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Airtightness of residential buildings in the Continental area of Spain

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ABSTRACT

Infiltration plays a relevant role regarding the energy performance of buildings. Many European countries have already established standards which aim to limit the energy waste through the envelope following the European Energy Performance of Buildings Directive guidelines. However, in Mediterranean countries there is still a lack of knowledge in this field. An extensive study has been carried out in order to characterize the air leakage through the envelope of the existing housing stock in the Continental climate area of Spain. Results of 129 dwellings tested, including different typologies and periods of construction, are shown. Blower door tests were performed, and thermal imaging was used to locate leakage paths. Single-family dwellings were found to be more airtight than apartments, given that the mean air permeability rate at 50 Pa (q_{50}) was 5.4 $m^3/h{\cdot}m^2$ and 6.8 $m^3/h{\cdot}m^2$ respectively. The mean air change rate at 50 Pa (n_{50}) was 6.1 h^{-1} for single-family dwellings and 7.1 h^{-1} for multi-family housing. Nevertheless, great dispersion of results and extreme values were found. In addition, the influence of several construction characteristics on permeability results was assessed.

1. Introduction

Building energy demand has become one of the most important concerns in the construction sector. The European Energy Performance of Buildings Directive (EPBD) is committed to achieve a highly efficient and decarbonised building stock, considering that almost 50% of the final energy consumption is used for heating and cooling, of which 80% is used in buildings [1].

Since infiltrations play an important role regarding the energy consumption of dwellings, many European countries have already established standards which aim to limit the energy consumption through the envelope. In Europe, minimum requirements on airtightness have been imposed in Czech Republic, Estonia, France, Germany, Ireland and UK, either in the context of the energy performance regulations or specific programmes. Systematic justification is only required in France, Ireland and UK [2].

However, in Mediterranean countries with mild climates and the tradition of natural ventilation by opening windows, air infiltration has complemented the natural air supply. Regulations still do not consider limitations regarding the airtightness of the envelope. In Spain specifically, since 2006 the Spanish Building Code (CTE) [3] stablishes the implementation of controlled ventilation systems in new and refurbished buildings to ensure adequate indoor quality. Equivalent leakage area can be considered as part of the effective area of the ventilation openings, but airtightness testing is very rarely performed to justify this considered area. Therefore, these ventilation systems are generally oversized since the envelope is presumed to be airtight.

Several studies regarding this matter have been carried out so far in dwellings across Europe, but they tend to focus on a particular aspect and therefore the data collected belong to a specific sample and are not representative of the current building stock [4]. Air leakage measurements are commonly performed in order to evaluate building design and construction practices. Countries like UK, Germany, Belgium, Czech Republic, Estonia and France have created a database [2] in order to have a record of the evaluated cases. Required reporting of the data must be enforced to support data analysis [4]. Average leakage rates (n_{50}) in Europe have been found to be around 7.5 [5]. As for other previous studies carried out in other Mediterranean countries [6,7], results have shown values around 7.0.

An experimental study carried out in Spain has been addressed [8]. This way, a national air leakage database which can set the basis to establish a series of real data and parameters for energy and ventilation

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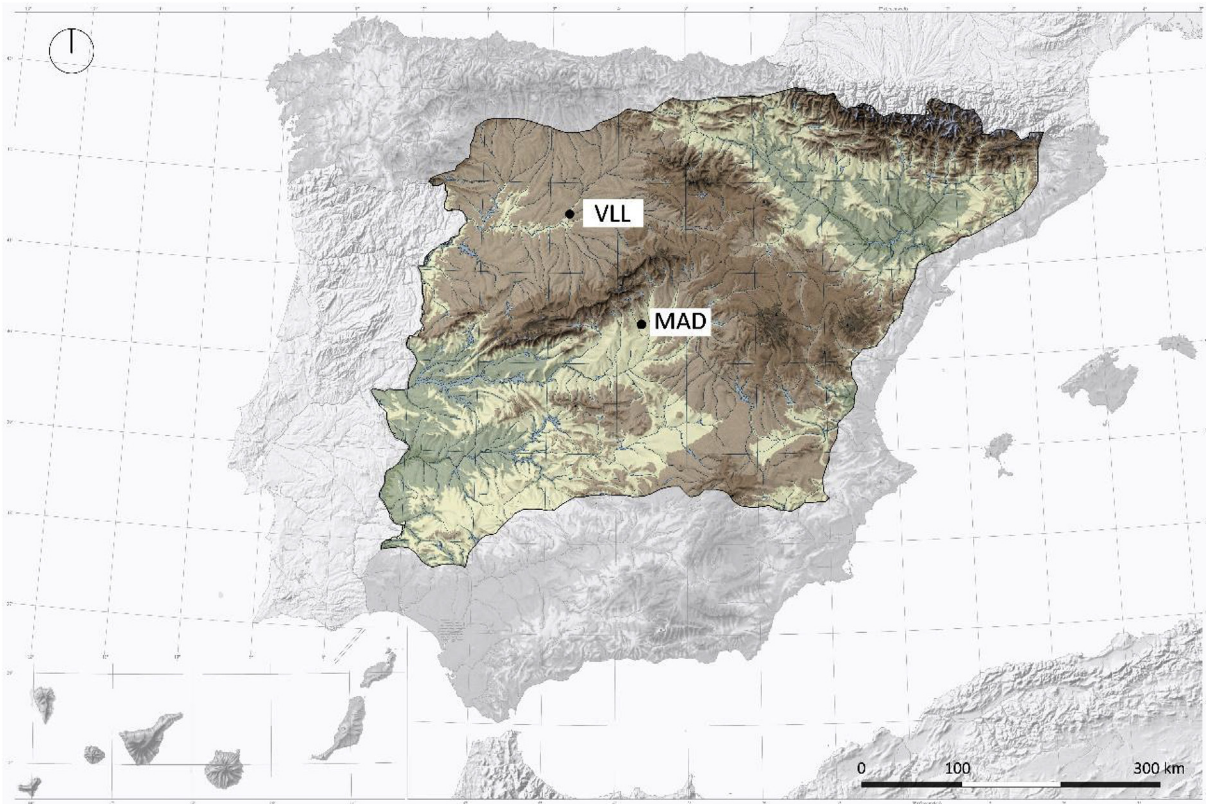


Fig. 1. Location of the tested dwellings in the Continental climate area of Spain [11].

calculations can be originated. A common protocol has been developed with the aim of performing the tests following the same guidelines and gathering a complete set of characterization data [9].

This paper focuses on the characterization of the residential building stock in the Continental area. Despite the fact that no evidence was found to justify that climate is a significant variable in terms of airtightness [10], it seems clear that there are different aspects associated to the region where the building is located such as differences in construction quality, dwelling design or materials, or due to differences in building size or age (status).

1.1. Climate conditions

There is a wide variety of climates in Spain. The country was divided into four main different climate areas: Continental, Oceanic, Mediterranean and Canary Islands. For the purposes of this paper, the study focused on the Continental region. The dwellings tested were located in two different cities in the hinterland of the country: Madrid (MAD) and Valladolid (VLL), that lie on the southern and north plateaus respectively (Fig. 1). Both cities were selected in order to provide representative examples of the Continental climate zone building stock.

In order to identify the climate of the areas analysed, the Köppen Climate Classification system was applied [12]. Both cities are classified as temperate climates-Type C, with a continental influenced climate. Madrid has a *Csa* climate (temperate with dry or hot summer), which covers most of the Iberian Peninsula and the Balearics, occupying approximately 40% of its surface. On the other hand, Valladolid has a *Csb* climate (temperate with dry or temperate summer), which covers the majority of the northeast of the Peninsula. In both cities rainfall is scarce during the summer. In terms of temperatures, perhaps the most important fact is the significant daily thermal oscillation, since thermal differences between day and night often exceed 20 °C.

1.2. The constitution of the building envelope

The housing stock in the Continental area of Spain is dominated by dwellings built over the past century, whose construction followed a common trend throughout the country conditioned by socioeconomic circumstances during this period. A progressive generalization of formal and constructive solutions, which were repeated frequently, can be found, both in Madrid, Valladolid, as well as in other cities of the continental climate area.

The prominence of the exposed brick in the architecture of the 20th century in this area can be highlighted [13]. Only after the 60's hollow brick is employed when exterior mortar plaster is applied.

Broadly speaking, façade systems evolved with the industrialization of metal structures and, above all, with the massive introduction of reinforced concrete in construction from the 40's [14]. The wall as a bearing system was abandoned giving way to the use of grid structures. This allowed the façade to have only function as enclosure and thus it could be thinner and lighter [13].

However, this evolution was gradual and, during the first years of the 20th century, the use of mixed solutions with internal framework and massive load-bearing walls [15] with one layer up to two feet thick was still common. The first examples of cavity walls in Madrid were originated as a result of the desire to hide the line of pillars on the façade. Thus, very wide air chambers were generated, conditioned by the section of the pillars. The use of this resource was a contradiction, since the enclosure, which did not have a structural function any more, gained in thickness [15].

Openings were commonly wooden swing windows with monolithic glass. When the metalwork window appeared, they came to be used in the main façade, placing the wooden windows in the courtyards facades [16].

After the Spanish Civil War (1933–1936), numerous cities received a growing migratory flow from the countryside [17]. There was an important demand for housing that private developers could not cope with, largely due to the period of autarchy that the country was going through and the important restrictions on steel, cement and the transport of materials to construction sites [18]. The State became the main housing developer [17], which favoured traditional constructive techniques. Quick, simple and repetitive solutions were employed [15]. The most widespread façade solution during the 40's was exposed brick of different thickness ranging from a foot and a half to half a foot [18]. In most cases the façade worked as load bearing wall with an internal reinforced concrete structure.

The regulations applied to public housing construction had a decisive influence. From 1940 onwards, the hygrothermal behaviour of the enclosure was contemplated, establishing minimum quality requirements [15].

In large cities like Madrid, the construction of low-cost housing in satellite neighbourhoods was frequently carried out with load-bearing walls perpendicular to the façade. On the other hand, high-class housing recovered the technical development started in the 30's with reticulated reinforced concrete structures, making use of insulating materials of cork on several occasions. Nevertheless, thick wall cavities for regularization of the wall and concealment of pillars were still employed [15].

In Valladolid, the State intervention in the field of housing was very early and ambitious. There were some municipal public housing construction interventions in the 40s, although the state did not act until a decade later when its first project was approved in 1951 [17].

During the period 1956–1961 the largest number of public housing was built in Spain (Fig. 2). These complexes prevailed in this first stage [17]. These were unitary operations with similar typological and constructive characteristics throughout Spain with slight adaptations to different climates [20], although there innumerable deficiencies affecting most of the public constructions can be found [21].

The construction of these neighbourhoods was based on solutions of maximum simplicity, although attention was payed to health standards and environmental comfort issues [15]. A new Standard in 1954 forced the use of the cavity walls, regulating the double layer system with national scope [15]. From this moment, it can be said that the façade abandoned its structural function, reducing its thickness [18]. The single foot brick wall was used especially as an outer layer, cladded with a simple hollow layer and, sometimes, insulating material in the cavity between them [14]. The appearance of new insulating materials offered by the industry (foams and glass fibres, wood sawdust, cellular glass …) allowed the cavity wall system to be economically competitive. Aluminium sliding windows with monolithic glass were also introduced [16].

In Madrid, however, the resistant role of the enclosure prevailed, with a single thick massive wall of a foot in the construction of low-rise social housing. In taller buildings, two layers with cavity were combined [15].

Around 1955 and 1960 a singular type of façade became very popular, fitting the enclosure between the slabs and beams of the main structure, reducing its thickness to the maximum. They assumed the function of pure enclosure of the exterior walls, with insulating material in most cases [15]. This solution was extended in Spain until the 80's [13,14]. In Valladolid, this system was usually employed with a single layer and it was not until the 60's that the cavity walls were introduced.

In the following decades there was a gradual entry of private development and the State initiative ended up assuming a mere subsidiary function from 1963 [17].

In the 70's, electromechanical conditioning systems were generalized. Façades were definitively lightened, already mostly cavity walls, executing the external layer with half a foot in an almost exclusive way [14], even replacing the perforated brick with the cheapest alternative: a half foot hollow brick wall covered and painted [16].

With the entry into force of the Standard NBE-CT-79 [22], thermal insulating were placed into the air chambers, already in a generalized way [16]. The enclosure was finally continuous, setting back the line of pillars towards the interior.

From 2006, new dwellings have to comply with CTE Regulations [23], paying special attention to its performance concerning energy saving and protection against noise. Although construction techniques have evolved, it can be said that conventional solutions still prevail: massive brick construction with air chamber and intermediate insulation is still a widespread solution in this area. A catalogue of constructive elements [24] collects information on the characteristics and benefits of generic constructive solutions related to the basic requirements of the CTE.

In general, the main hygrothermal problem of the most used façade solutions in the Continental climate area of Spain throughout the century is the interruption of the external layer of the massive wall and the insulating material in the joint with the horizontal structure or the pillars. There were no movement joints between structural components and facades, which caused numerous cracks and fissures in the brick walls [16]. Thermal bridges and problems of interstitial condensation and water leaks appeared in the joints between brick and mortar and cracks [14].

Another problematic point of the façade solutions is rolling shutters. Traditionally, the protection and solar control function had been solved with rope or booklet blinds [25]. It is from the decade of the 50's when the use of the rolling shutters in the inner sheet of the enclosure, without insulation in most cases, was generalized. Only in the last decades has this solution been improved with integrated shutters in windows with insulation.

2. Methods

2.1. Fundamentals

Airtightness is usually expressed by means of a power law (Equation (1)) that measures the flow through the building envelope as a function of the pressure gradient across the building envelope:

$$V_{env} = C_{env}(\Delta p^{n}) \quad (1)$$

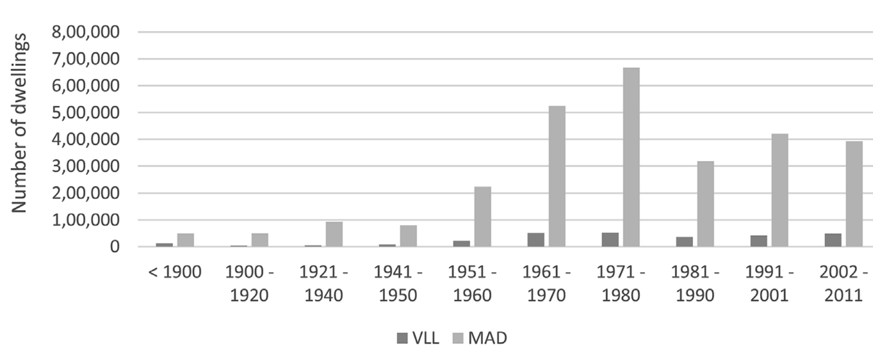


Fig. 2. Number of dwellings built in Madrid and Valladolid for decades [19].

Table 1
Parameters obtained from the power law.

Parameter		Equation	Unit
V_{50}	air flow rate at 50 Pa	$C_{env}(50)^n$	m^3/h
n_{50}	air change rate at 50 Pa (ACH_{50})	V_{50}/V	h^{-1}
w_{50}	specific leakage rate at 50 Pa	V_{50}/A_F	$m^3/h{\cdot}m^2$
q_{50}	air permeability rate at 50 Pa	V_{50}/A_E	$m^3/h{\cdot}m^2$

where:

V_{env}: air flow rate through the envelope of the dwelling (m^3/h)
C_{env}: air flow coefficient, which is related to the size of the opening ($m^3/(h{\cdot}Pa^n)$)
Δp: induced pressure gradient (Pa)
n: pressure exponent

The parameters obtained from the power law, defined in the EN 13829 standard [26] that allow the comparison of results in different buildings are listed below (Table 1):

V (m^3): internal volume. Volume of air inside the measured building, calculated by multiplying the net floor area by the ceiling height. The volume of the furniture is not subtracted. A_E (m^2): envelope area. Total area of walls, floors, and ceilings bordering the internal volume subject to the test. A_F (m^2): net floor area. Total floor area of all floors belonging to the internal volume subject to the test.

Additionally, two parameters can be considered:

- EqLA (10 Pa): equivalent leakage area (cm^2)—National Research Council (NRC) of Canada Model. It is defined as the area of a sharp-edged orifice that would leak the same amount of air as the building does at a pressure of 10 Pa.
- ELA (4 Pa): effective leakage area (cm^2)—Lawrence Berkeley Laboratories Model (LBNL). It is defined as the area of a special nozzle-shaped hole that would leak the same amount of air as the building does at a pressure of 4 Pa.

2.2. Studied dwellings

A total of 129 dwellings located in Madrid and Valladolid (Fig. 3) were analysed in the Continental area of Spain. The cases were chosen according to a stratified sampling scheme [9] with the purpose of gathering a representative sample of the existing residential stock in this climatic area.

The sample reflects the fact that the stock is considerably larger in Madrid. Thus, a total of 112 dwellings (86.8% of the sample) were tested in Madrid and 17 (13.2%) in Valladolid. The sampling method took also into account the prevalence of multi-family housing. 111 cases (86%) were dwellings within blocks of apartments whereas only 18 (14%) were single-family houses. The relative position within the building was also considered for apartments: 15 cases (13.5%) were located in the lower floor, 74 cases (66.7%) had an intermediate position and 22 (19.8) were in the upper floor.

The sample chosen is also representative in terms of the age of the dwellings. Airtightness tests were conducted in dwellings built between 1880 and 2011. The periods of a major construction activity in the Continental climatic area during the decades 1960–1979 (48 cases, 37.2% of the sample) and the period 1980–2006 including the years of the real state bubble, just before its bursting in 2007 (59 cases, 45.7% of the sample), are represented in the sample with a prevalence of cases belonging to these periods.

All the dwellings had a massive construction system, prevailing brick as the main material used to build the opaque area of the envelope. Lightweight construction systems are very rarely used in this area. The construction system of the façade was classified according to its composition: number of massive layers, presence and position of the air chamber and insulation layer. It must be noted that there was not often availability concerning construction details or building specifications, so in most of the cases the construction system had to be deduced visually from the width of the wall and the year of construction. Table 2 shows the types of envelope found in this area and the number of cases associated to each one. Double massive wall prevails, with no insulation nor air chamber (F.03), with air chamber but no insulation (F.06) and with intermediate insulation and air chamber (F.08).

As for ventilation characteristics, the vast majority of the tested cases (98.4%) was ventilated in a natural way, by manually opening the windows, meaning that infiltration is the only constant source of air intake. Most kitchens are supplied with a hood (90.7% of the sample).

Given the extreme winter temperatures in the Continental area of Spain, all the tested dwellings were provided with some sort of heating system. Most of them were based on radiators or individual units (118 cases, 91.5% of the sample), although radiant panel systems (5 cases, 3.9%) or duct systems (6 cases, 4.7%) could also be found. The situation is different concerning cooling systems. Only 73 cases (56.6%) were refrigerated, 74% of them by individual units (ductless split air conditioners) and 26% by a central duct-based system.

2.3. Measurement methods

The prime building factor in determining infiltration and air leakage is airtightness [27], which was determined by the fan-pressurization method, according to EN 13829:2000 standard [26]. For single-family houses the test was performed within the deliberately conditioned space, excluding garages, warehouses, non-conditioned attic spaces or attached structures. The permeability of apartments in blocks was measured individually, considering that the measured air leakage can include possible flows through leaks to adjacent apartments or non-conditioned spaces. Equal pressures were not induced in adjacent zones. In any case, leakages must be considered not only from an energetic point of view but also considering that noise, pollutants and odours transmission can affect the comfort of the occupants and the lack of airtightness can compromise the fire safety of the dwelling.

Recent studies performed with and without guard-zone pressure have shown that inter-zone leakage can represent around 27% of the total leakage [28].

The dwellings were tested following two methods with different preparation of the building described in EN 13829:2000 standard [26]. Method A was performed to measure the air permeability of the building in use in its condition during the season in which heating or cooling systems are used, while Method B was performed to measure the permeability of the building envelope. All the intentional exterior openings were closed, the terminal devices of mechanical ventilation or air conditioning systems were sealed and the interconnecting doors in the part of the building to be tested were opened for the purposes of both tests. In addition, intentional openings were sealed for Method B.

An automated test was performed taking measurements of the air flow rate over a range of applied pressure differences of 11–65 Pa in increments of 6 Pa. Two sets of measurements for pressurization and depressurization tests were undertaken (Fig. 4). According to EN 13829:2000 standard [26] the overall uncertainty is highly dependent upon the environment during the test, being lower than 10% in most cases in calm conditions. Therefore, tests were avoided if the presence of wind was expected during the test in order to minimise uncertainty.

It is essential to know the main sources of infiltration to be able to propose effective constructive solutions to improve the airtightness of existing buildings. During the depressurization stage the main air leakage paths were identified using thermal imaging when there was sufficient temperature difference between the internal volume and the outside environment (Fig. 5). Tests were carried out mostly during the winter season (period November 2016 to March 2017 in Madrid and January to April 2016 in Valladolid). This way a large temperature

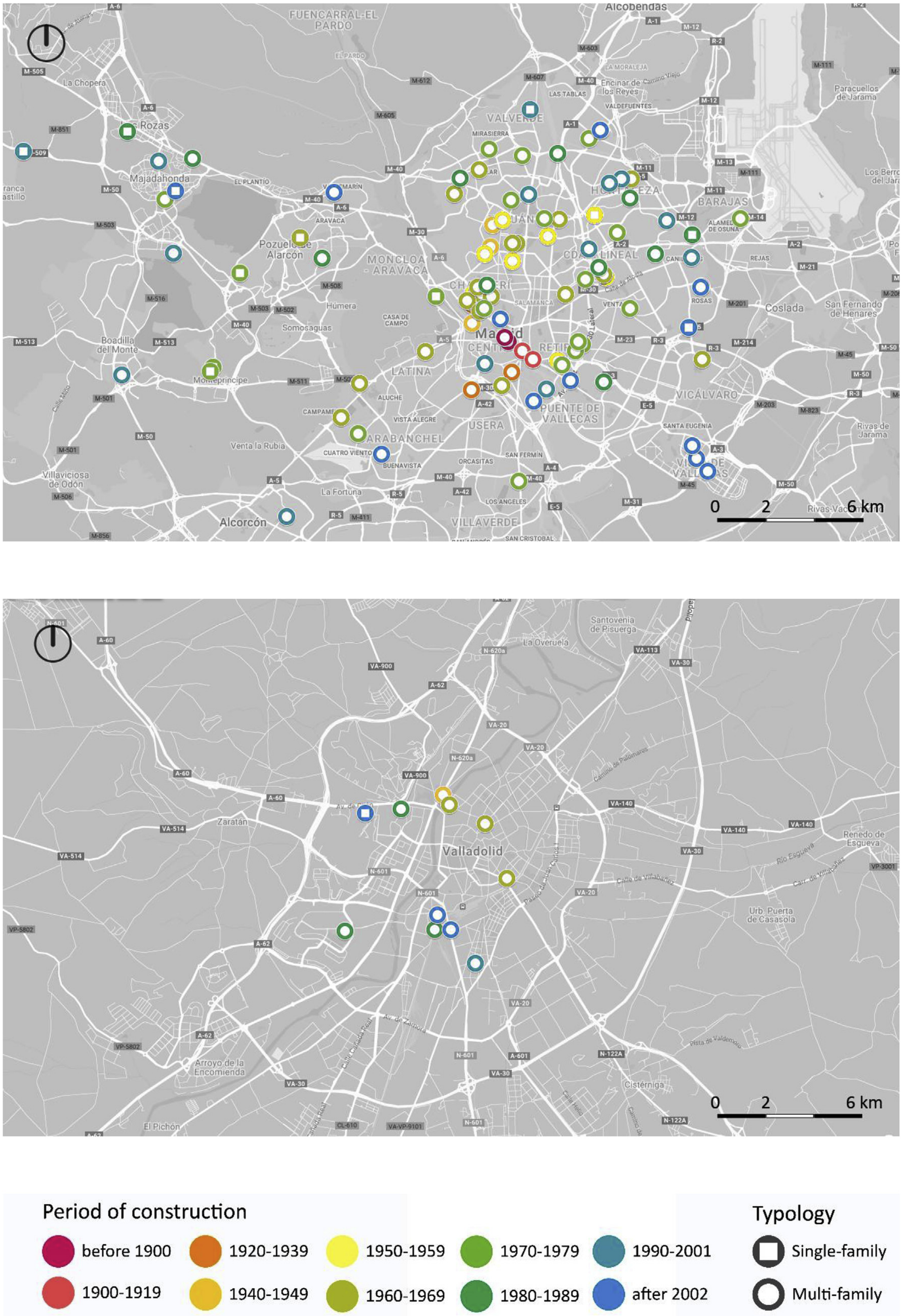
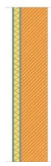
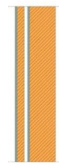
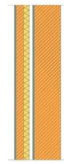
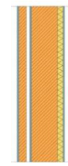
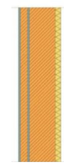


Fig. 3. Location of the tested dwellings in Madrid and Valladolid.

Table 2
Types of envelope of the tested cases.

Code	F.01	F.02	F.03	F.04	F.05	F.06	F.07	F.08	F.09	F.10
										
Layers (in-out)	IP-ML-(EC)	IP-IL-ML-(EC)	IP-ML-ML-(EC)	IP-IL-ML-ML-(EC)	IP-ML-IL-ML-(EC)	IP-ML-AC-ML-(EC)	IP-ML-IL-AC-ML-(EC)	IP- IL-ML- AC-ML-(EC)	IP- ML- AC-ML-IL- EC	IP- ML- ML- IL-VAC-EC
n	9	1	17	1	2	60	6	28	2	3
%	7	0.8	13.2	0.8	1.6	46.5	4.7	21.7	1.6	2.4

Where IP: interior plaster; ML: massive layer; EC: exterior cladding; IL: insulation layer; AC: air chamber; VAC: ventilated air chamber.

gradient was guaranteed, with a mean value of 19.9 °C for the indoor air temperature and 12.9 °C for the outdoor air.

The performed pressurization method does not allow to quantify specifically the contribution of each leakage point to the global air flow rate. Nevertheless, the exponent of the air flow *n* is a non-dimensional parameter that provides information relative to the resistance to the passage of air of the leakage paths. The theoretical limit of the *n* value is within the range 0.5–1 [29]. When the envelope is leaky *n* tends to approach 0.5 (fully turbulent flow), while in very airtight dwellings, the resistance offered by the facade is high and *n* approaches 1 (fully laminar flow). Normally, the air flow adopts a turbulent character in a variable intensity, taking an intermediate *n* value.

Apart from blower door test results, characterization information of each case was gathered by means of a specific tool developed for the purposes of the study: "infil-APP". Different parameters including basic information, dimensions, environmental conditions during the test, type of building, conservation state, construction technology or systems were stored in a tabulated way to facilitate a subsequent analysis of the data. Further details concerning the methodology followed can be found in Ref. [9].

3. Results

The results obtained for the 129 cases analysed are shown. Only data from the tests carried out following protocols for Method B are analysed, given that this method measures the permeability of the building envelope, discarding ventilation openings.

Firstly, the distribution of the dataset obtained for air permeability rate results (q_{50}) of the 129 cases studied was analysed by means of Lilliefors corrected Kolmogorov-Smirnov test [30] and graphically by means of a histogram and a Q-Q' plot (Fig. 6) using the extended statistics tool IBM SPSS Statistics [31]. The null hypothesis of normality H_0 was rejected, given the obtained *p-value* = 0.00 with a significance level applied for the analysis $\alpha = 0.05$ (5%), which indicates non-normal distribution of the data. The obtained values for skewness and kurtosis were 1.7 and 4.8 respectively. Outliers were not excluded from the dataset, given that they were not considered as experimental errors, but as very leaky dwellings.

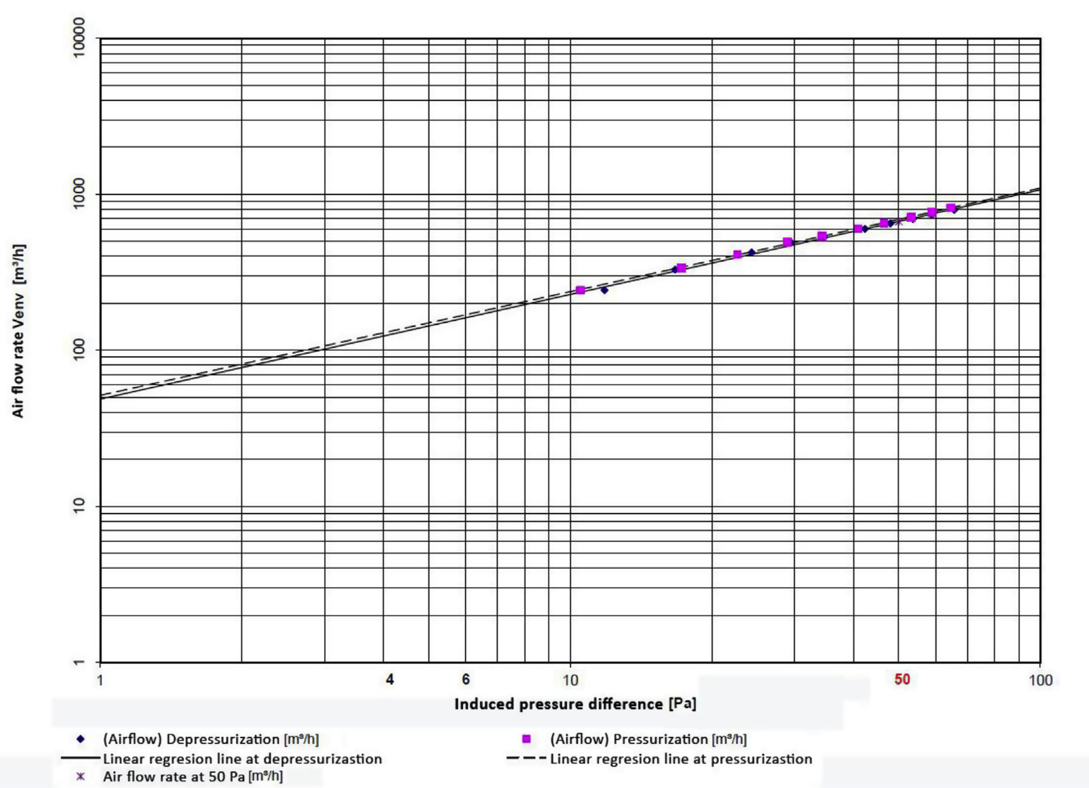


Fig. 4. Example of an automated test graphic.

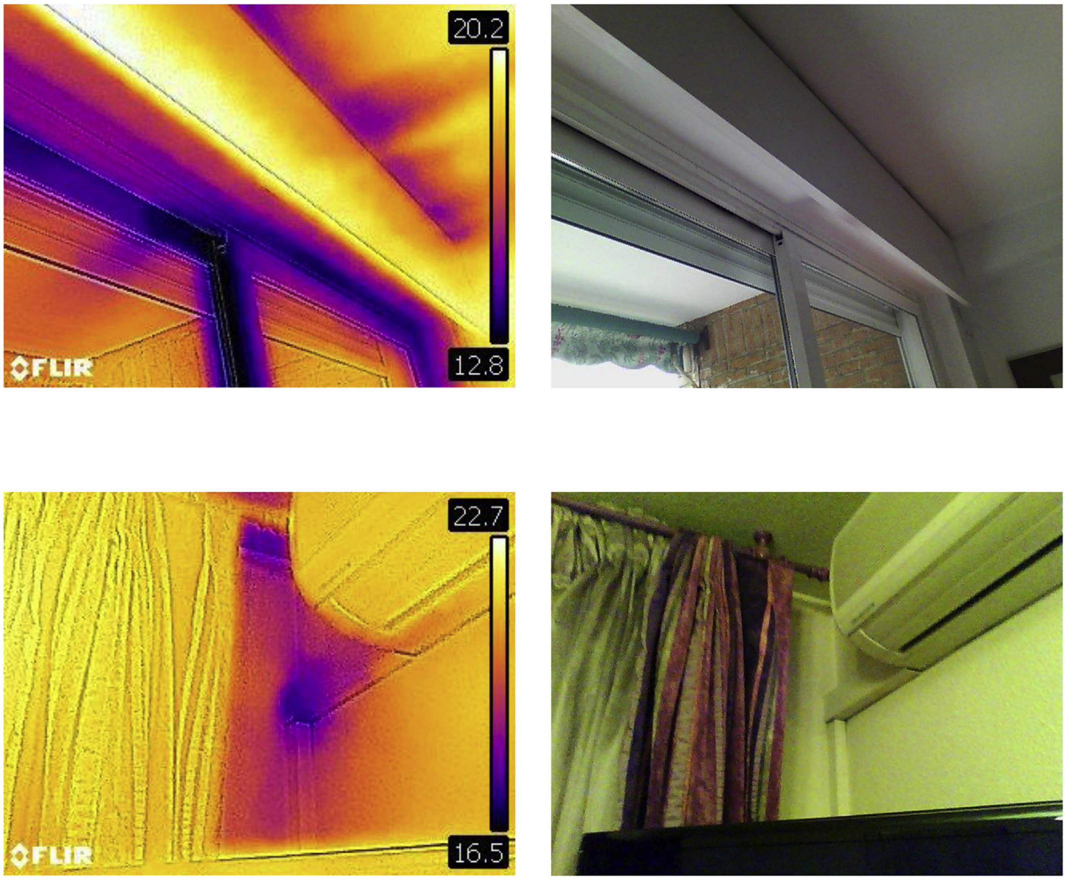


Fig. 5. Thermal images of typical air leakage paths in window, rolling shutter box and duct.

Detailed results of the most significant parameters obtained from the power law are shown in Table 3. Results have been considered separately for multi-family and single-family dwellings given that results obtained for dwellings placed within blocks of apartments include external leakages, internal leakages from other apartments and leakages from non-conditioned spaces such as the hallway, elevator or vestibule. The envelope of the apartments measured delimited 23.7% with the outdoors, 57.5% with other apartments, 12.2% with non-conditioned spaces, 4.9% with other buildings, 1.5% with other spaces and 0.2% with the ground.

The range of the permeability measurements (q_{50}) was large, ranging from 1 to 18.6 $m^3/h{\cdot}m^2$ for multi-family dwellings and from 1.6 to 19.0 $m^3/h{\cdot}m^2$ for single-family dwellings. Single-family dwellings were found to be more airtight than apartments, given that the mean air permeability rate at 50 Pa is 5.4 $m^3/h{\cdot}m^2$ and 6.8 $m^3/h{\cdot}m^2$ respectively.

Accordingly, the air change rate (n_{50}) was also lower for single-family houses (6.1 h^{-1}). The mean air change rate obtained for multi-family dwellings (n_{50} = 7.1 h^{-1}) was closer to the average leakage rates at 7.5 h^{-1} found in other case studies on dwellings in different European countries [5].

Leakage paths were identified by means of a thermographic camera. Typical leakage places were located mostly in window frames, rolling shutters, pipe and duct paths and construction joints. It is shown in many cases that the quality of carpentry is scarce and, above all, that the execution of construction joints has been careless.

The flow exponent *n* is related to the size of the opening. It can be

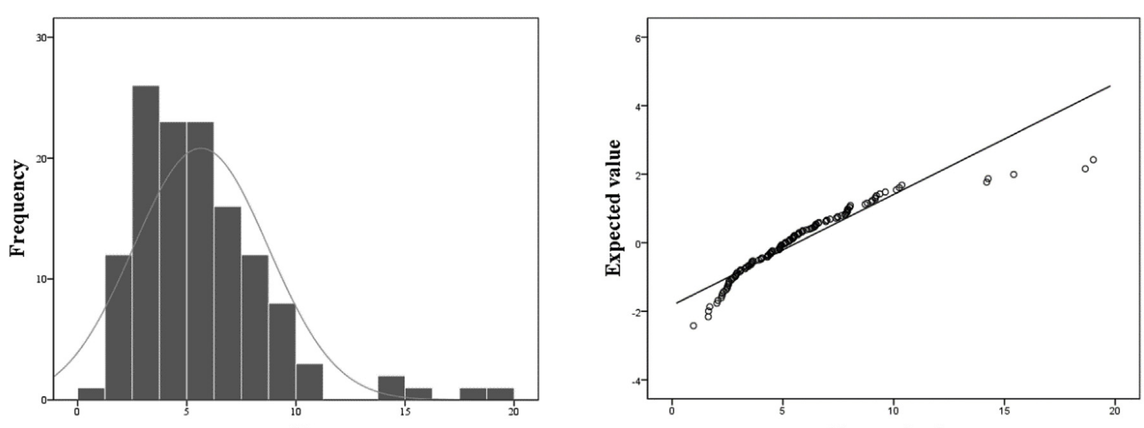


Fig. 6. Distribution of the dataset and Q-Q′ plot of the observed and expected values for air permeability results.

Table 3
Results obtained for the 129 cases analysed expressed by typology.

Parameter	mean		median		sd		minimum		maximum	
Cases	M	S	M	S	M	S	M	S	M	S
V_{50} (m^3/h)	1436.9	2966.0	1212.9	2458.6	891.0	2045.6	226.9	662.0	484.7	9099.3
n_{50} (h^{-1})	7.1	6.1	6.7	5.4	3.7	2.9	1.2	1.4	21.8	12.4
q_{50} ($m^3/h{\cdot}m^2$)	5.4	6.8	4.9	6.1	2.8	4.3	1.0	1.6	18.6	19.0
w_{50} ($m^3/h{\cdot}m^2$)	18.0	15.3	16.3	13.6	9.3	7.6	3.2	3.1	54.5	32.5
n	0.62	0.62	0.61	0.63	0.04	0.03	0.54	0.55	0.72	0.66
ELA 4 Pa (cm^2)	599.3	1239.3	510.4	1022.9	372.5	891.7	87.0	267.7	2117.2	4068.6
EqLA 10 Pa (cm^2)	331.4	675.8	281.0	568.4	206.9	512.8	45.8	145.3	1195.9	2337.3

Where, M: multi-family housing (111 cases).
S: single-family housing (18 cases).
sd: standard deviation.

Table 4
Test results according to different parameters and Kruskal-Wallis test values.

Variable	Category	n	n_{50}	q_{50}	w_{50}	n	Chi-square	Sig.
Regulations	None	65	7.0	5.5	17.9	0.62	3.17	0.20
	NBE-CT-79	59	6.8	5.7	16.9	0.62		
	CTE	5	8.9	6.8	22.2	0.61		
Façace type	F.01	9	5.7	4.2	15.1	0.61	12.63	0.18
	F.02	1	3.2	2.5	8.4	0.66		
	F.03	17	7.77	6.0	19.9	0.62		
	F.04	1	5.3	4.1	13.4	0.63		
	F.05	2	10.5	8.0	25.4	0.60		
	F.06	60	6.9	5.6	17.3	0.62		
	F.07	6	7.4	6.5	18.7	0.62		
	F.08	28	6.9	5.8	17.1	0.62		
	F.09	2	4.3	3.3	11.0	0.66		
	F10	3	9.7	6.5	24.0	0.61		
Insulation layer	None	86	6.9	5.6	17.6	0.62	2.35	0.50
	Interior	8	6.6	5.7	16.7	0.63		
	Intermediate	31	7.2	5.9	17.8	0.61		
	Outer	4	7.2	5.0	17.7	0.63		
Air chamber	None	30	7.1	5.4	18.2	0.62	3.49	0.17
	Non-ventilated	91	6.8	5.6	17.0	0.62		
	Ventilated	8	8.6	6.55	21.6	0.59		
Outer coating	No	96	7.2	5.8	18.1	0.62	0.59	0.44
	Yes	33	6.4	5.1	16.2	0.61		
Window material	Steel	1	11.1	6.6	26.9	0.59	6.77	0.08
	Aluminium	86	7.4	6.0	18.5	0.6		
	Wood	7	7.7	6.4	20.4	0.63		
	PVC	35	5.8	4.6	14.5	0.62		
Rolling shutters	With	122	6.9	5.6	17.4	0.62	0.76	0.38
	Without	7	8.3	6.3	20.9	0.62		
Position within the building	Lower floor	15	8.0	6.3	20.5	0.61	2.48	0.29
	Intermediate position	74	6.7	5.1	16.8	0.62		
	Upper floor	22	8.0	6.2	20.1	0.62		

seen in Table 4 that the mean flow exponent found was 0.62 for both typologies. This value is slightly lower than the one commonly accepted as a reference value ($n = 0.65$) when the flow exponent is unknown, taken from a study with measurements from Canada, Netherlands, New Zealand, UK and USA [32]. This difference can be explained due to the different building systems employed in Mediterranean areas, where massive construction prevails, and handwork plays an important role. Flow exponent n tends to be higher in leakage openings with larger flow resistance than those found in the Mediterranean area [7]. Values around 0.6 are associated with leakage through the interfaces between openings and their opaque surrounds [33].

Furthermore, the influence of different parameters on the airtightness results was analysed (Table 4 and Fig. 7). Given the non-normal distribution of the sample, non-parametric tests were performed for that purpose. Kruskal-Wallis test [30] was performed in order to statistically verify the independence of the variables with the permeability values obtained (q_{50}). The test statistic *Chi-square* value (also known as *Kruskal-Wallis H*) expresses the differences between the compared groups and it is used to assess the null hypothesis that the medians are equal across the groups. On the other hand, the significance (Sig.) is the *p-value* based on the chi-square approximation. It is considered significant for values below 0.05, that is, with a 5% risk of concluding that a difference exists when there is no actual difference. However, the test did not allow to verify a statistically significant relationship between permeability results and any of the parameters assessed (*p-value* > 0.05).

The influence of constructions systems on airtightness was statistically addressed. Since there is a dependency relationship between the construction system and regulations applied, results were analysed according to three periods: 1800–1979 (no regulations regarding the energy performance of buildings were in force), 1980–2006 (after the entry into force of NBE-CT-79), after 2007 (with the obligatory compliance of CTE). It is remarkable that mean airtightness values do not improve with the entry into force of more recent regulations. The fact that none of them considers airtightness nor establish any limitation could explain that building systems and construction is done careless regarding this aspect.

Results for the different types of façade described in section 3.2 are also shown in Table 4. There is a wide spread of the results and differences between the categories, but it must be noticed that the sample size for some categories is scarce so as to draw further conclusions.

Permeability results regarding the insulation layer follow no clear trend. Dwellings without any insulation layer do not have necessarily a worse performance, whereas its position does not seem relevant given that the sample size is not representative for some categories.

The impact of the air chamber was also analysed. Cases with a ventilated chamber (only 8 samples) obtained the worse results. On the other hand, dwellings with a non-ventilated air chamber were found to be the most airtight.

Another relevant factor regarding the permeability of the envelope is the presence of an outer coating, usually mortar. As explained on section 3.2, there is a prominence of the exposed brick in the architecture of this area. However, dwellings with an outer coating performed better in terms of airtightness. It seems logical that a continuous coating can substantially reduce the presence of leakage paths.

Regarding windows, the impact of different materials was assessed. It must be taken into account, that the most representative material was considered when more than one type of window was found. Aluminium and PVC windows prevail in the sample, with better results obtained for PVC windows.

Rolling shutters play an important role on airtightness. However, results do not indicate that these elements constitute important leakage paths. This fact can be explained given that most of the dwellings without rolling shutters were the oldest ones and often in an original state. In Spain, it is a common practice that owners incorporate shutters when dwellings are retrofitted.

Finally, the position of the apartment for multi-family housing has

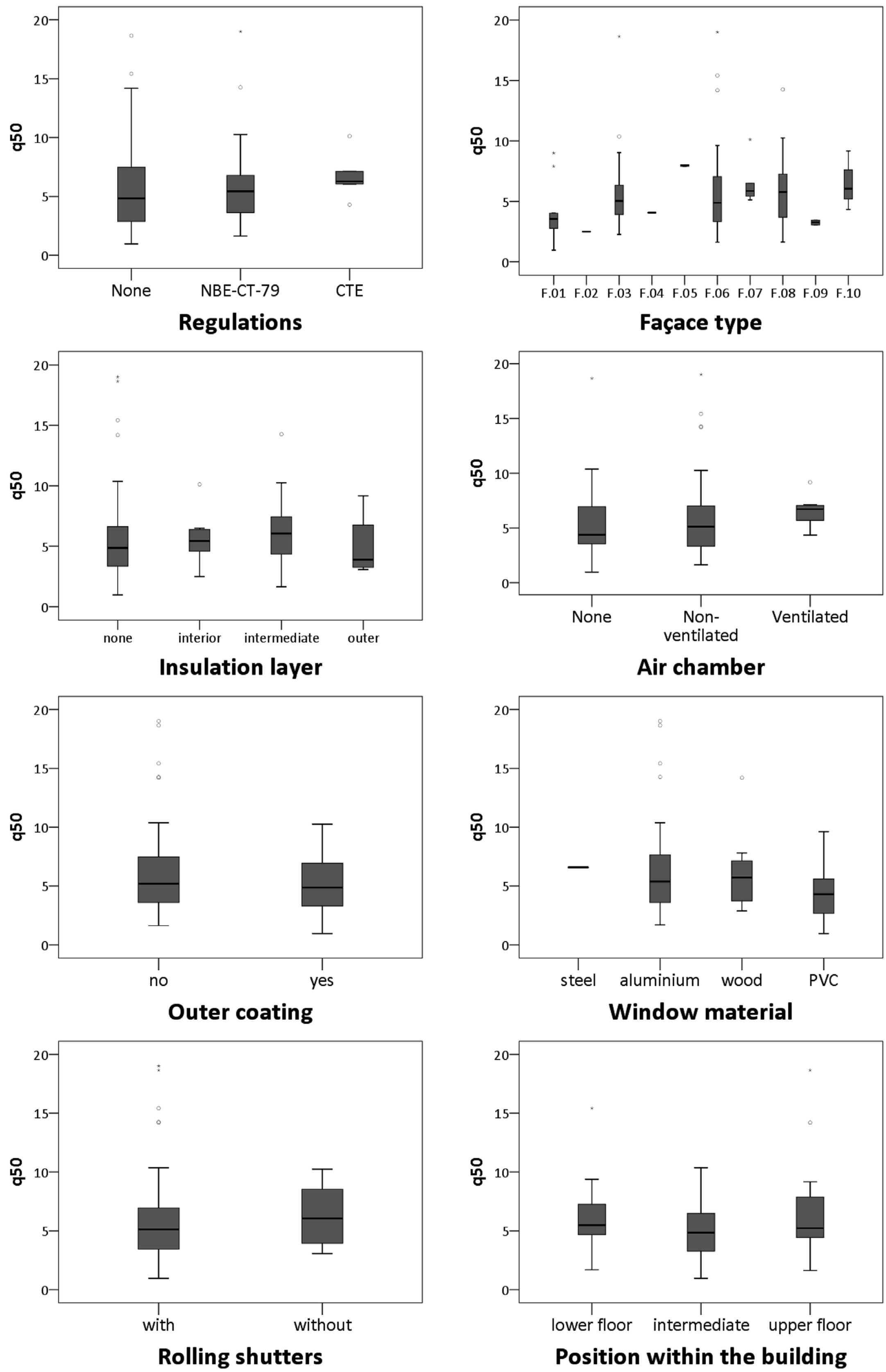


Fig. 7. Boxplots of permeability results of the tested dwellings.

been addressed. Although most of the dwellings where placed in an intermediate position, it seems clear that those are more airtight than the ones placed in an extreme position.

4. Conclusions

Airtightness tests on 129 dwellings in the Continental climate area of Spain were performed. The sample was chosen according to a stratified sampling scheme, which aimed to be representative of the existing residential building stock. Each case was tested by means of an automated blower door test and fully characterized for its inclusion in a new national airtightness database.

Leakage paths were identified with thermal imaging and were found mostly around windows, pipe and duct paths and construction joints. Rolling shutters, a widespread element in this area, constitute a discontinuity of the envelope and thus an especially relevant leakage path. A mean value of 0.62 was obtained for the flow exponent *n*, associated with leakage through the interfaces between openings and their opaque surrounds. These values are consistent with the ones found in precedent studies in other Mediterranean countries.

Permeability results show a wide spread of values, ranging from 1.0 to 18.6 $m^3/h{\cdot}m^2$ for multi-family-dwellings and from 1.6 to 19.0 $m^3/h{\cdot}m^2$ for single-family buildings. Results were considered differently for both typologies in order to differentiate the type of air infiltration source.

In addition, the influence of several construction characteristics on permeability results was assessed. General trends have been identified. Nevertheless, no statistically significant results could be obtained, in part due to the reduced sample size for some categories and also because of the difficulty of isolating the variables.

Further research includes a deeper analysis of the results regarding the parameters that have a major impact on the global result and its impact on ventilation and the energy performance of the dwelling.

Declarations of interest

None.

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