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Air-tightness field data for dwellings in Ireland

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> This paper reports the air permeability test results of 28 houses. > Results are used to assess the effect of age and stage of retrofit on air tightness. > Newer buildings are not by default more airtight than older buildings. > Good design, high-quality workmanship, and rigorous control are critical to create a good building. > first step to a national database.

ACCEPTED MANUSCRIPT

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1. Introduction

Air-tightness is an important contributor to energy efficiency, thermal comfort and indoor air quality of dwellings [1-4]. For these reasons, understanding air-tightness is important for new design and retrofitting of existing buildings. As an aid to reducing energy consumption, the Technical Guidance Document Part L (2008) - Conservation of Fuel and Energy (Dwellings) refers to Envelope Air Permeability testing of new dwellings, setting a 'reasonable upper limit for air permeability' of $10\text{m}^3/\text{hr}/\text{m}^2$ at 50Pascals[5]. This limit is undemanding when compared with other European countries, such as Estonia which limits air permeability to $3\text{m}^3/\text{hr}/\text{m}^2$ [6] and the increasingly popular PassivHaus standard requiring an n50 of 0.6 air changes per house (ach) [7].

Ireland's National Methodology for the calculation of energy performance of buildings, the Building Energy Rating (BER), includes provision for the assessment of heat loss due to air infiltration. The standardised software estimates air permeability using air-tightness test results or alternatively by applying an algorithm related to the buildings parameters.

There have been many studies relating to the characteristics of building air-tightness across Europe [3, 8, 9] and in particular in the USA where over 70,000 fan pressurisation measurements have been collected and analysed, comparing air-tightness in terms of age, size, and construction type [10, 11]. However, there is a paucity of real data relating to the air-tightness characteristics of existing dwellings in Ireland. There is often the perception that newer dwelling air-tightness is better than for older buildings. However, in Ireland with the lack of empirical data this cannot be confirmed.

This paper reports the air permeability test results of 28 dwellings ranging in age from 1944 to 2008. A number of the older houses have undergone varying stages of retrofit. The results are compared to past studies and compliance with the existing standards. The relationship of construction type, age range, design details, and effect of retrofitting on air permeability is examined. An evaluation is made of the effect of the air-tightness testing on BER of the dwellings in the study. While statistically small the dwellings are broadly representative of the many dwellings that will be retrofitted over the coming years.

2. Building Typology

Previous studies have established a relationship between air-tightness, building age and construction type [8, 10]. In Ireland, 70% of the existing housing stock, was built prior to

1991, 88% of which was built prior to 1980 when minimum insulation standards were implemented [12]. These energy inefficient houses fall well below the current building regulations requirements and offer the good potential for energy savings from retrofitting. This study focuses on the quantitative data gathered from 28 occupied single family residential semi-detached and terrace houses, which combined make up the largest proportion of the 1.46 million dwellings in Ireland, 27.3% and 17.6% respectively [12]. Chan [10] found that US dwelling air-tightness can be normalised according to year of construction and divided the database into four broad age categories. This study adopted a similar approach, grouping the dwellings in three categories, based on year of construction, as shown in Table 1. The buildings studied are of similar construction type; dwellings have two-storeys, three bedrooms, slab-on-grade floors, load bearing external cavity walls and cold roof construction. The average floor area and volume of the studied houses was 80m^2 and 202m^3 , respectively. Natural ventilation is provided by passive wall vents designed with closable hit and miss or permanently open louvered vent grilles in each room. However, many of the pre-1975 houses have no wall vents.

A number of the pre-1975 and 1980's dwellings had undergone different phases of an energy efficiency retrofit scheme. The full retrofitting process of each of the houses consisted of four operations:

- Installation of new double glazed windows and doors (DG);
- Placing bonded- beaded cavity wall insulation (CI);
- Placing 200mm glass fibre insulation in the attic (AI);
- Installation or upgrading of gas fired central heating (CH).

Hereafter, complete retrofitting refers all four operations being complete and partially complete refers any three or less of the operations being complete.

Table 1. Dwellings studied grouped by year of construction

a) Pre- 1975 house type b) 1980's house type c) 2008 house type

Fig. 1. Typical house type for each age category

3. Test Procedure

The location of individual air-leakage paths are often difficult to identify by visual inspection, thus, assessing the building envelope as a whole, using the standardised blower door test, is the only reliable means of assessing building air-tightness. Testing was carried out in accordance with ATTMA (the Air Tightness Testing and Measurement Association) Technical Standard [13]. The Technical Standard is generally compliant with IS EN 13829:2001 Thermal performance of buildings – Determination of air permeability of buildings – Fan pressurization method. Prior to testing, dwellings were surveyed and the internal envelope area (A_E) and volume (V) accurately calculated.

Due to the variety of methods used to deal with intentional openings during testing, direct comparison of blower door test results between countries is often difficult [14, 15]. Testing to

determine the air permeability was largely compliant with Method A, of EN 13829. External doors and windows, intentional vents, attic hatches, letterbox and extract fans were closed but not sealed; open fireplaces were sealed.

Testing was carried out using a Retrotec Q46 Automated Blower-Door. The Retrotec Q46 has Maximum Flow at 50 Pascal test pressure of 9,514m³/h and Minimum Flow at 10 Pascal of 65m³/h and incorporates regulated variable frequency speed controllers to provide a stable speed control, making it suitable for testing dwellings. The fan was secured to the house front door using the Retrotec soft panel frame. Pressure and flow rate were controlled using a laptop, connected to a DM-2A Automatic Micro-manometer, which controlled the fan. In addition to the DM-2 the test software continuously logged a number of parameters including fan flow, test pressure and the area measurements.

Both pressurisation and depressurisation test cycles were undertaken to a pressure differential across the envelope of 50 Pascals. The average of both results was recorded as the air permeability for the building. Averaged results are an important component of the test as leakage paths have complicated shape and different aerodynamic characteristics depending upon air flow direction. The 'value effect' can also occur where by a component can be pushed up during pressurisation and pulled down generating a seal during depressurisation. The BRE have shown that pressurisation and depressurisation results can differ by up to 20% [16]. During testing, wind speed and ambient temperature conditions were measured using a hand held thermo-anemometer to ensure compliance with IS EN 13829:2001. A smoke pencil was used to identify the key air leakage locations.

Normalised air permeability characteristics are usually expressed as:

- 1) Air Permeability, q₅₀, - measured as the volume of air passing through each square metre of building envelope, including ground floor area, in one hour (m³/hr/m²);
- 2) Air Leakage Rate, n₅₀, – air flow rate at a reference envelope pressure difference by the gross internal volume of the dwelling. Unit: air changes per hour (ach).

From a measurement standpoint, air-tightness means measuring the flow through the building envelope as a function of the pressure across the building envelope and thus leakage testing is based on the fundamental mechanics of airflow. ATTMA[13] utilises the power law equation to establish the relationship between the recorded fan flow (Q) and building pressure differentials (Δ_p) and is given as:

$$Q = C (\Delta_p)^n \quad (1)$$

where Q is the leakage air volume flow rate in (m³/hr);
 C the flow coefficient that is related to the size of the opening;
 Δ_p the internal/external pressure difference across the envelope, Pa;
 and n the flow exponent characterising the flow regime.

Flow exponent, n, values are presented in Table 1, and addressed later in the paper.

4. Measurement Results

The mean air permeability of the test result dataset presented in Table 2 was $9.1 \text{ m}^3/\text{hr}/\text{m}^2$, with the minimum $5.12 \text{ m}^3/\text{hr}/\text{m}^2$ recorded in a pre-1975 terrace house, and maximum $14.42 \text{ m}^3/\text{hr}/\text{m}^2$ recorded in a 1980's semi-detached house. Fig. 2 demonstrates that 50% of all dwellings exceeded the Part L 'reasonable upper limit' of $10 \text{ m}^3/\text{hr}/\text{m}^2$. Sub-dividing the dwellings by age category, counter intuitively, on average, the older buildings were more air-tight than the new dwellings with the pre-1975 dwellings, 1980's dwellings and 2008 dwellings mean air permeability of $7.5 \text{ m}^3/\text{hr}/\text{m}^2$, $9.4 \text{ m}^3/\text{hr}/\text{m}^2$ and $10.4 \text{ m}^3/\text{hr}/\text{m}^2$ respectively. The air permeability of the 2008 dwellings ranges from $6.02 - 13.24 \text{ m}^3/\text{hr}/\text{m}^2$, with just 2 from 7 houses tested within $10 \text{ m}^3/\text{hr}/\text{m}^2$ upper limit.

Smoke pencil test observations correlated with previous research [4, 17] uncovering an array of different leakage paths. Typical leakage locations were junctions between floor and wall at 1st floor level, gaps around attic hatch, letterbox, leakage through and around windows and doors, penetrations in envelope for plumbing and electrical installations such as light switches and sockets, fire alarms and around waste pipes.

Table 2 Measured air permeability and related parameters of dwellings in this study

Fig. 2. Measured air permeability of dwellings studied, categorised by age (n =28)



Fig. 3. Typical leakage paths: a and b) passive wall vents, c) accidental hole in plasterboard and d) plumbing to attic.

Notably, intentional passive vents in many houses were not sealed to the external wall and large gaps remained when the slotted vents when closed, as shown in Fig. 3 a and b. Significant leakage occurred through accidental voids in the stud partition internal walls at first floor level of 1980's houses, as shown in Fig. 3c. Piecemeal sealing was frequently of poor quality using unsuitable materials and often ineffective, as shown in Fig. 3d.

5. Energy Performance

The Dwelling Energy Assessment Procedure (DEAP), Ireland's official procedure for calculating the BER of new and existing dwellings, assesses compliance with the EPBD and Building Regulations. The DEAP software program, based on I.S. EN ISO 13790 [18] Energy Performance of Buildings - Calculation of energy use for space heating and cooling, utilises the UK Standard Assessment Procedure (SAP) [19] incorporating modifications for Ireland's climate. The methodology utilises standardised fan pressurisation test results to calculate the air permeability heat loss rate (W/K). Air permeability, q_{50} , expressed in $\text{m}^3/\text{hr}/\text{m}^2$, must be modified to represent infiltration under normal conditions. The adjusted result of the air permeability test in air changes per hour (ach_{adj}) is calculated by dividing q_{50} by 20 [5, 9, 20]. In the absence of air-tightness test results DEAP applies an algorithm to

estimate air permeability characteristics. Calculations take into account floor area, number of storeys, structure type, floor type, percentage of windows and doors draft stripped and number of sheltered sides.

Table 2 presents the change in theoretical energy consumption ($\text{kWh/m}^2/\text{yr}$) from BER's, contrasting the DEAP algorithm method (Method A) and the inclusion of actual air-tightness tests results (Method B). The change in theoretical energy consumption was calculated by $(\text{Method B} - \text{Method A})/\text{Method A}$, expressed as a percentage. In general the DEAP algorithm yielded slightly conservative results, overestimating the air permeability of the dwellings. When air-tightness test results are included a nominal 5% reduction in theoretical energy was recorded for the retrofitted dwellings; for dwelling No 3, an as-built terrace house, the calculated reduction is 7%. Some notable exceptions are the 2008 houses where theoretical energy increased in 5 from 7 dwellings by 1%. This demonstrates that BER predicted energy use is in reasonable agreement when air-tightness results are included, but that the influence of building fabric, such as in the case of retrofitting, should be considered in more detail.

6. Dwelling Age and Stage of Retrofit

The pre-1975 dwellings yielded the lowest mean permeability of $7.5\text{m}^3/\text{hr}/\text{m}^2$. This was considerably lower than the 1980's and 2008 dwelling results having a mean of $9.4\text{m}^3/\text{hr}/\text{m}^2$ and $10.4\text{m}^3/\text{hr}/\text{m}^2$ respectively. Figs. 4 and 5 illustrate that retrofitting had a positive effect on air-tightness. Partial retrofitting of the 1980's dwellings, having an identical construction type, showed little improvement in leakage rates compared to as built dwellings. This suggests that placing attic insulation and installing central heating systems (often cited as adding to building leakiness) has a nominal effect on air-tightness. However, the study shows that cavity wall insulation and installing double glazing offer the greatest impact, reducing air permeability by 28% and 39% for the pre-1975 and 1980's dwellings respectively.

With no modification since construction, dwelling number 3, as shown in Figure 4, was an anomaly, having the lowest air permeability of $5.12\text{m}^3/\text{hr}/\text{m}^2$. The survey found the single glazed windows were in good condition and in many cases had been painted such that the windows could not be opened. The house did not have any permanent wall vents or central heating system, which meant there were minimum openings through the buildings envelope.

Fig. 4. Air-tightness measurements of pre-1975 dwellings categorised by stage of retrofit

Fig. 5. Air-tightness measurements of 1980's dwellings categorised by stage of retrofit

7. Design and Workmanship

Fig. 2 demonstrates that by 5 from 7, 2008 dwellings tested exceeded the Part L reasonable upper limit of $10\text{m}^3/\text{hr}/\text{m}^2$. The dwellings were part of one development; all had full fill cavity insulation, double glazing and 200mm attic insulation. Surveys and smoke pencil tests, in addition to common leakage paths, identified the critical leakage pathways as follows:

- a) The internal soil vent and waste pipes were located inside the building envelope with the pipes extending from the ground floor, through the attic and exiting through the roof. Although the pipes were concealed within a service duct, the joints to internal walls were not sealed as shown in Fig. 6a and hence provided a leakage pathway into the attic space.
- b) Window frames not fitted correctly, while the draught seal was partly detached from the frame, or completely missing, as shown in Fig. 6b and c, which again created leakage pathways.
- c) Many of the wall vent covers were not sealed correctly to the walls, thus leakage pathways remain when vent were closed, as shown in Fig. 6d.

The results do not correlate well with Pan [3] and Chan [10] who found evidence suggesting that air-tightness of newer dwellings has increased compared with older dwellings. However, the survey does support Kalamees [6], finding that workmanship and supervision had a large affect on building air-tightness. The results clearly demonstrate that good design, detailing, specification of materials and construction practice are of fundamental importance when constructing new houses.

8. Air-tightness and the Exponent, n

The average flow exponent, n , at 50Pascals, for each dwelling, is presented in Table 2. The airflow exponent can be used as an aid to describe the flow regime through the envelope. Ranging between 0.5 and 1, n values approaching 0.5 indicate turbulent airflow through rather large apertures, while values closer to 1 indicate laminar flow through small cracks and holes [21]. From the dataset average of 0.64, it is evident that flow regimes are towards the turbulent end of the spectrum, indicating airleakage through the large apertures. These results provide positive correlation with the findings of the surveys and smoke pencil test.



Fig. 6. Critical leakage pathways for 2008 dwellings

9. Conclusions

The field study provides data set of air permeability measurements for a range of new and retrofitted single family dwellings. Air permeability testing was carried out using a Retrotec Q46 Automated Blower-Door in accordance with the ATTMA Technical Standard. The 28 houses included in the survey comprised three periods of house building in Ireland ranging from 1941 to 1974 and 1980 to 1986 and more recent construction in 2008. In each case, the construction method involved cavity wall construction; which meant that the survey allowed a critical assessment to be made of the air-tightness properties of modern compared with retrofitted cavity wall houses. The outcome of the survey summarised below highlights the importance of workmanship and construction detailing in order to achieve the air-tightness standards set in current Irish Building Regulations. The field measurements indicate that in the case of retrofitted properties there is a direct link between improved insulation of cavity walls, double glazing and air-tightness. Whereas for the modern 2008 construct properties the

increased provision of wall and roof insulation still lead to relatively high air leakages in excess of $10\text{m}^3/\text{hr}/\text{m}^2$.

The key findings are summarised as follows:

1) Testing found the mean air permeability of the pre-1975, 1980's, and 2008 dwellings to be $7.5\text{m}^3/\text{hr}/\text{m}^2$, $9.4\text{m}^3/\text{hr}/\text{m}^2$ and $10.4\text{m}^3/\text{hr}/\text{m}^2$ respectively. The air permeability of 5 from 7, 2008 dwellings tested were in excess of the $10\text{m}^3/\text{hr}/\text{m}^2$, while the most air-tight dwelling, at $5.12\text{m}^3/\text{hr}/\text{m}^2$, was constructed in 1961. As a result, new dwellings cannot automatically be assumed more air-tight than older dwellings.

2) Leakage paths in the dwelling were wide-ranging and non-uniform across all dwelling ages. Smoke pencil testing found a number of pathways but there were many hidden and inaccessible. Air flow exponent records identified airflow as being through rather large apertures.

3) For relatively air-tight dwellings, the inclusion of air-tightness test results can have a positive influence on dwellings Building Energy Rating (BER). Calculated energy use for the most air-tight dwelling reduced but 7%. Inversely for the less air-tight 2008 dwelling energy use increased by 1%.

4) Retrofitting dwellings can have a considerable positive effect on air-permeability. While attic insulation and installing central heating systems had a nominal effect on air-tightness, combined with full fill cavity wall insulation and double glazing, the air permeability of the dwellings tested was on average 35% lower than houses which had not undergone upgrading.

5) In the 2008 dwellings, poorly designed and executed on site the internal soil vent and waste pipes provide a significant leakage path to the attic. Also, poorly manufactured and installed windows and passive wall vents allows considerable leakage pathways through the building envelope.

This paper highlights the lack of practical research in air-tightness for new and retrofitted dwellings in Ireland and offers the first step to developing a comprehensive national database. The results may form a basis to policy makers and designers towards making informed decisions about improving air-tightness of new and existing dwellings. The study is limited when drawing conclusions as the dataset is limited and does not represent the characteristics of every dwelling type in Ireland. Furthermore, while the dwellings described in this paper were of similar construction, to ensure a robust dataset when comparing the effect of upgrading on airtightness, tests should be carried out on each dwelling pre- and post-retrofitting.

To date, the 'softer' options of developing standards and best practice documentation have already been undertaken. It is now to address the complexities of attitude change. Building professionals need to be educated and taught to embrace the positive benefits of building air-tightness for both of new and existing dwellings being retrofitted.

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Table 1. Dwellings studied grouped by year of construction

Category	Number of Houses	Comments
Pre- 1975 (see Fig. 1a)	8	Typical of the older housing stock in the Ireland. Year of construction ranges from 1944 to 1974. Broadly similar construction: 100mm cavity with no insulation provided at construction.
1980's (see Fig. 1b)	13	Typical of houses constructed prior to the implementation of minimum insulation standards in Ireland. 100mm cavity with no insulation provided at construction. Typically nominal 100mm fibre attic insulation provided at construction stage which has degraded over time, providing little insulation value. In some cases no attic insulation was present.
2008 (see Fig. 1c)	7	All houses tested were part of one development of over 70 houses. Brick outer leaf and block inner leaf wall of 100mm cavity wall construction with full fill bonded bead insulation, 200mm of attic insulation, gas fired central heating and double glazing. Mechanical extractor fans fitted in bathrooms. The houses typically have a draught lobby to the front and WC to the rear of the building. Built in compliance with the building regulations.

Table 2 Measured air permeability and related parameters of dwellings in this study

House Number	Year of Construction	Construction Type	Retrofit Complete*	Envelope Area m ² (A _e)	Internal Volume m ³ (V)	Ave Air Changes @ 50Pa (ACH)	Ave. Air perm @ 50Pa (m ³ /hr/m ²)	Air Flow Exponent n	Change in kWh/m ² /yr including test results (%)
Pre- 1975									
1	1941	Terrace	DG, CH	219	171	10.96	10.45	0.630	+ 1
2	1958	Semi-Detached	DG, CH, AI, CI	187	173	8.38	7.85	0.610	- 2
3	1961	Terrace	None	189	175	5.53	5.12	0.622	- 7
4	1963	Terrace	DG, CH, AI, CI	180	163	5.46	5.20	0.670	- 4
5	1963	Terrace	DG, CH, AI, CI	180	163	6.30	6.02	0.641	- 5
6	1966	Terrace	DG, CH, AI, CI	192	180	8.26	7.75	0.609	- 6
7	1973	Semi-Detached	CH, AI, CI	204	195	9.28	8.45	0.654	- 5
8	1974	Semi-Detached	CH	220	211	9.98	9.08	0.654	+ 1
1980's									
9	1980	Semi-Detached	DG, CH, AI, CI	215	205	6.31	5.96	0.623	- 5
10	1981	Semi-Detached	none	215	205	11.66	10.64	0.658	+ 4
11	1981	Semi-Detached	CH, AI	215	205	10.89	10.38	0.670	- 2
12	1981	Semi-Detached	CH, AI	215	205	10.89	10.39	0.650	- 2
13	1981	Semi-Detached	CH, AI	215	205	11.12	10.60	0.625	- 2
14	1981	Semi-Detached	DG, CH, AI, CI	215	205	9.44	9.00	0.622	- 1
15	1981	Semi-Detached	CH, AI	215	205	11.74	11.19	0.634	+ 1
16	1981	Semi-Detached	none	215	205	14.90	14.42	0.644	+ 3
17	1981	Semi-Detached	CH, AI	215	205	14.54	13.86	0.626	+ 1
18	1981	Semi-Detached	DG, CH, AI, CI	215	205	11.07	10.55	0.645	- 1
19	1986	Semi-Detached	DG, CH, AI, CI	215	205	5.61	5.35	0.671	- 5
20	1986	Semi-Detached	DG, CH, AI, CI	215	205	5.39	5.14	0.649	- 5
21	1986	Semi-Detached	DG, CH, AI, CI	199	188	5.55	5.25	0.668	- 3
2008									
22	2008	Semi-Detached	none	246	224	11.44	10.90	0.617	+ 1
23	2008	Semi-Detached	none	250	221	13.99	13.34	0.642	+ 1
24	2008	Semi-Detached	none	246	224	9.02	8.60	0.653	- 2
25	2008	Semi-Detached	none	246	224	12.19	11.69	0.651	+ 1
26	2008	Semi-Detached	none	246	224	11.84	11.36	0.635	+ 1
27	2008	Semi-Detached	none	246	224	11.58	10.72	0.637	+ 1
28	2008	Semi-Detached	none	246	224	6.65	6.02	0.624	- 4

*DG - Double Glazing, CI - Cavity Wall Insulation, AI - 200mm glass fibre attic insulation, CH - Gas fired central heating system where there was none.



a) Pre- 1975 house type



b) 1980's house type



c) 2008 house type

Fig. 1. Typical house type for each age category

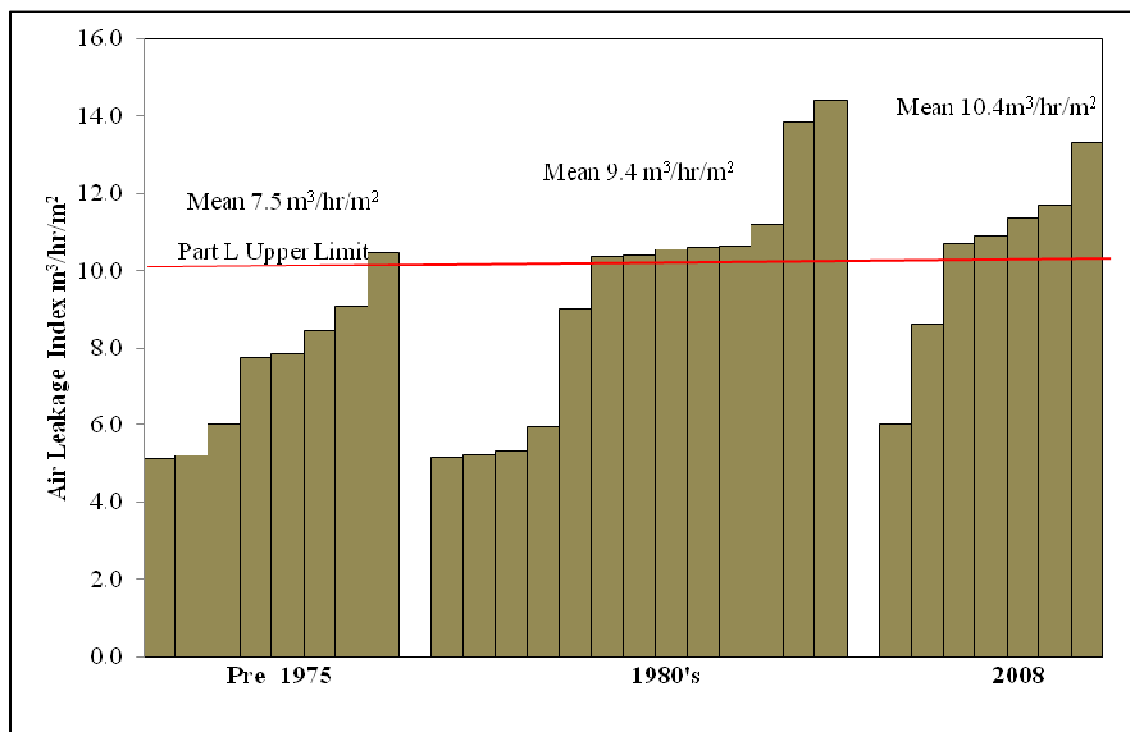


Fig. 2. Measured air permeability of dwellings studied, categorised by age (n =28)

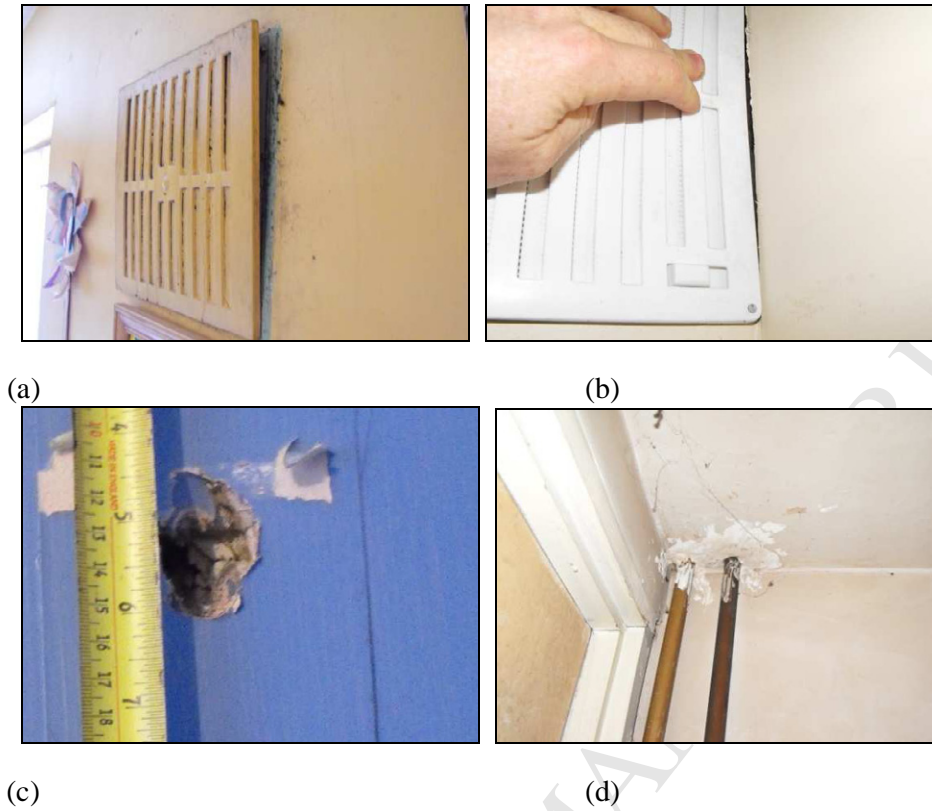


Fig. 3. Typical leakage paths: a and b) passive wall vents, c) accidental hole in plasterboard and d) plumbing to attic.

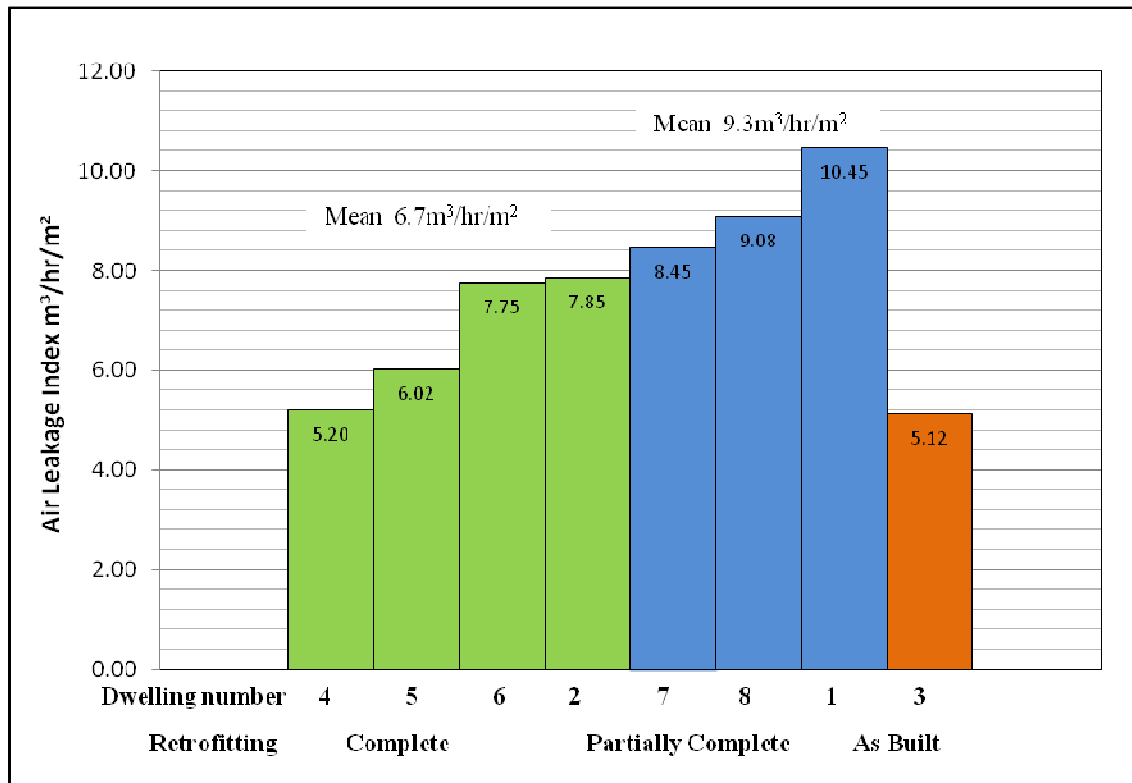


Fig. 4. Air-tightness measurements of pre-1975 dwellings categorised by stage of retrofit

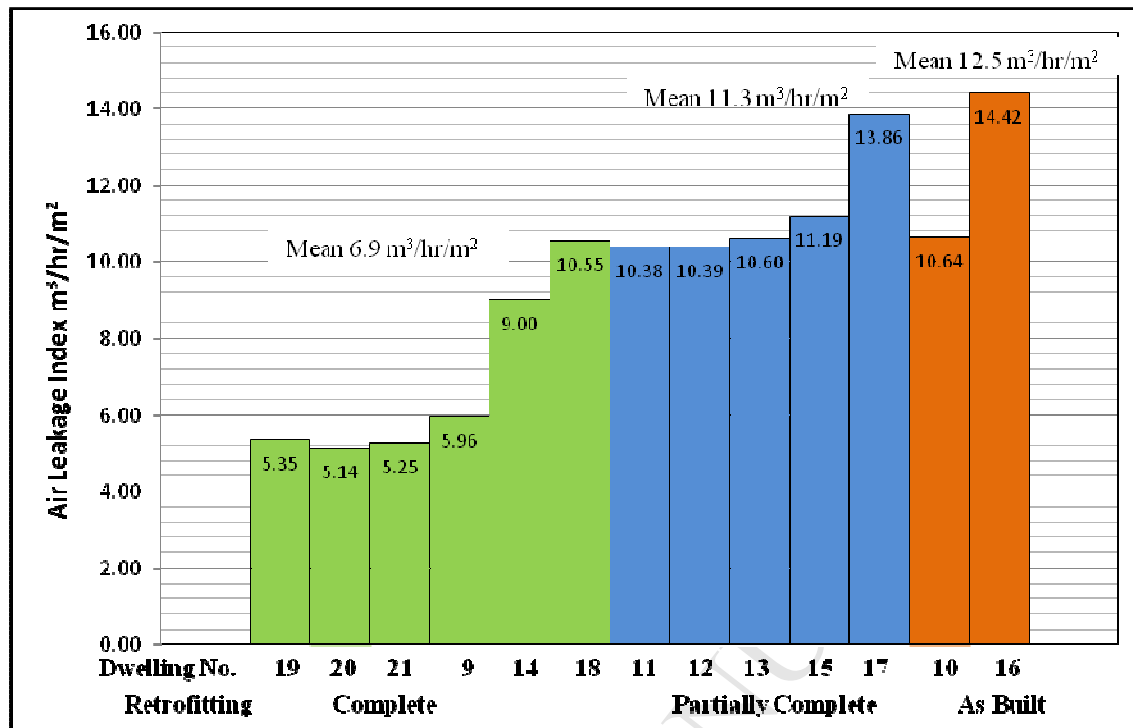
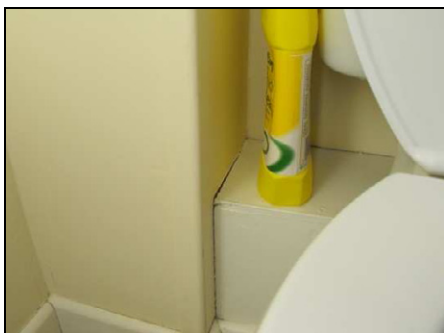
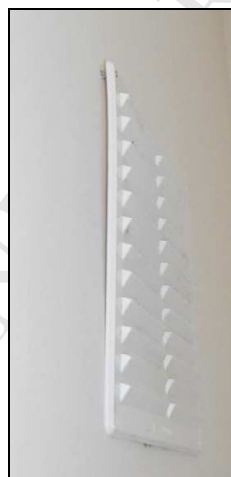


Fig. 5. Air-tightness measurements of 1980's dwellings categorised by stage of retrofit

**(a)****(b)****(c)****(d)****Fig. 6.** Critical leakage pathways for 2008 dwellings