AIRTIGHTNESS AND INDOOR AIR QUALITY IN SUBSIDISED HOUSING IN SPAIN

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ABSTRACT

Over three million subsidised dwellings were built in Spain between 1940 and 1980. Most of these buildings are now obsolete and fail to comply with thermal comfort and ventilation standards. A building's existing energy performance, including its airtightness, should be determined prior to conducting low-energy refurbishment, for those factors, particularly the latter, impact thermal comfort, energy demand and indoor air quality (IAQ) fairly heavily.

This paper introduces a study on airtightness and IAQ in subsidised housing built in Spain in the aforementioned 40-year period. Airtightness and CO_2 measurements taken in 2014-2015 in six units in multi-dwelling buildings, three each in Seville and Madrid, are described.

The results show that in a building in Madrid, the number of air changes per hour at a pressure of 50 Pa (n_{50}) ranges from 3.2 to 8.3. The winter time CO_2 concentration in bedrooms is 1900 ppm and in living rooms 1400 ppm, with peaks of 5000 ppm and 4700 ppm, respectively. The number of air changes per hour at 50 Pa (n_{50}) in Seville, ranges from 5.0 to 9.5. The winter time CO_2 concentration in bedrooms is 1500 ppm and in living rooms 800 ppm, with peaks of 6000ppm and 4000 ppm, respectively. In the summer, however, when users tend to open windows at night primarily to let in cooler air, the CO_2 concentration values observed in Seville drop to 700 ppm and in Madrid to 1100 ppm.

As those values are much higher than recommended in the standards on good indoor air quality, the inference is that winter time housing ventilation must not be allowed to rest solely on users' voluntary opening of windows.

KEYWORDS

Carbon dioxide concentration, infiltration, airtightness, blower door, dwellings

1 INTRODUCTION

Given the impact of building envelope airtightness (measured as air infiltration) on energy efficiency, occupants' thermal comfort and indoor air quality, it has become a standard area of research in the United States in general and the Lawrence Berkeley National Laboratory (LBNL) in particular (Sherman et al, 2007), and in regions of Europe with cold climates (Montoya et al, 2010; Jokisalo et al; 2009, Pan, 2010). In Southern Europe, however, studies on which to base a sound analysis and interpretation of the interaction between these factors are largely lacking (d'Ambrosio et al, 2012, Pinto et al, 2011). Spain's Technical Building Code (CTE, 2006), for instance, does not specify the airtightness to be met by building envelopes, but only the ex-factory permeability of the carpentry, i.e., irrespective of its subsequent on-site assembly.

Most of the studies on the relationship between IAQ and airtightness conducted in the US (Prince et al., 2006, Less et al., 2015) and other cold climates (Sharpe et al, 2014; Mickaël et al, 2014; McGill et al, 2015) conclude that resident behaviour is instrumental to effective ventilation and that mechanical ventilation is needed to improve the quality of indoor air. The LBNL is pioneering research on the link between indoor air quality and minimum ventilation rates (Turner et al, 2013; Turner et al, 2012; Sherman et al, 2011).

Many papers have been published on low-energy refurbishment in Spain, although the focus is primarily on improving envelope insulation (Dominguez et al, 2012; Cuerda et al, 2014), with scant attention in airtightness to its impact on indoor air quality. In light of that paucity of research, this study analysed envelope airtightness in subsidised housing built in Madrid and Seville in 1940-1980 and its relationship to indoor air quality. During much of that (post-Civil War) period, the construction industry's primary objective was to provide housing for large swathes of the population in a context in which environmental requirements were simply not envisaged. The end date, the early nineteen eighties, marked the institution of the country's earliest legislation limiting energy demand.

Moreover, as most of the housing built in the period studied has no specific ventilation system, air replenishment depends on the voluntary opening of windows in mild weather. Against that backdrop, the primary aims of this study were to characterise air tightness in a group of social housing developments erected in the period 1940-80 and assess air quality at various levels of air tightness in these dwellings in different seasons of the year.

2 METHODOLOGY

The methodology followed included:
-choosing and defining the housing units for the study sample
-taking in situ measurements, including blower door airtightness tests, smoke tests to locate air leaks and CO_2 concentration measurements to determine indoor air quality

These tasks are described in greater detail below.

2.1 Case studies

Six units in multi-dwelling buildings, three in Seville and three in Madrid, were chosen for the airtightness tests and CO_2 measurements. The sampling criterion for the units chosen was that they had to be sufficiently representative of the architectural typologies and construction solutions for façades most commonly deployed in 1940-1980. A number of user profiles were chosen, given their effect on use and occupancy. The buildings sampled also exhibited different degrees of envelope refurbishment.
Figure 1 shows the location of the units in Madrid (A, B, C) and Seville (D, E, F), while Table 1 lists the dwelling characteristics and user profiles.

Figure 1: Location of units studied in Madrid and Seville

Table 1: Case study

Case study	Quarter	Year built	Type of façade	Floor area (m^2)	Façade area (m^2)	Volume (m^3)	No. occupants	User profile	Extent of refurbish-ment
A	Manoteras	1960	1- ft brick	63	36	145	2	Couple	Basic
B	Manoteras	1976	0.5-ft brick+air chamber+partition	64	69	159	3	Couple with child	Major (outer)
C	Hispano-américa	1965	0.5-ft brick+air chamber+partition	76	45	193	4	Couple with children	Intermediate
D	Bami	1963	1- and 0.5-ft brick	63	49	205	3	Stu-dents	Basic
E	San Pablo	1965	0.5-ft brick+air chamber+partition	51	31	112	2	Couple	Basic
F	Diez Mandamientos	1964	0.5-ft brick+air chamber+partition	64	47	163	4	Couple with children	Intermediate

The clearance height in all the units ranged from 2.20 to 2.50 m, except in unit D, where it was 3.25 m.

Basic refurbishment consisted in everyday maintenance with no changes in the envelope other than repainting; intermediate in upgrading the unit and replacing the carpentry; and major in replacing the carpentry and adapting the building envelope. Major refurbishment in the unit in Madrid even involved removing the kitchen vents with on-site inspection during the work.

2.2 Fan pressure trials

The blower door test, a technique consolidated among the scientific community, was conducted in this study further to the procedure set out in Spanish and European standard UNE EN 13829:2002 (UNE-EN 13829:2002). The test was performed in all the units in the sample to determine building envelope airtightness. The findings were subsequently used to ascertain its possible effect on air quality, defined as indoor CO_2 concentration. Table 2 shows Parameters defined in UNE 13829

The test consisted in measuring the air flow when a fan was positioned on the outside door (Figure 2) to remove air out of (depressurise) or force air into (pressurise) the dwelling to a positive or negative pressure of around 50 Pa. All windows and any other outer doors in the unit were sealed and all the inner doors kept open during the test. Outdoor air consequently flowed into the dwelling across any infiltrations in the envelope. Smoke generators and infrared thermographic analysers were used to locate such air leaks. Envelope infiltrations were accurately located by this joint use of blower door trials and thermographic and smoke analyses.

Figure 2: Blower door position during airtightness trials

Table 2: Parameters defined in UNE 13829

Parameter	Name	Unit	Definition
V50	Air Leakage rate at 50 Pa	m^3/h	Air flow across the building envelope including the flow rate through joints, fissures and the superficial porousness
n50	Air change rate at 50 Pa	h $^{-1}$	Infiltration air flow rate per internal volume (V)
w50	Specific leakage area at 50 Pa	m/h	Relationship between the rate of infiltrated air and the usable area (S).

2.3 Monitoring environmental conditions

The environmental conditions were monitored in all the units studied with a multi-parametric data logger that recorded ambient temperature, relative humidity and air quality (with a CO_2 probe) at 10-minute intervals. Two such data loggers were positioned in each unit, one in the daytime and the other in the night time living area. The loggers had USB connectivity to download the data to a computer. Their positions in one of the units are depicted in Figures 3 and 4.

Figure 3. Plan view of unit E, showing data logger positions

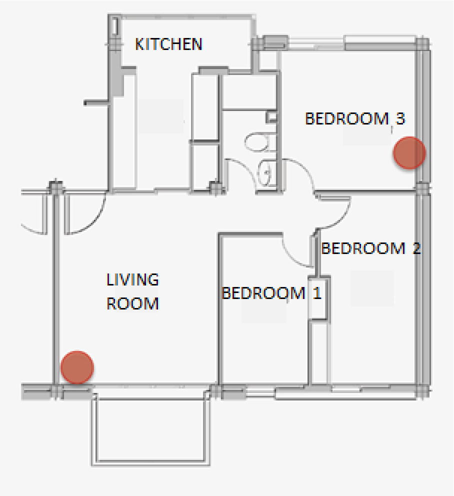
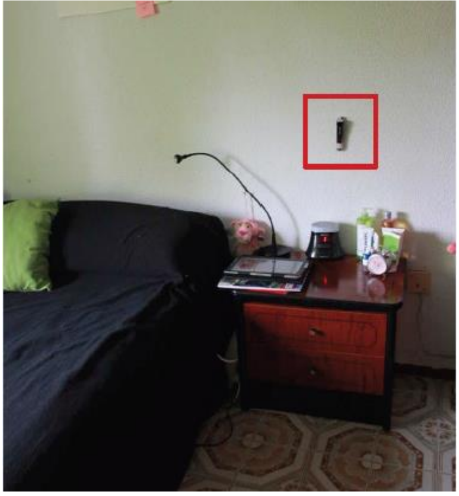


Figure 4: Data logger installed in bedroom in unit E



3 ANALYSIS AND DISCUSSION OF THE RESULTS

3.1 Airtightness measurements

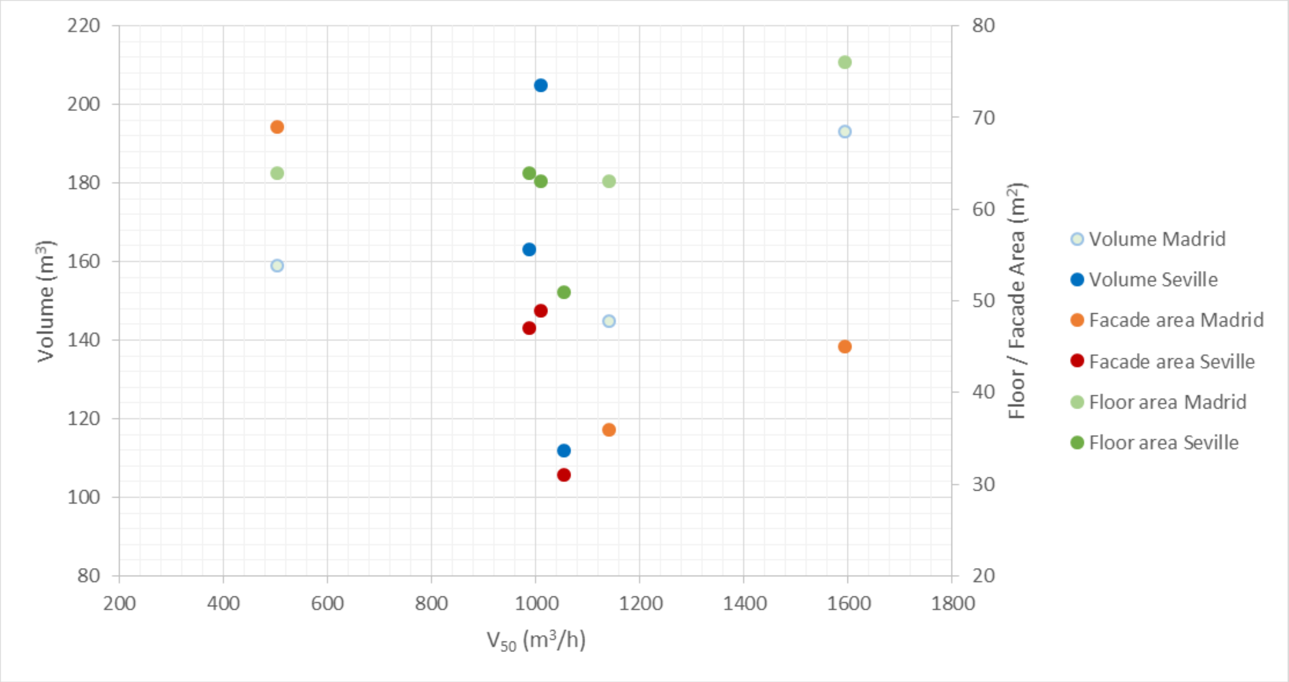
Table 3 gives the blower door trial findings for the six units studied, which are plotted against a number of parameters in Figure 5. No relationship was observed between infiltration air flow (V_{50}) and any of the other parameters: façade area, dwelling area, dwelling volume or extent of refurbishment.

In Madrid n_{50} ranged from 8.9 to 3.2 and w_{50} from 7.9 to 21. The unit that underwent the most extensive refurbishment had the lowest infiltration rate, due to the exhaustive control conducted during the works. In Seville, given the greater disparity in clearance heights, w_{50} (which ranged from 15.4 to 20.6) was deemed to be a more suitable parameter, inasmuch as most air leaks occurred at abutments between construction elements rather than on the continuous areas of the façade. Here the values were similar for the unit with basic maintenance only and the one where the windows had been replaced because workmanship during installation of the new windows went largely uncontrolled. That further to the smoke test findings most of the air leaks were located at the connection between the window and the enclosure stands as proof of the importance of on-site quality control.

Table 3: Blower door test results

Case Study	Floor area (m^2)	Facade area (m^2)	Volume (m^3)	V_{50} (m^3/h)	n_{50} (m/h)	w_{50} (h^{-1})
A	63	36	145	1140	7.9	18.1
B	64	69	159	504	3.2	7.9
C	76	45	193	1594	8.3	21.0
D	63	49	205	1010	4.9	16.0
E	51	31	112	1053	9.4	20.6
F	64	47	163	988	6.1	15.4

Figure 5: Infiltration air flow vs dwelling volume, façade area and dwelling area.



3.2 Air quality measurements

Figure 6 shows that in a typical winter month, the highest CO_2 concentrations were recorded in the most air-tight dwelling in Madrid, with mean values on the order of 2500 ppm. In all the other cases studied, the mean ranged from 1100 to 1800 ppm (absolute concentration in air). The peak CO_2 concentration values, which ranged from 4000 to 5000 in Madrid and from 4000 to 6000 in Seville, were recorded in the bedrooms in the winter. The highest peaks were observed in the most airtight units.

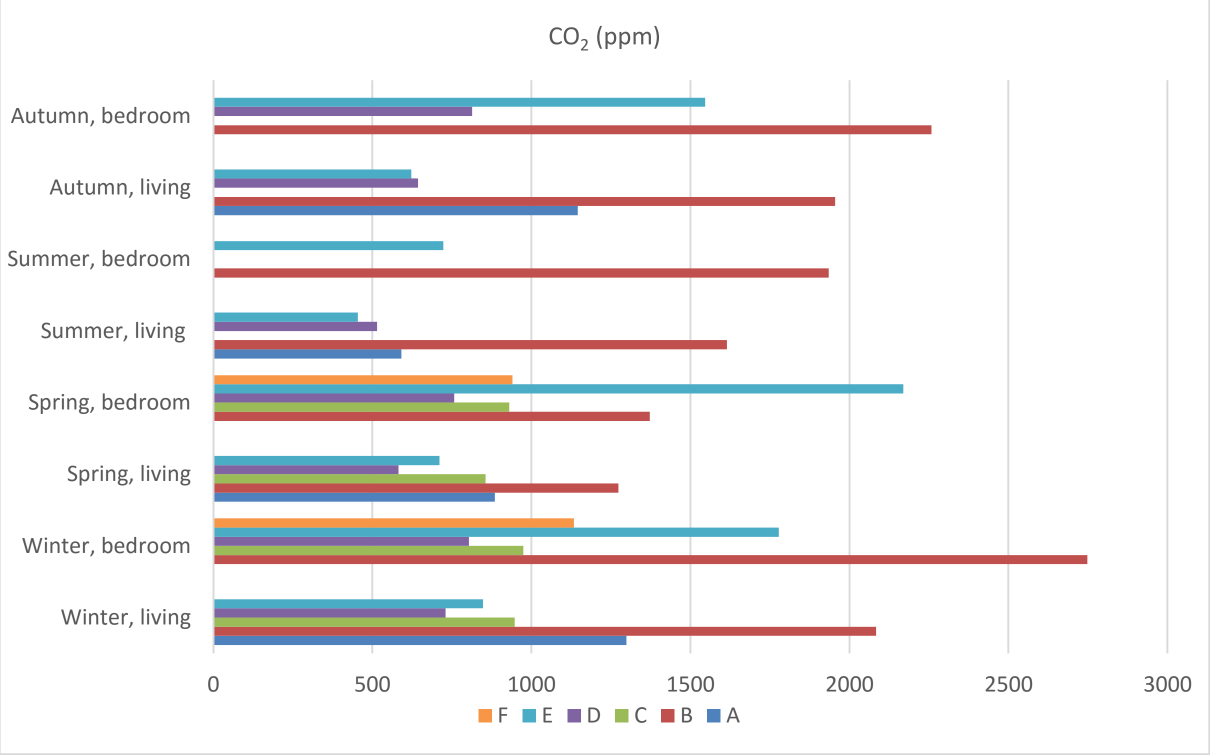
The highest living room concentrations were logged late at night, with peaks of 3000 to 4700 in Madrid and 3000 to 4000 in Seville.

Figure 6: Winter time CO_2 concentration in ppm in bedrooms occupied by two people in selected units

The CO_2 concentrations found for the dwellings are shown in Figure 7. The values recorded were lower in summer and spring than in winter and autumn. The concentration was substantially higher in the bedrooms than in the living rooms in all seasons, as would be expected given the longer periods of time, at night especially, that the former were continually occupied. The highest values in the living room were observed in the middle hours of the day as well as in the hours shortly before bedtime.

Seasonal fluctuation differed in Madrid and Seville. In the former, the variation between winter-autum and summer was approximately 30 % in the living room and 40 % in the bedroom. In Seville, the living room winter-to-summer values fluctuated by 60 % and the autumn/spring-to-summer concentrations by 30 %, while the bedroom values were twice as high in winter as in summer. These findings have to do with user-mediated ventilation (by opening windows), a more frequent practice in Seville where the climate is warmer than in Madrid.

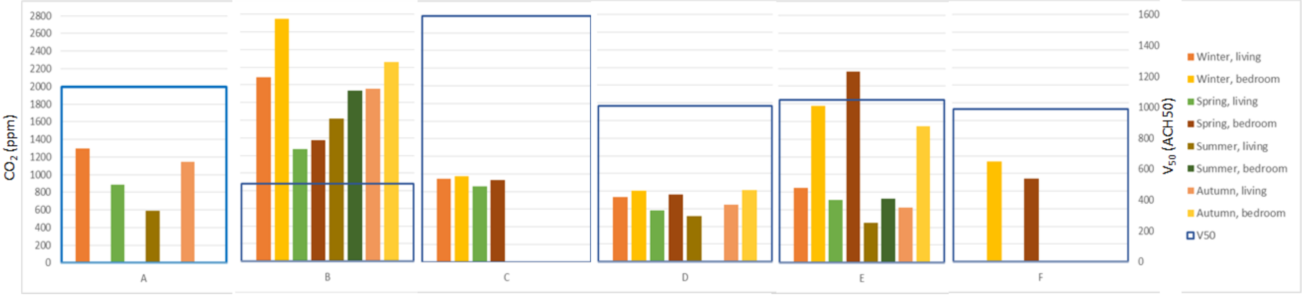
Figure 7: Mean CO_2 concentration (ppm) in all four seasons in all the units studied



3.3 Relationship between air tightness and air quality

Figure 8 shows mean CO2 concentration (ppm) vs air tightness. As noted, occupant behaviour differed in Madrid and Seville. In the former, where temperatures are usually lower, users tend to open and close windows less routinely. As a result, envelope airtightness in Madrid is related more closely to air replenishment, which is clearly insufficient most of the time, unless windows are opened. In Seville, where annual temperatures are more temperate, windows and doors are opened more frequently to replenish the air. The outcome is a more random distribution of indoor CO_2 concentrations, which depend less on airtightness, for indoor replenishment is observed to vary widely among dwellings with similar airtightness values.

Figure 8: Mean CO_2 concentration (ppm) vs air tightness in the units studied



Note: The bedroom in dwelling D was occupied by only one person.

4 CONCLUSIONS

The V_{50} values measured were apparently unrelated to dwelling area and volume, as well as to façade area. With one exception, however, w_{50} and the extent of refurbishment were found to be related. Case dwelling B (Madrid), where extensive refurbishment had been conducted, had the lowest w_{50} value, at around 7.9 h^{-1}, lower even than required by European standards. Case dwelling F (Seville), also extensively refurbished, exhibited a value of around 15.4 h^{-1}, clearly lower than in the dwellings in Madrid and Seville with scant refurbishment, where it ranged from 16 to 20.6 h^{-1}.

The V_{50} values, together with the lack of specific ventilation systems outside of user-dependent opening and closing of windows, led to low n_{50} values and a generally deficient quality of indoor air with high CO_2 concentrations, particularly in bedrooms in the winter. This was especially apparent in housing where extensive refurbishment had been performed: dwellings B (Madrid) and F (Seville) exhibited the highest CO_2 concentrations throughout the year. Concentration values were widely scattered, however, due especially (in addition to dwelling use and room occupancy) to the voluntary opening and closing of windows (particularly in Seville), which was the sole system of ventilation in the six dwellings analysed.

Users failed to perceive the deficient indoor air quality. That, in conjunction with the lack of ventilation systems in these homes, even in the ones with extensive refurbishment, gave rise to generally poor and often unhealthy indoor environments with high CO_2 concentrations and the risk of condensation damp, especially in the most air-tight dwellings. Low-energy refurbishment in housing must, then, aim not only to improve the thermal resistance of the building envelope and its airtightness, but also to ensure that ventilation systems are suitable and efficient.

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