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Air permeability of naturally ventilated Italian classrooms

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Abstract

The study is focused on the evaluation of air permeability and ventilation rate in Italian classrooms. Measurements were performed in 16 naturally ventilated classrooms located in Cassino, Central Italy. Classrooms' airtightness was evaluated through the fan pressurization method. Air exchange rates where both estimated from the blower door results and measured using a CO_2 decay test method. The effect of the periodic manual airing of the classrooms (through window and door opening) was also investigated performing CO_2 and particle number concentration measurements during the school time.

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Keywords: indoor air quality; schools; CO_2; pressurization test; airborne particles

1. Introduction

The Organization for Economic Co-operation and Development (OECD) estimated that children living in OECD countries receive, on average, almost 7000 hours of instruction in classroom between the ages of 7 and 14 [1]. New learning and teaching strategies, policies, and technologies were adopted by the education systems to improve student's learning outcomes [2], whereas less attention was paid to the healthiness of such microenvironments. Actually, the evaluation of the indoor air quality in schools is a key aspect since recent researches reported that indoor environments cannot be considered safer than outdoor ones in terms of exposure to different pollutants [3].

Schools' buildings can reduce the exposure to outdoor pollutants due to their low gas and particle infiltration efficiencies [4, 5] but, consequently, they do not allow a proper exfiltration of indoor-generated pollutants. In fact,

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high indoor pollutant concentrations (e.g. radon, particles emitted by indoor sources, volatile organic compound and formaldehyde from furniture) were measured in classrooms elsewhere in the world [6-11]: this phenomenon is magnified where the air exchange is only relied upon natural ventilation systems [12, 13].

The long-lasting exposure to pollutants in classrooms may result in significant adverse impact on students' health due to their higher inhalation rates resulting in larger specific doses than adults while their organs and tissues are growing [14, 15]. Moreover, the high CO_2 concentration level in classrooms itself was found having significant adverse impact on students' health and performance, such as lower attention and vigilance [16, 17]. Therefore, adequate ventilation rates need to be guaranteed in order to improve classroom air quality [18].

From a regulatory point of view both US and European standards provide minimum ventilation rates for classrooms as function of the required indoor air quality. As example, the American Society of Heating, Refrigeration and Air-Conditioning Engineers Standard 62.1 [19] recommends a default minimum ventilation rate for acceptable indoor air quality in school classrooms of 6.7 to 7.4 L s^{-1} per person, depending on the children age. Similarly, the European EN 13779 [20] standard provides ventilation rate values for non-smoking rooms equal to 20, 12.5, 8, and 5 L s^{-1} per person when high, medium, moderate, and low air quality targets have to be reached.

Few field studies were carried out by the scientific literature to evaluate the classroom ventilation rates and the related indoor air quality. Most of them resulted in ventilation rates lower than those required by the standards [6, 16] and in significantly high pollutant concentrations (e.g. CO_2 concentrations higher than 1000 ppm [12, 21], indoor concentrations of some VOCs higher than outdoor [22]). Anyway, a gap in the scientific literature was recognized about the data on Italian school air quality and ventilation rate. In fact, (few) studies were mainly focused on residential building to evaluate their ventilation heat losses [18, 23].

To this purpose, in the present paper were evaluated: i) the air permeability of naturally ventilated Italian classrooms, ii) their air exchange rates, and iii) the effect of the manual airing on the indoor pollutant concentrations during the school time. To this purpose primary schools placed in Cassino (Italy) were investigated during the winter period.

2. Methodologies

The experimental analysis was performed considering 16 classrooms of 7 different public primary schools located in the area of Cassino (Central Italy). All the schools under investigation present a natural ventilation system. Moreover, schools with different period of construction/refurbishment, type of opening (single/double-glazed), type of envelope, maintenance condition, were considered in the survey. In Table 1 details of the schools/classrooms analyzed were reported as well as notes on the maintenance conditions.

In order to measure the ventilation rates of a building envelope two different methods can be considered: the fan pressurization method and the tracer gas dilution method. Actually, the latter allows to measure the effective ventilation rate since it depends on the climatic conditions (e.g. wind speed and direction, outside-inside temperature difference), but, for this reason, it is less repeatable. On the contrary, the pressurization test provides ventilation rates under a fixed pressure difference, which is higher than natural pressure differences generated by typical climatic conditions. Therefore, the pressurization test allows to classify the different classrooms on the basis of their airtightness as they were subjected to the same pressure difference: an indirect estimation of the natural ventilation rate can be only carried out.

In the present study a pressurization test was performed in all the classrooms under investigation; in particular, a blower-door-test instrument was used. Moreover, a CO_2 decay test was carried out in 5 classrooms to measure directly the natural ventilation rate.

The blower-door test is based on the mechanical fan pressurization/depressurization of the room/building to evaluate the airtightness by measuring the air flow rate through the envelope under different indoor-outdoor pressure differences, Δp.

Table 1. Details of the classrooms analyzed: geometric data and opening characteristics.

School	Classroom	Floor area (m^2)	Volume (m^3)	Notes
A	Entire School	1060	3960	Building made up of 7 classrooms (e.g. classroom A2), one recreational room (classroom A1), 5 bathrooms, 2 storage closets, 2 aisles and 3 entrance halls. Aisles and halls present several single-glazed aluminum outward opening emergency exits and inward opening windows
	A1	135	581	4 single-glazed aluminum inward opening windows; 1 single-glazed aluminum outward opening emergency exit
	A2	59	216	5 single-glazed aluminum inward opening windows
B	B1	41	151	3 single-glazed aluminum vasistas (inward opening) windows; 1 single-glazed aluminum inward opening door
	B2	45	165	3 single-glazed aluminum vasistas (inward opening) windows
	B3	82	302	2 single-glazed aluminum inward opening door
C	C1	47	151	2 single-glazed aluminum inward opening hopper windows (Plexiglas was used to replace some glass panes)
	C2	47	151	2 single-glazed aluminum inward opening hopper windows (Plexiglas was used to replace some glass panes)
D	D1	43	130	3 double-glazed aluminum sliding windows with sealing. Possible air infiltration due to the observable detachment of beam–column joints
	D2	43	130	3 double-glazed aluminum sliding windows with sealing. Possible air infiltration due to the observable detachment of beam–column joints
	D3	34	104	2 double-glazed aluminum sliding windows with sealing. Possible air infiltration due to the observable detachment of beam–column joints.
E	E1	57	200	2 double-glazed aluminum inward opening windows; window handles replaced by latches.
	E2	59	206	2 double-glazed aluminum inward opening windows; 1 window handle replaced by latch.
F	F1	46	139	1 single-glazed aluminum inward opening windows
	F2	46	139	1 single-glazed aluminum inward opening windows
G	G1	47	150	4 single-glazed iron inward opening windows; 4 single-glazed iron vasistas (inward opening) windows
	G2	47	150	4 single-glazed iron inward opening windows; 4 single-glazed iron vasistas (inward opening) windows

The pressure-flow relationship for the blower-door test can be evaluated through the equation:

$$q_{env} = C_{env}(\Delta p)^n \qquad (1)$$

where q_{env} is the air flow rate through the building envelope ($m^3\ h^{-1}$), and n and C_{env} are the air pressure exponent and the flow coefficient, respectively, estimated by means of a simple linear regression [24]. The flow coefficient C_{env} is a function of the size of the building openings, whereas the air pressure exponent n characterizes the flow (usually a reference value of 0.65 is chosen). The air leakage rate, q_{50}, is obtained from the air leakage coefficient C_L by correcting the air flow coefficient C_{env} at standard conditions (20 °C and 101325 Pa) and at reference pressure difference Δp=50 Pa. Then the air exchange rate at 50 Pa (n_{50}) is obtained dividing the q_{50} by the room/building volume. In the present analysis, both pressurization and depressurization tests were performed according to the fan pressurization method reported in the ISO 9972 [24] standard for each classrooms: the Method A “test of a building in use” was applied. This method allowed to perform measurements under the real condition of the building envelope then not sealing/fixing intentional opening (e.g. detachment of beam–column joints, window handles replaced by latches). This is not a trivial aspect since the maintenance of the Italian public schools is typically lacking. The experimental apparatus used to perform blower-door tests includes: i) an airproof fan at calibrated flow rates fitted to the door by means of an extensible frame allowing the measurement of pressure differences (positive and negative); ii) a flow rate regulation system producing indoor-outdoor pressure differences by varying the fan speed; iii) two primary elements for the flow rate measurement, i.e. a calibrated orifice plate on the plate for low flows and a Pitot tube for high flow rate on the fan with an uncertainty of about 5%; iv) a digital micromanometer with an uncertainty of about 1 Pa, to measure the pressure difference both indoor/outdoor and up/downstream to the primary element (in order to calculate the flow rate); v) a thermo-hygrometer for air temperature and humidity measurements, to correct flow rates at standard conditions.

The CO_2 decay test was performed through a CO_2 probe based on the infrared absorption principle (measuring range: 0-10000 ppm). The CO_2 concentration decay in the classroom was measured as soon as the students left the classrooms for about 4 hours: this sampling method guaranteed high and homogeneous CO_2 concentrations inside the room, the latter is a key aspect to apply a tracer gas decay method [25]. Windows and doors were kept close during the test. The air exchange rate ($n_{\text{CO2-decay}}$) was determined through the equation:

$$n_{\text{CO2-decay}} = (1/\Delta t)\ln\left[(C_1 - C_0)/(C_2 - C_0)\right] \tag{2}$$

where C_1, C_2 and C_0 represent the peak, final and outdoor CO_2 concentrations and Δt the time interval between C_1 and C_2. Outdoor CO_2 concentrations were measured before and after the decay test: C_0 represents the average value.

In order to evaluate the effect of the manual airing on the indoor pollutant and CO_2 concentrations during the school time a further experimental campaign was performed in 5 classrooms. Indoor and outdoor particle number concentrations, and indoor CO_2 concentrations where measured during the school time. A questionnaire reporting window and door opening periods, classroom start and end times, and classroom empty periods (e.g. recreational activities performed in other rooms) was filled out by the teachers. Indoor and outdoor particle number concentrations were continuously measured through two Diffusion Charger Particle Counters; CO_2 concentrations were continuously measured through the CO_2 probe with 1-min time resolution.

3. Results and Discussions

The air exchange rate at 50 Pa (n_{50}), across all the classrooms tested, excluding the entire building School A, ranged between 1.10 e 4.60 h^{-1} with an average value of 2.46 h^{-1}. Therefore, the permeability of the classrooms under investigation resulted not sufficient to guarantee an adequate air exchange rate. In fact, roughly dividing the n_{50} by the empirical conversion factor of 20 [26], the average air exchange rate at natural pressure (n) resulted equal to 0.12 h^{-1}, then confirming the poor ventilation of the classrooms when compared to the minimum regulatory value. The authors point out that such n values can be useful to compare the air exchange rate of the classrooms under investigation when exposed to the same climatic conditions: i.e. the n value estimated through the pressurization test allows to compare the building airtightness of the different schools/classrooms; the actual natural air exchange rate, under the typical climatic condition of the location, can differ from estimated n values. Considering the maximum crowding index and the minimum ventilation rate per person (5 L s^{-1} per student) required by the European standard EN 13779 for primary schools, the minimum air exchange rate for each classroom was evaluated. Estimated air exchange rate at natural pressure resulted only 3-11% (average 5%) of the EN 13779 required values. The authors point out that the minimum ventilation rate here considered corresponds to the lowest indoor air quality class reported by the EN 13779 standard. Whatever the opening characteristics, all the classrooms under investigation showed n_{50} for depressurization (n_{50_dep}) higher than pressurization ones (n_{50_p}): in particular, the ratio n_{50_dep}/n_{50_p} was measured in the range 1.2-2. This is related to the poor quality of the openings and their poor sealing. The maintenance condition effect was also recognized: in fact, classrooms in the same schools showing the same type of opening, orientation, and geometry (C1 vs. C2 and G1 vs. G2) presented n_{50} value differences up 100% (e.g. C1=1.43, C2=2.89). The kind of opening was also recognized to affect the air exchange rate, as example, data concerning the School A, revealed that outward opening emergency exits can cause lower ventilation rates than inward opening vasistas windows. Finally, analyzing the data of the entire School A, the n_{50} of the School A resulted equal to 3.87 h^{-1} which is higher than A1 and A2 n_{50} values. Since all the classrooms of the School A are similar to the A2 one in terms of opening characteristics and maintenance state, the air leakages of aisles, halls, bathrooms of that school can be supposed significantly higher than the classroom ones. Therefore, the building presents higher air exchange rates where is not required, then only increasing its ventilation heat losses.

Table 2. Air exchange rates at 50 Pa (h^{-1}) for depressurization (n_{50_dep}), pressurization (n_{50_p}), and mean value (n_{50}); estimated natural air exchange rates (n), measured natural ventilation air exchange rate through CO_2 decay test ($n_{CO2\text{-}decay}$) and EN 13779 n values ($n_{required}$).

Classroom	n_{50_dep}	n_{50_p}	n_{50}	n	$n_{CO2\text{-}decay}$	$n_{required}$	Classroom	n_{50_dep}	n_{50_p}	n_{50}	n	$n_{CO2\text{-}decay}$	$n_{required}$
Entire School	5.19	2.55	3.87	0.19	-	-							
A1	1.28	0.93	1.10	0.06	0.07	1.93	D2	3.49	2.72	3.10	0.16	0.12	2.70
A2	3.72	1.90	2.81	0.14	-	1.67	D3	2.94	1.89	2.41	0.12	-	2.35
B1	6.14	3.06	4.60	0.23	0.27	1.97	E1	1.56	1.16	1.36	0.07	-	2.31
B2	4.62	2.77	3.70	0.18	0.21	2.19	E2	1.81	1.13	1.47	0.07	-	2.31
B3	2.69	1.75	2.22	0.11	0.26	2.19	F1	2.37	1.71	2.04	0.10	-	2.66
C1	1.89	0.98	1.43	0.07	-	2.19	F2	2.60	2.21	2.40	0.12	-	2.66
C2	3.13	2.65	2.89	0.14	-	2.53	G1	3.91	2.93	3.42	0.17	-	2.53
D1	2.88	1.92	2.40	0.12	-	2.53	G2	2.44	1.48	1.96	0.10	-	2.53

In Table 2 air exchange rates measured through the CO_2 decay test ($n_{CO2\text{-}decay}$) are also reported for classrooms A1, B1, B2, B3 and D2. $n_{CO2\text{-}decay}$ values ranged from -57% to 25% of the estimated n values then resulting in an actual conversion factor ($n_{50}/n_{CO2\text{-}decay}$) ranging from 9 to 25 (average value of 17): a similar range of the actual conversion factor was measured by Dubrul [27] for residential buildings of European Countries different from Italy. The authors point out that $n_{CO2\text{-}decay}$ values here reported are referred to few-day measurements in the winter season. Performing several measurements for each room could be useful to evaluate the average actual air exchange rate of the classroom (which is a function of the average micro-climatic conditions and the classroom airtightness) and the actual conversion factor of each classroom. This could be only performed through expensive and extended experimental analyses. As regard the effect of the manual airing on the indoor pollutant and CO_2 concentrations during the school time, tests performed in the 5 classrooms clearly highlight that students are exposed to high CO_2 concentrations (Table 3). Such concentrations are lowered by the periodic opening of the windows (typically 30 minutes during the recreation activities) but this approach is not sufficient to keep the average CO_2 concentrations under 1000-1200 ppm, which is the default value for low indoor air quality stated by the EN 13779 [20]. In terms of particle number concentrations, the students' exposure to particles is lower than outdoor: the average indoor particle number concentration was equal to 1.18×10^4 part/cm^3 with an average (effective) indoor-outdoor concentration ratio equal to 0.85.

Table 3. Average CO_2 and particle number indoor concentrations (N_{in}), outdoor particle number concentrations (N_{out}) and N_{in}/N_{out} ratios.

Classroom	CO_2 (ppm)	N_{in} (part/cm^3)	N_{out} (part/cm^3)	N_{in}/N_{out}
A2	1503±405	$8.24\pm1.81\times10^3$	-	
B1	3130±1283	$1.29\pm0.27\times10^4$	$1.72\pm0.46\times10^4$	0.75
B2	2746±1235	$9.08\pm3.00\times10^3$	$1.03\pm0.30\times10^4$	0.88
B3	1907±463	$1.38\pm0.18\times10^4$	$1.78\pm0.25\times10^4$	0.77
C1	1747±559	$1.52\pm0.50\times10^4$	$1.54\pm1.05\times10^4$	0.99

Conclusions

The study showed that in Italian schools it is not possible to rely on natural ventilation method solely for maintaining adequate indoor air quality conditions in the classrooms in the winter period. Sufficient ventilation cannot be guaranteed even when the opening airtightness is scarce and the building opening/envelope maintenance is missing. Manual periodic airing of the classrooms resulted not effective too, thus, mechanical ventilation system represents the only technique able to guarantee minimum indoor air quality in the classrooms.

Finally, the present paper also determined a conversion factor between ventilation rate at 50 Pa and natural ventilation rate typical of the area under investigation and its climatic conditions. The conversion factor was lower than the one reported in the scientific literature obtained in other European countries and in US. The authors point out that different conversion factors are expected in different regions of Italy due to the different climatic conditions and building construction techniques. Future developments of the study will be focused on an in-depth indoor air quality evaluation in the classrooms, investigating other indoor pollutant concentrations such as radon and VOCs.

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