due to the tendency toward an increase in the ratio of the volume of the housing unit, to the floor area. Multiple regression analysis was performed based on the measured airtightness data to derive an airtightness prediction model. The airtightness predictions according to the area of each component of the envelope, was found to be more accurate than that according to the joint length between components.

6 ACKNOWLEDGEMENTS

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