Interim Report to Communities and Local Government Building Regulations Division under the Building Operational Performance Framework

AIRTIGHTNESS OF BUILDINGS — TOWARDS HIGHER PERFORMANCE

Milestone Number: D9 (Revised)

Discussion Paper 1 — Performance and Implementation

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Discussion Paper 1 — Performance and Implementation

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Executive Summary

1 This paper discusses the results obtained on this project, identifying the levels of air permeability currently being achieved within new UK dwellings meeting the requirements of Approved Document Part L1 (2001) and investigating practical ways of achieving the higher levels of airtightness performance described in Approved Document L1A (2006). The paper addresses those issues relating to airtightness in the domestic sector.

2 Following a preliminary literature review, Phase 1 of this project considered the design and construction of a selection of UK domestic dwellings through drawing assessments, extensive site surveys and dwelling pressurisation tests and leakage detection. Of the 25 dwellings observed in Phase 1, only eight achieved a mean air permeability of below the ADL1 recommended limit of 10 $m^3/(h.m^2)$ @ 50Pa, six of these being apartments. Phase 2 involved presenting these results to each developer by way of individual feedback sessions, where general information on airtightness of dwellings and site-specific guidance was presented and possible methods of increasing the airtight performance of the developers' properties was discussed. Phase 3 repeated the procedure adopted in Phase 1, but with the Leeds Met research team establishing a two-way dialogue with the developers throughout the construction of the Phase 3 dwellings, offering further guidance and on-site quality control. Whereas site surveys conducted in Phase 1 were purely observational, in Phase 3 observations were reported back to the developers immediately allowing on-site alterations and remedial action (where necessary) to take place before construction progressed much further.

3 The project results highlight a number of issues that require consideration when constructing dwellings to meet any particular airtightness target.

a) Certain construction types are intrinsically more airtight than others. The results from the project overall suggest that wet plastering and quasi-wet plastering (parging) of masonry cavity construction can default to a reasonable level of airtightness by UK standards. Other construction types, such as dry-lined masonry cavity and steel framed construction appear to require much greater attention to detail if they are to achieve an air permeability below 10 $m^3/(h.m^2)$ @ 50Pa. The construction type that presented the greatest difficulty was light steel frame. Air permeability values of below 10 $m^3/(h.m^2)$ @ 50Pa are possible with this type of construction, but are likely to require considerable additional attention to detail on site and changes to the design to ensure that continuity of the primary air barrier is maintained. In fact it is difficult to see how it would be possible to achieve an air permeability consistently less than 10 $m^3/(h.m^2)$ @ 50Pa without a fundamental rethink of airtightness design in this form of construction.

b) Complexity can have a significant effect on airtightness. Results illustrate that significant variations in air permeability can be observed in dwellings of the same form, constructed by the same site team, where the only observed difference was the number of complex details associated with these dwellings. These disparities were most common where certain design features required the primary air barrier to cope with complex changes in plane, negotiate structural members and accommodate changes in material. Such details included ground floor projections, rooms adjacent to semi-exposed areas, timber bays in masonry construction and complex junctions with ventilated cold roof loft-spaces.

c) The approach adopted to increase airtightness can influence the potential level of air permeability achievable. The lowest levels of air permeability were achieved where attention was given to design modifications in which the primary air barrier was designed and made explicit as well as ensuring that the design was executed successfully on site.

d) The level and consistency of feedback and guidance is important. Results suggest that providing general feedback and guidance on airtightness may have little effect on the air permeability of dwellings constructed. Feedback and guidance should therefore be continuous and targeted. However, providing this sort of feedback and guidance on a site by site, or even dwelling by dwelling basis can be onerous and labour intensive. Although during any learning phase the need for such intensive feedback will be inevitable, in the long term, ensuring that airtight design is built into the routine quality control culture of design and site teams (including an element of testing) will be critical.

e) The results illustrate that certain approaches to improving airtightness are likely to be more robust than others. Approaches that involve no change to design but instead concentrate efforts on secondary sealing measures (such as many of those implied in the current edition of Part L Robust Details — DEFRA, 2001) are likely to be much less robust than those approaches that concentrate on ensuring that there is an effective and continuous primary air barrier. Approaches that are easy to build and are most amenable to simple and effective quality procedures are also likely to be more robust.

f) Anecdotal observations of non-test dwellings on the sites involved would suggest that on-site knowledge and experience gained through feedback with respect to the test dwellings does not always appear to be utilised more generally. Although the team were not able to carry out any random tests on non-test dwellings visual inspections suggest that it is unlikely that the other dwellings on-site will achieve around the same levels of airtightness as the dwellings featured in this project. The results also suggest that achieving consistent levels of airtightness in dwellings of the same size, construction type and form may be difficult within existing design and construction cultures.

4 The results obtained from Phase 1 of this project suggest that the impact of the 2002 edition of Approved Document Part L1 on airtightness has not been as successful as anticipated. The failure of the majority of the dry-lined masonry cavity and steel framed dwellings in Phase 1 to achieve the ADL1 2002 airtightness target also suggests that the adoption of Robust Construction Details, at least in the current form, provides no guarantee that the current regulatory standard is achieved with any degree of consistency. The results from Phase 3 of the project suggest that an air permeability of less than 10 $m^3/(h.m^2)$ @ 50Pa is achievable within mass-produced housing in the UK using existing techniques, materials and practices, and without incurring significant cost. However ensuring consistency and robustness is likely to present the greatest challenge. To reliably reduce the air permeability to much lower levels (5 $m^3/(h.m^2)$ @ 50Pa and below) will require more significant changes to the design and the approach to construction.

Introduction

5 This paper constitutes milestone D9 (Performance and Implementation of the Communities and Local Government Project reference CI 61/6/16 (BD2429) *Airtightness of Buildings — Towards Higher Performance* (Borland and Bell, 2003). The purpose of this paper is to discuss the results obtained to date on this project with a view to identifying the levels of air permeability that could be achieved within new UK dwellings within the context of existing mainstream practice and readily available techniques. It is anticipated that this discussion paper will form one of the inputs into the Forward Thinking Paper on energy conservation which is due to be updated in 2006. It is also intended that the findings of this work will be used to inform future revisions to Part L of the Building Regulations.

Airtightness and Building Regulations: ADL1 2002 and ADL1A 2006

6 Airtightness is crucial to improving the energy performance of buildings. This was recognised in the June 2000 consultation paper on Part L of the Approved Document (DETR, 2000) which, for the first time, proposed a maximum air leakage target of 10 $m^3/(h.m^2)$ @ 50Pa. for both domestic and non-domestic buildings. In April 2002, the amended editions of the Approved Document came into effect; Part L1 for dwellings (DTLR, 2001a) and Part L2 for buildings other than dwellings (DTLR, 2001b). These amendments were intended to be the first of a series of changes that are proposed to take place to the Building Regulations over this decade, with the next major review currently taking place (see DTI, 2003). The 2002 amended edition of the Approved Document L1 (ADL1) required that reasonable provision should be made to reduce unwanted air leakage, and suggested that this can be achieved by adopting the guidance given in the report on Robust Construction Details (see DEFRA, 2001), or by pressure testing.[1] The consultation document that was published in July 2004 for the 2005 review of Part L required the inclusion of airtightness as part of the calculation of the total carbon emission rate for a particular dwelling design (ODPM, 2004).

7 The final version of the approved document, *L1A Work in New Dwellings*, was published in April 2006 and defines three specific concepts:

a) TER — Target CO_2 Emission Rate: the minimum energy performance requirement as defined using the SAP2005[2] calculation tool and expressed in kg of CO_2 per m^2 of floor area per year. The target is defined in terms of a 20% reduction in carbon emissions from space and water heating and lighting compared to a notional gas heated dwelling built in accordance with the guidance given in ADL1 2002.

b) DAP — Design Air Permeability is included in the SAP2005 calculation tool. The expected overall limit to permeability is 10 $m^3/(h.m^2)$ @ 50Pa but designers are free to specify a lower value in order to achieve the required TER. However, a verification and testing regime is incorporated in the regulations to ensure that actual construction is commensurate with the values required to ensure that the regulatory requirement is achieved. This means that designers and developers need to be able to specify air permeability levels with a high degree of confidence that they can be achieved in practice.

c) DER — Dwelling CO_2 Emission Rate, as determined by the SAP[3] software, must be equal to or better than the TER.

8 For buildings containing multiple dwellings, both the TER and DER for individual dwellings can be calculated using floor area weighted averages based on the whole building TER and DER; with each block of flats being regarded as a separate development, regardless of the number of blocks on the site.

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[1] The method for pressure testing of dwellings is currently outlined in CIBSE technical memorandum TM23 (CIBSE, 2000). The recommended good practice air permeability for naturally ventilated dwellings is therein given as 10 $m^3/(h.m^2)$ @ 50Pa, and 5 $m^3/(h.m^2)$ @ 50Pa for dwellings with balanced whole house mechanical ventilation.

[2] SAP2005 to be used for individual dwellings of 450 m^2 total floor area or less; larger individual dwellings will be calculated using the Simplified Building Energy Model (SBEM).

[3] For dwellings over 450 m^2 SAP is not appropriate and in such cases the Simplified Building Model or other approved calculation tool must be used.

9 Compliance with regulation will usually be achieved either by using accredited construction details and satisfying the above requirements, or by a more rigorous pre-completion testing regime, as described in L1A, Section 2: Criterion 4. Whichever approach is adopted by the developer, it is therefore expected that all dwellings will have to achieve a maximum value of 10 $m^3/(h.m^2)$ @ 50Pa irrespective of the TER and DER realized.[4] However, in order to achieve an acceptable TER/DER, the airtightness specification of many dwelling designs (particularly where fuels with a higher carbon intensity than gas are to be used) may have to be much lower than this and 5 $m^3/(h.m^2)$ @ 50Pa or less may become a common design requirement.

10 When using accredited construction details as a method of compliance, one example of each dwelling type will require pressure testing. Dwelling type is defined in L1A (2006) as a dwelling of the same generic form; e.g. detached, semi-detached, end-terrace, mid-terrace, ground-floor flat, mid-floor flat, top-floor flat, with no further reference to building form. However, they may vary in complexity. When compliance is sought without using accredited construction details, on each development a minimum of either two units or 5% of each dwelling type will require testing, whichever is the greater. This number may be reduced if the first five dwellings tested all perform within their respective DAPs. For developments of one or two dwellings, the developer has the option to adopt a DER based upon an air permeability of 15 $m^3/(h.m^2)$ @ 50Pa and dispense with any obligation for a pressure test to be performed, this would have to be off-set against substantial improvements in energy efficiency elsewhere in the dwelling(s). Compliance through a third-party accreditation scheme is provided for, subject to approval by the Secretary of State.

11 L1A (2006) also introduces new guidelines over who should perform the obligatory pressure testing of dwellings and the procedures to be followed. ADL1A 2006 states that local authorities are authorised to accept as evidence a certificate from a person who is registered by the British Institute of Non-Destructive Testing (BINDT) in respect of pressure testing for the airtightness of buildings. In addition, tests are to be performed using the procedure approved by the Secretary of State for air pressure testing, which is set out in the Airtightness Testing and Measurement Association (ATTMA) publication *Technical Standard 1* (TS1) ATTMA's TS1 is based on techniques and methodologies outlined in CIBSE Technical Memorandum TM23 (CIBSE, 2000) and BS EN Standard 13829:2001 (British Standards Institute, 2001).

Airtightness of New UK Housing

12 There is a commonly held perception that new dwellings in the UK are built to a high standard of airtightness (Olivier, 1999). This is not generally found to be the case. Cohort data contained within the Building Research Establishment's (BRE's) air leakage database[5] suggest that dwellings built between 1980 and 1994 are, on average, as airtight as those built at the beginning of the twentieth century (see Figure 1). Whilst the air leakage data for the older dwellings are not likely to be representative of the airtightness of these dwellings when they were first built, the data suggest that the airtightness of new dwellings has not improved significantly over the last century.

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[4] An adjustment period of up to 31 October 2007 is included to allow for dwellings failing to achieve the target figure to temporarily be subject to less stringent re-test targets.

[5] The BRE's database of air leakage is the largest and most comprehensive source of information on the airtightness of UK dwellings (see Stephen, 1998 and 2000). This database contains information on some 471 dwellings of different age, size, type and construction. However, despite its size, this database is not the result of random sampling and cannot claim to be unequivocally representative of the UK housing stock.

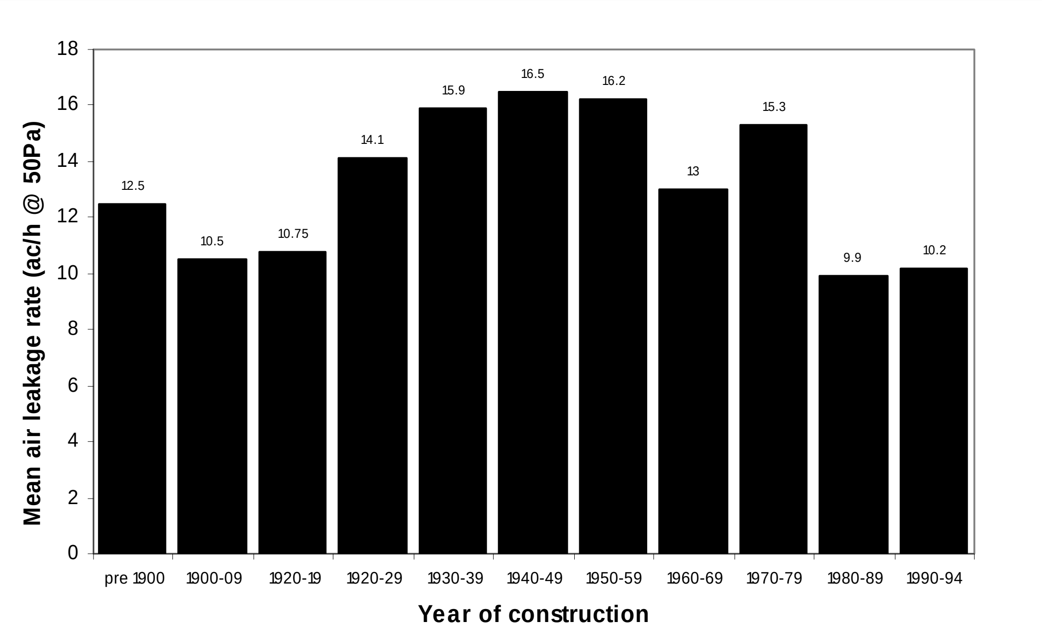

Figure 1 Relationship between dwelling age and air leakage. After Stephen (2000).

13 Air leakage data on dwellings built from 1995 onwards remain somewhat limited. Measurements undertaken by the BRE (see Stephen, 2000) on 32 post 1995 dwellings show that there is still a very wide range of airtightness observed within the sample (6.0 to 19.3 $m^3/(h.m^2)$ @ 50Pa), and that the average value is only marginally more airtight than the average for the stock as a whole (air permeability of 11.3 $m^3/(h.m^2)$ @ 50Pa as opposed to 11.5 $m^3/(h.m^2)$ @ 50Pa). This difference is very small and given the non-random nature and size of the sample cannot be considered to be even remotely significant. This suggests that there has been no real improvement in the airtightness of dwellings built post 1995.

14 A limited amount of air leakage data is available on dwellings that have been built to conform to the requirements set out in the 2002 edition of the Approved Document Part L1 (DTLR, 2001). Early work undertaken by the BRE for the Office of the Deputy Prime Minister (ODPM) on a small number of dwellings built to Part L1 2002 indicated that about two-thirds of the dwellings failed to achieve an air permeability of 10 $m^3/(h.m^2)$ @ 50Pa (cited in Grigg, 2004). In 2004, the BRE undertook airtightness measurements on a much larger non-random sample of 99 dwellings that had been built to Part L1 2002 (see Grigg, 2004). The sample included a range of dwelling types,[6] of both masonry and framed construction, which were located in various geographical locations and were from both the private and social housing sectors. The results showed that a relatively wide range of airtightness was observed within the sample (see Figure 2). The air permeability of the dwellings ranged from 3.2 to 16.9 $m^3/(h.m^2)$ @ 50Pa, with a mean of 9.2 $m^3/(h.m^2)$ @ 50Pa and a standard deviation of 2.8 $m^3/(h.m^2)$. In addition, approximately two-thirds of the sample (68%) achieved an air permeability that was lower than or equal to the maximum specified level of 10 $m^3/(h.m^2)$ @ 50Pa set in the 2002 edition of the Approved Document L1 (DTLR, 2001a). These results contrast with the earlier much smaller BRE sample where two-thirds of the sample failed to achieve an air permeability of 10 $m^3/(h.m^2)$ @ 50Pa.

15 The results for the apartments and the other dwelling types in the BRE sample were also analysed separately (see Figures 3 and 4) as apartments had been under-represented in the earlier study and may have skewed the results.[7] The analysis indicated that the air permeability of the apartments ranged from 3.2 $m^3/(h.m^2)$ @ 50Pa to 12.4 $m^3/(h.m^2)$ @ 50Pa, with a mean of 8.0 $m^3/(h.m^2)$ @ 50Pa. This compared with the other dwelling forms which achieved an air permeability

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[6] The sample comprised 36 apartments, 21 mid-terrace houses, 10 end terrace houses, 19 semi-detached houses, 10 detached houses, 2 semi-detached bungalows and 1 detached bungalow.

[7] The reason for this is that apartments tend to be more airtight than other dwelling forms of equivalent area, as they are more likely to have solid intermediate floors, fewer external door and window openings and fewer service penetrations.

of between 5.6 $m^3/(h.m^2)$ @ 50Pa and 16.7 $m^3/(h.m^2)$ @ 50Pa, with a mean of 9.8 $m^3/(h.m^2)$ @ 50Pa. The results also showed that 83% of the apartments achieved 10 $m^3/(h.m^2)$ @ 50Pa or better compared with 57% of the other dwelling forms. The results of this analysis suggest that the high rate of compliance for the tested dwellings (68%) is likely to be due, in part, to the number of apartments in the sample. However, the overall rate of compliance in new dwellings may be slightly higher than that indicated by Grigg since the proportion of flats within the annual new-build total is some 5% higher than the 36% in the Grigg sample.[8]

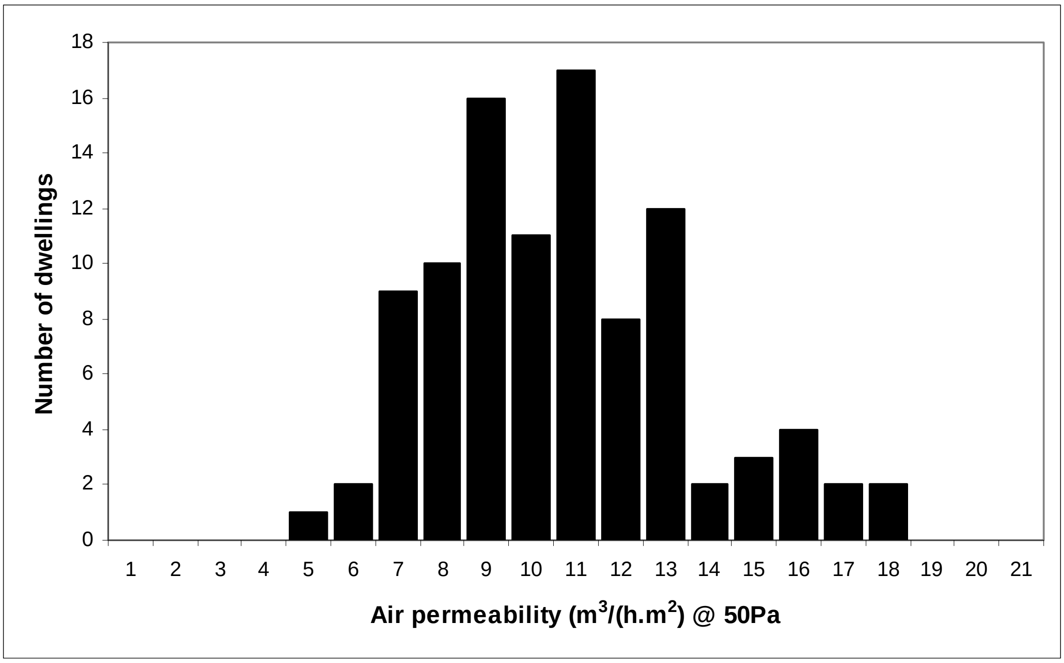

Figure 2 Mean air permeability of dwellings built to Part L1 2002. After Grigg (2004).

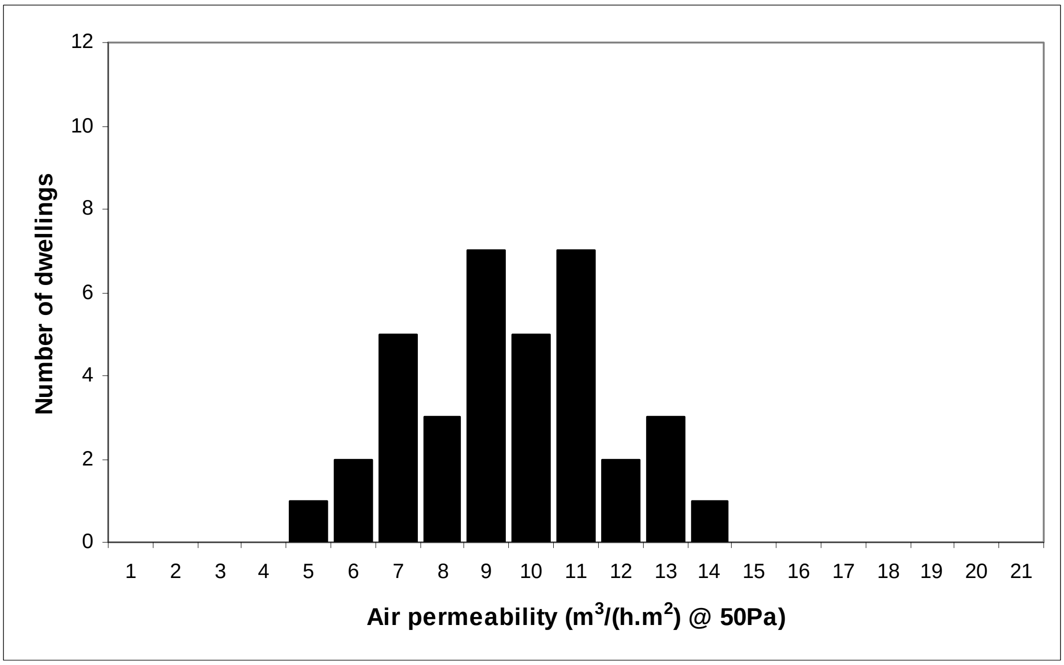

Figure 3 Mean air permeability of flats built to Part L1 2002. After Grigg (2004).

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[8] Recent housebuilding statistics from Communities and Local Government indicate that flats represented 41% of all new dwellings completed in England in the financial year 2004/5.

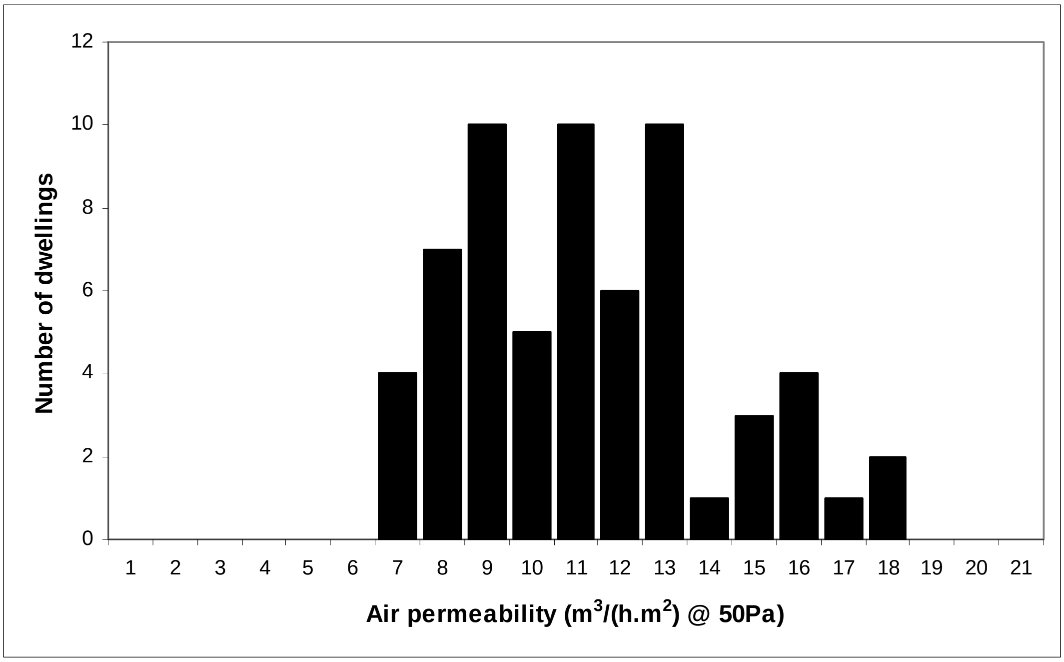

Figure 4 Mean air permeability of other dwelling types built to Part L1 2002. After Grigg (2004).

Project Summary

16 The overall aim of this project is to investigate practical ways of achieving higher levels of airtightness performance than the current requirements of Approved Document Part L1 and L2. This report addresses those issues relating to the domestic sector. Work is being undertaken in parallel on the airtightness of buildings in the non-domestic sector.

17 The project was undertaken in two parts:

a) Literature review — A conventional literature review was undertaken, which was supplemented by a small number of field tests of airtight dwellings, together with open-ended questionnaires with the current occupiers and those responsible for their design and construction. The purpose of these questionnaires was to assess the occupant experience of airtightness within their dwelling and to assess the experience gained from those involved in the design and construction of airtight dwellings.

b) Participatory action research — This part of the project was undertaken in three distinct phases and involved five developers from the commercial and social housing sectors.

c) Phase 1 — In this phase the design and construction of 25 dwellings, selected from five developments (five dwellings per developer) were monitored in detail.[9] This was done based on detailed reviews of design drawings, and extensive site survey work carried out as dwellings were constructed. Upon completion each dwelling was pressure tested and the main air leakage paths were investigated using smoke tests.[10] The objective of this phase was to establish those factors of design and construction that are likely to influence the eventual airtightness of the dwellings.

d) Phase 2 — The results from Phase 1 were fed back in a participatory seminar (one per developer) and ways of improving airtightness were discussed with the developer and their design and construction teams. The developer was encouraged to set an airtightness standard

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[9] As one dwelling (B85) was handed over to the customer prior to completion, an additional dwelling from developer E was included in the project to maintain the total number of dwellings at 25.

[10] Smoke tests were performed from inside the dwelling using hand held smoke puffers, with the dwellings pressurised to 75~80Pa. The direction and rate at which smoke flowed into the building structure provided indications of internal points of air leakage and their comparative significance; however, this method alone cannot identify or quantify many of the more complex air leakage paths.

(commensurate with existing ventilation strategies) for the design and construction of a further set of dwellings that would be assessed and tested in Phase 3.

e) Phase 3 — This phase mirrors Phase 1 in which the design and construction of a further set of dwellings (five from developers A, B, C and D, and six from developer E) were monitored following the feedback and enhanced understanding gained during Phase 2. Two further dwellings were subsequently included for developer C to include an additional dwelling type. Upon completion and testing, a feedback seminar will be held to review the design and construction experience from the developer's point of view.

f) Details of the dwellings that were selected to participate in Phases 1 and 3 of the action research project are contained within Tables 1 and 2.

Developer	Type of construction	Dwelling	Built form	Internal floor area (m^2)
A	Dry-lined masonry cavity, partial fill.	A09	Mid-terrace	83
		A11	Mid-terrace	117
		A12	End terrace	117
		A13	Detached	117
		A14	Semi-detached	80
B	Dry-lined masonry cavity, full fill.	B79	Detached	129
		B80	Detached	164
		B81	Detached	149
		B82	Detached	149
C	Dry-lined masonry cavity, full fill.	C236	Mid-terrace	72
		C237	Mid-terrace	71
		C238	End terrace	61
		C239	Semi-detached	69
		C240	Semi-detached	68
D	Light steel frame.	D39	Semi-detached	72
		D42	Detached	91
		D43	Detached	84
		D44	Detached	91
		D59	Detached	102
E	Mechanically/ manually wet plastered[11] masonry cavity, partial fill.	ECG01	Ground-floor apartment	57
		ECG02	Ground-floor apartment	43
		EC201	Mid-floor apartment	58
		EC202	Mid-floor apartment	44
		EC301	Top-floor apartment	59
		EC302	Top-floor apartment	44

Table 1 Size, built form and construction type of the dwellings selected for Phase 1.

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[11] All of the plots were originally intended to be mechanically plastered. However, due to delays in the construction and the drying out times associated with the mechanical plastering system that was being applied, Plots C301 and C302 were manually wet-plastered.

Developer	Type of construction	Dwelling	Built form	Internal floor area (m^2)
A	Dry-lined masonry cavity, partial fill.	A64	Mid-terrace	113
		A65	Mid-terrace	113
		A66	End terrace	117
		A79	Mid-terrace	117
		A80	End terrace	117
B	Dry-lined masonry cavity, full fill.	B14	Detached	164
		B16	Semi-detached	132
		B17	Semi-detached	132
		B21	Semi-detached	132
		B22	Semi-detached	132
C	Dry-lined masonry cavity, full fill.	C17	End terrace	61
		C18	Mid-terrace	72
		C19	Mid-terrace	71
		C20	End terrace	61
		C21	End terrace	61
		C193	Detached	106
		C194	Detached	106
D	Light steel frame.	D73	Detached	119
		D74	Detached	94
		D75	Detached	118
		D76	Detached	125
		D96	Detached	100
E	Wet plastered masonry cavity, partial fill.	EAG01	Ground-floor apartment	57
		EAG02	Ground-floor apartment	43
		EA201	Mid-floor apartment	58
		EA202	Mid-floor apartment	44
		EA301	Top-floor apartment	59
		EA302	Top-floor apartment	44

Table 2 Size, built form and construction type of the dwellings selected for Phase 3.

Project Results

18 The results from Phase 1 and those obtained to date for Phase 3 of the project are detailed within Tables 3 and 4 and Figures 5 and 6. A more detailed analysis of these results can be found in Johnston, Miles-Shenton and Bell (2004 and 2005c).

Dwelling	**Pressurisation test**		**Depressurisation test**		**Mean air permeability ($m^3/(h.m^2)$ @ 50Pa)**
	Permeability ($m^3/(h.m^2)$ @ 50Pa)	**r^2 coefficient of determination**	**Permeability ($m^3/(h.m^2)$ @ 50Pa)**	**r^2 coefficient of determination**	
A9	13.95	0.999	13.86	0.999	13.91
A11	15.46	0.996	14.66	0.997	15.06
A12	12.12	0.990	12.49	0.999	12.31
A13	14.51	0.999	14.16	0.999	14.33
A14	15.33	0.993	15.71	0.994	15.52
B79	8.96	1.000	9.02	0.983	8.99
B80	11.76	0.992	11.20	0.990	11.48
B81	10.11	0.999	9.66	0.993	9.89
B82	12.04	0.996	11.53	0.999	11.79
C236	16.81	1.000	16.26	1.000	16.53
C237	14.08	1.000	13.98	1.000	14.03
C238	11.17	0.998	11.02	1.000	11.09
C239	12.46	0.997	11.90	0.986	12.18
C240	12.11	0.971	11.40	0.981	11.76
D39	12.82	0.992	12.61	0.984	12.72
D42	15.55	1.000	16.37	0.999	15.96
D43	12.10	0.997	11.44	0.999	11.77
D44	14.58	1.000	14.94	1.000	14.76
D59	12.50	0.990	11.76	0.984	12.13
ECG01	5.13	0.999	4.90	0.996	5.01
ECG02	4.37	0.998	4.32	0.997	4.35
EC201	4.79	1.000	4.43	0.997	4.61
EC202	3.94	0.999	3.96	1.000	3.95
EC301	7.46	0.995	7.38	0.997	7.42
EC302	5.53	0.999	4.98	0.995	5.25

Table 3 Mean air permeability of the dwellings tested during Phase 1.

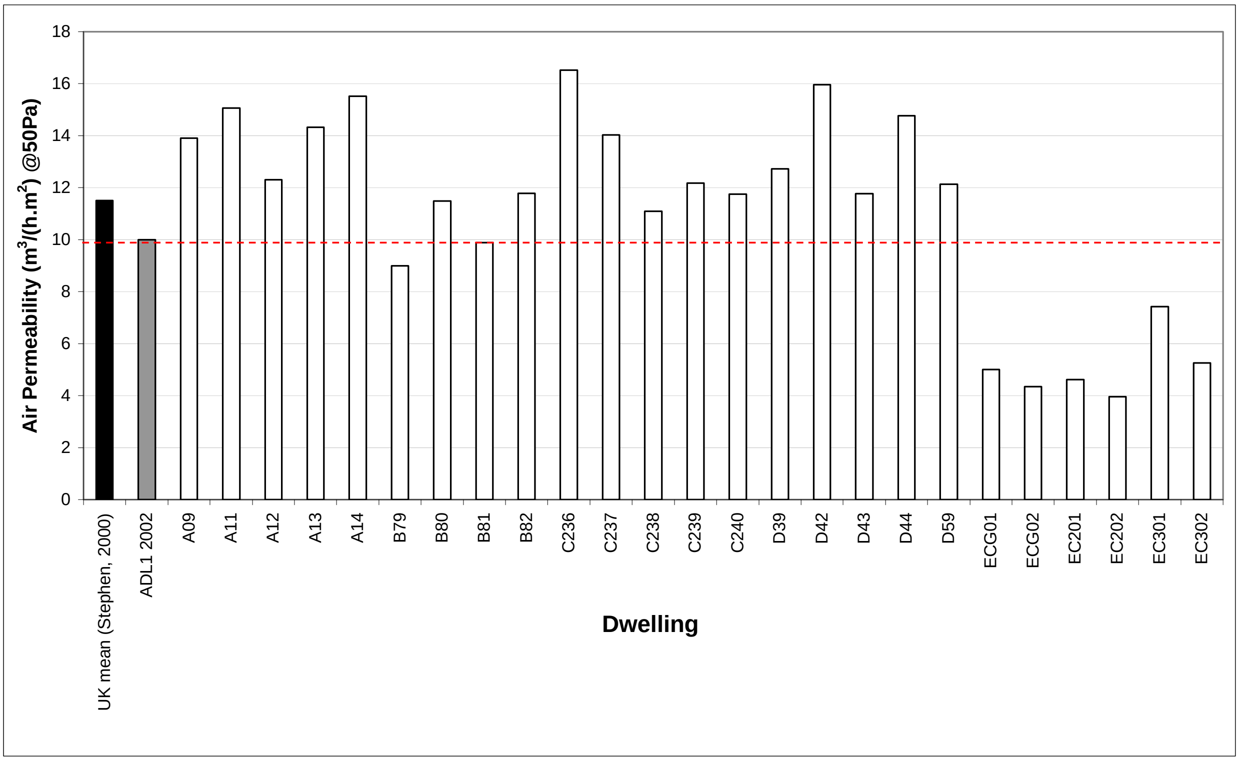

Figure 5 Mean air permeability of the dwellings tested during Phase 1.

Dwelling	**Pressurisation test**		**Depressurisation test**		**Mean air permeability ($m^3/(h.m^2)$) @ 50Pa)**
	Permeability ($m^3/(h.m^2)$) @ 50Pa)	**r^2 coefficient of determination**	**Permeability ($m^3/(h.m^2)$) @ 50Pa)**	**r^2 coefficient of determination**	
A64	10.68	0.996	10.19	0.999	10.44
A65	8.44	0.998	7.67	0.997	8.06
A66	8.01	0.999	7.96	0.999	7.98
A79	6.45	0.998	6.59	0.999	6.52
A80	5.54	1.000	5.65	1.000	5.59
B14	9.33	0.996	8.15	0.980	8.74
B16	5.50	0.987	5.69	0.993	5.59
B17	5.61	0.990	5.76	0.991	5.69
B21	7.31	0.996	7.27	0.997	7.29
B22	7.44	0.995	7.31	0.991	7.37
C17	6.17	1.000	5.95	1.000	6.06
C18	9.13	0.987	9.69	0.992	9.41
C19	7.32	0.999	7.29	0.985	7.30
C20	10.77	0.991	10.12	0.993	10.45
C21	10.40	0.990	9.60	0.994	10.00
C193	9.82	0.987	9.45	0.996	9.64
C194	15.90	0.996	14.02	0.992	14.96

Dwelling	Pressurisation test		Depressurisation test		Mean air permeability ($m^3/(h.m^2)$ @ 50Pa)
	Permeability ($m^3/(h.m^2)$ @ 50Pa)	r^2 coefficient of determination	Permeability ($m^3/(h.m^2)$ @ 50Pa)	r^2 coefficient of determination	
D73	13.39	0.991	13.22	0.991	13.31
D74	12.62	0.970	12.80	0.949	12.71
D75	10.97	0.979	10.22	0.990	10.60
D76	9.23	0.982	8.56	1.000	8.89
D96	11.52	0.995	10.77	0.999	11.14
EAG01	6.56	0.999	6.57	0.997	6.56
EAG02	4.98	0.989	4.74	0.997	4.86
EA201	7.11	0.991	6.89	0.995	7.00
EA202	5.47	0.978	5.36	0.992	5.41
EA301	6.24	0.990	6.05	0.998	6.15
EA302	4.92	0.995	4.96	0.975	4.95

Table 4 Mean air permeability of the dwellings tested during Phase 3.

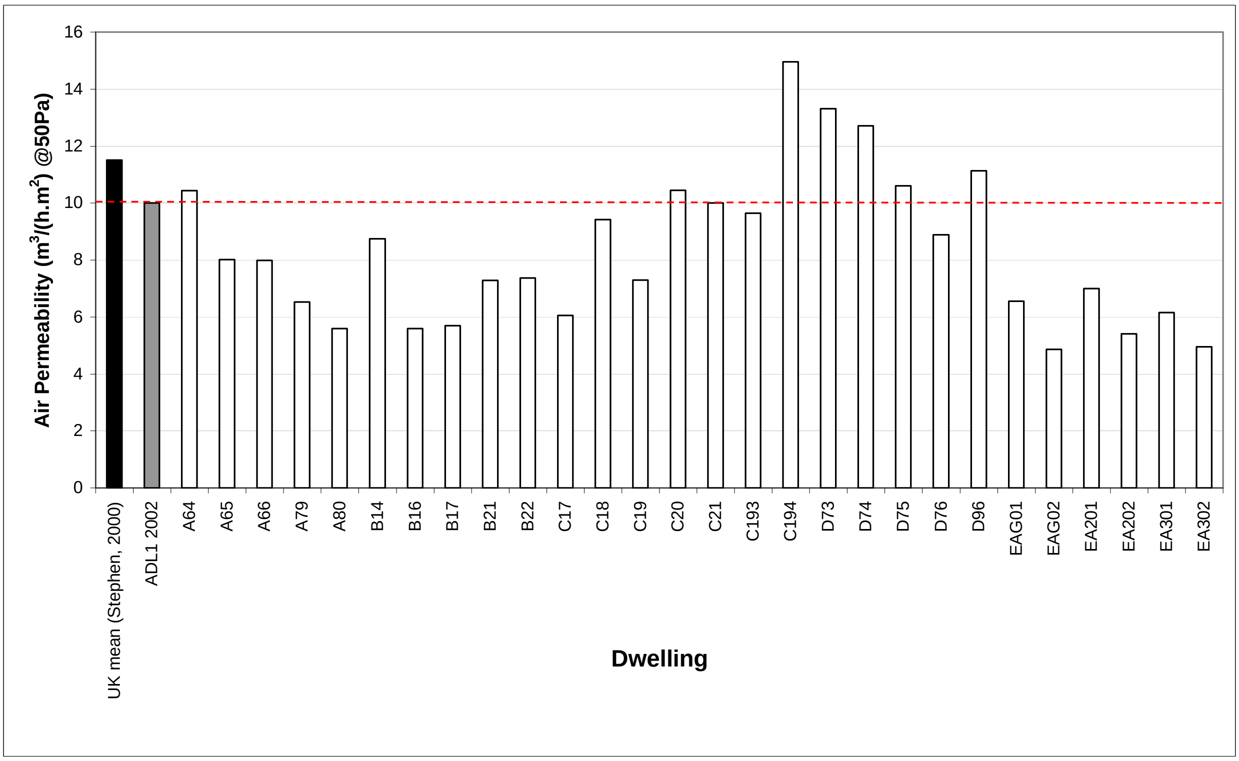

Figure 6 Mean air permeability of the dwellings tested during Phase 3.

19 It is important to realise that the results obtained from this project are based upon a non-random sample of dwellings. In addition, the sample sizes for both phases of the project are small, precluding absolute certainty when comparing the data. Consequently, conclusions drawn from the study are essentially qualitative in nature; future work would be required to establish whether the results reported are truly indicative of the UK house building industry as a whole.

Discussion of the Project Results

20 The measurements undertaken during Phase one of the project[12] showed that a relatively wide range of air permeability was measured for the tested dwellings. The air permeability of the dwellings ranged from 4.0 to 16.5 $m^3/(h.m^2)$ @ 50Pa, with a mean of 11.1 $m^3/(h.m^2)$ @ 50Pa and standard deviation of 3.8 $m^3/(h.m^2)$. Although the range of air permeability measured within these dwellings was consistent with the recent measurements undertaken by the BRE (see Grigg, 2004), the mean for these dwellings was higher (11.1 as opposed to the BRE's 9.2 $m^3/(h.m^2)$ @ 50Pa). This is probably a result of the larger proportion of apartments (36%) included in the BRE sample compared with this sample (24%). The data also indicated that only 10 of the 25 dwellings (40%) had an air permeability that was lower than or equal to the UK mean of 11.5 $m^3/(h.m^2)$ @ 50Pa. The mean of all 25 results (11.1 $m^3/(h.m^2)$ @ 50Pa) suggests that these dwellings are broadly in line with existing data on the UK stock as a whole and that, at least in these cases, the impact of the 2002 edition of ADL1 has been minimal. Given the qualitative nature of the project it is not possible to extrapolate to the post 2002 new build stock with any confidence but the Grigg data would suggest that the results obtained are not untypical.

21 The results obtained from Phase 1 also suggest that despite all of the developers using Robust Construction Details – Part L (DEFRA, 2001) as the basis of the application for regulatory approval, only eight of the tested dwellings (six flats and two houses) (32%) had air leakage values that were lower than the maximum specified level of 10 $m^3/(h.m^2)$ @ 50Pa set in the 2002 edition of the Approved Document Part L1 (DTLR, 2001a). If the six flats tested are excluded (flats tend to be a more airtight dwelling form), only two out of 19 houses achieved a level below the value given in ADL1. In addition, only one of the developers (developer E — flats) managed to satisfy the air leakage criterion with all of their tested dwellings. The other four developers were unable to achieve the airtightness target in the majority of cases. This suggests that simply adopting Robust Construction Details, at least in their current form,[13] provides no guarantee that the current regulatory standard will be achieved with any degree of consistency.

22 A review of available literature (see Johnston, Wingfield and Bell, 2004) has revealed that it is possible to construct relatively airtight dwellings in the UK using a variety of different construction techniques. Such dwellings include the Autonomous Urban House (masonry cavity, 4.4 $m^3/(h.m^2)$ @ 50Pa; Johnston, 2004), the Hockerton Housing Project (earth-sheltered, 1.1 $m^3/(h.m^2)$ @ 50Pa; Johnston, 2004) and the Low Energy House at Stenness (timber-frame, ~1.0 $m^3/(h.m^2)$ @ 50Pa; Bullen, 2000). Despite this, there is a still significant gap in airtightness between the best performing dwellings constructed in the UK (around 1 $m^3/(h.m^2)$ @ 50Pa) and the most airtight dwellings constructed abroad (mean of less than 0.3 $m^3/(h.m^2)$ @ 50Pa for the CEPHEUS houses; Feist, Peper and Gorg, 2001). Another issue associated with the dwellings that have been constructed in the UK is that these dwellings tend to be one-off 'specials' that have been designed and constructed to be very airtight by concerned individuals. Although these dwellings illustrate the levels of airtightness performance that could be achieved in the UK, they are not representative of the systems that produce the vast majority of new dwellings in the UK.

23 An indication of the levels of airtightness that could potentially be achieved within the current system of mass-produced housing in the UK has been obtained from the results of Phase 3 of the project. During this phase of the project, each of the developers identified a range of measures[14] that they would incorporate within their dwellings, in order to improve their airtightness performance. The results obtained from this phase of the project indicate that in the majority of the dwellings where measures were identified and applied, reductions in air permeability from the Phase 1 mean were achieved. The only instance where this was not the case was with developer

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[12] Further details of the Phase 1 results can be found within Johnston, Miles-Shenton and Bell (2005a)

[13] It is worth observing that the apparent failure of the adoption of Robust Details in these cases could be due to a wide range of causes relating not only to the intrinsic nature of the details themselves and the general level of guidance provided but also to the general quality control system into which they are embedded. In fact evidence from elsewhere (Bell, Smith and Miles-Shenton 2005) would suggest that levels of awareness of the details themselves among designers and constructors are low and that their adoption is rarely seen in the context of a design and construction quality control system. This contrasts with the separate system of Robust Detail accreditation used by many developers in support of achieving the performance requirements of Part E (sound).

[14] Details of the individual measures incorporated by each developer are detailed within Johnston, Miles-Shenton and Bell (2005c).

E, where the air permeability of four[15] of the Phase 3 apartments (Plots EAG01, EAG02, EA201 and EA202) were on average 1.5 $m^3/(h.m^2)$ @ 50Pa (33%) higher than the corresponding apartments constructed during Phase 1 of the project. The reasons for the increase in air permeability was felt to be attributable to differences in the way in which these dwellings were tested[16] and the use of liner boards on dabs at the window reveals in these apartments, instead of wet plaster.

24 The scale of the reductions in air permeability that were achieved also varied considerably, as did the absolute levels of air permeability. Despite this, the results suggest that mass-produced housing in the UK can be constructed to be relatively airtight by UK standards, with an air permeability as low as 5 or 6 $m^3/(h.m^2)$ @ 50Pa being obtainable with relatively small changes in design and approach to construction.

25 Given the level of feedback provided in Phase 3 it is, perhaps, surprising that only 21 of the 28 houses tested have achieved air leakage values meeting the 10 $m^3/(h.m^2)$ target level, although three of the 28 houses (Plots C194, D73 and D74) were built without taking the feedback on board in order that the developer could compare alternative dwelling types or new designs that had been built by the same construction team at the same time.[17] As in Phase 1 of the project, all of the dwellings to date were using Part L Robust Details (DEFRA, 2001) as the basis of the application for regulatory approval. In addition to this, each developer also received detailed and targeted feedback from the Leeds Met research team on any potential areas or issues that may have an influence on the eventual airtightness performance of the selected dwellings.

26 The data also show that the tightest dwelling tested was constructed by developer E. All of the dwellings constructed by this developer achieved air leakage values less than the target of 10 $m^3/(h.m^2)$. The leakiest dwelling tested was constructed by developer C, which was built as per their standard Phase 1 construction. Only one of the five dwellings constructed by developer D achieved an air leakage rate of less than 10 $m^3/(h.m^2)$ @ 50Pa.

27 Further analysis of the results obtained for both phases of this project has highlighted a number of factors that are likely to influence the airtightness performance of new UK dwellings. These factors are as follows:

a) The type of construction.

b) The complexity of design.

c) The approach adopted to improve the airtightness performance of the dwelling.

d) The use of feedback and guidance.

e) Robustness of approach.

f) Repeatability.

Type of construction

28 Construction type is known to have an influence on airtightness (see Stephen, 1998 and 2000). This is illustrated in the results from both phases which appear to show a difference in permeability between the different types of construction method used by the various developers (see Figures 7 and 8 and Tables 5 and 6). The tightest dwellings were the apartments built using wet plastered masonry cavity construction. These dwellings were on average a factor 2 more airtight than all of the other construction types. The reasons for this are two-fold. First of all, wet plastered masonry dwellings tend to be intrinsically more airtight than comparable dry-lined masonry or steel frame

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[15] The other two Phase 3 apartments constructed by developer E (Plots EA301 and EA302) showed a reduction in air permeability from the corresponding Phase 1 apartments of around 12%.

[16] In Phase 1, the apartments were pressure tested by placing the blower door in the front door frame of each apartment. In Phase 3, the blower door was positioned in the patio door of the apartments, as the closer mechanism for the front door prevented the blower door frame from being installed correctly. Air leakage was subsequently detected around the front door and its fixings that had not been possible to detect in Phase 1.

[17] In the case of developer C, Plot C194 was included to explore the issues associated with constructing a different house type (in this case a detached dwelling as opposed to a semi-detached or terraced dwelling). Plots D73 and D74 were included by developer D so that they could examine the effect of new house designs and detailing that had been introduced in response to the introduction of the 2002 Building Regulations (the Phase 1 dwellings adopted an older design that had been adapted for 2002 compliance).

construction (Olivier, 1999). Secondly, apartments tend to be more airtight than comparable dwellings of different built form. The least airtight dwellings were those constructed using light steel frame, although these were only marginally leakier than the dry-lined masonry cavity dwellings in Phase 1 (see Figure 7). A more significant difference was displayed in Phase 3 (see Figure 8). However, type of construction should not be considered in isolation when analysing either set of results, as the other variable factors listed previously also need to be taken into consideration.

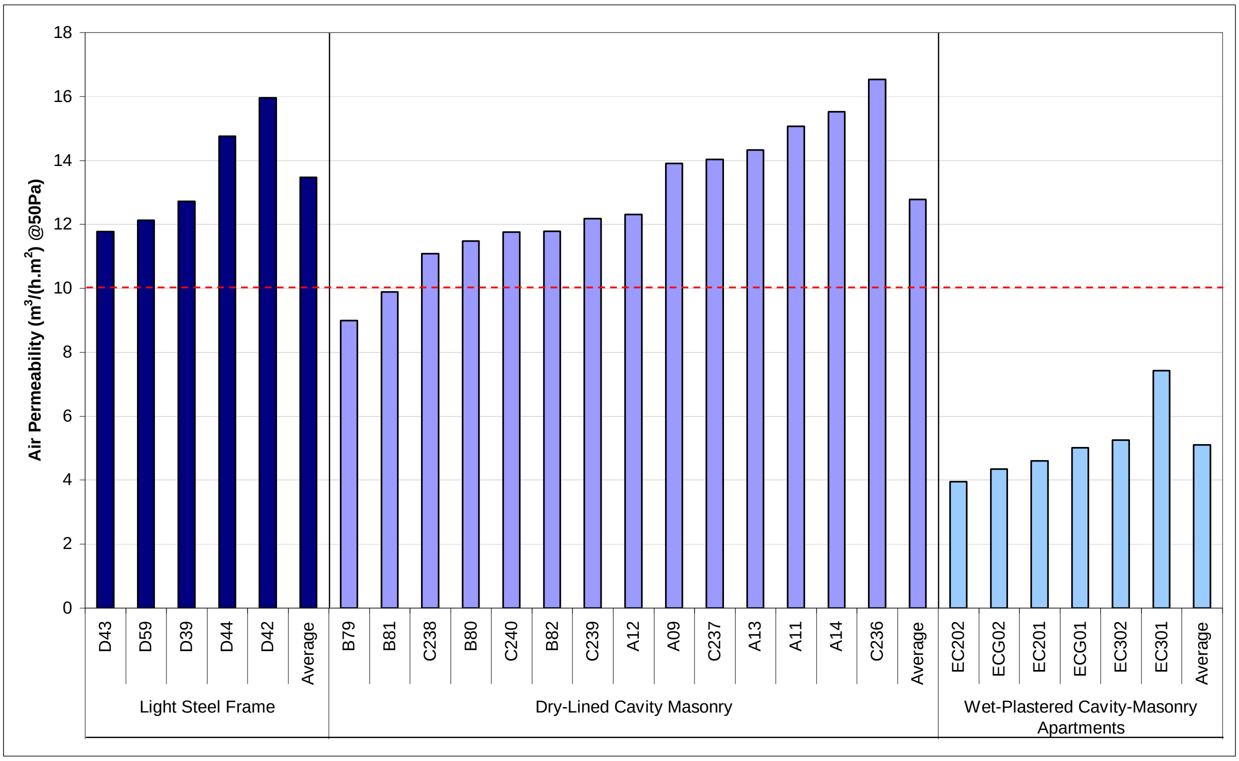

Figure 7 Mean air permeability of the Phase 1 dwellings by construction type.

Construction type	Mean air permeability ($m^3/(h.m^2)$ @ 50Pa)
Dry-lined masonry cavity (Developers A, B and C)	12.6
Light steel frame (Developer D)	13.5
Mechanically/manually wet plastered masonry cavity (Developer E)	5.1

Table 5 Mean air permeability of the Phase 1 dwellings by construction type.

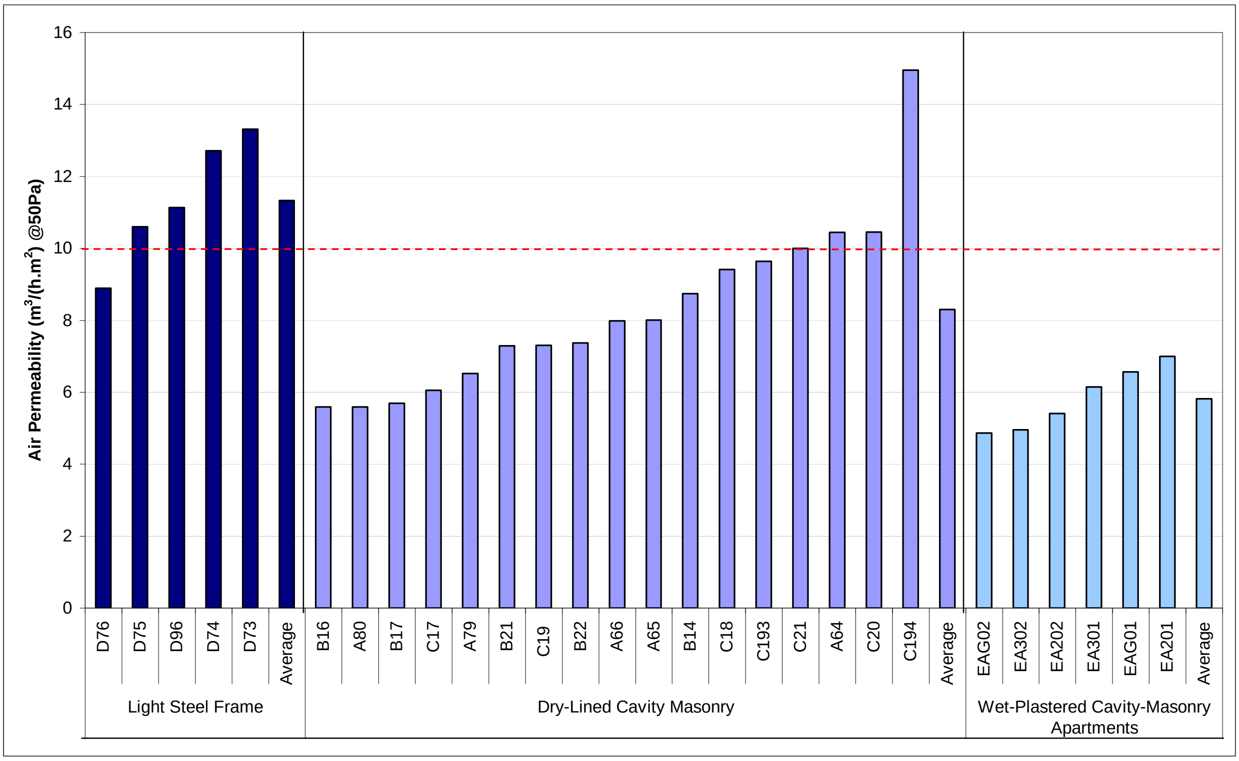

Figure 8 Mean air permeability of the Phase 3 dwellings by construction type.

Construction type	Mean air permeability (m^3/(h.m^2) @ 50Pa)
Dry-lined masonry cavity houses (Developers A, B and C)	8.3
Light steel frame houses (Developer D)	11.3
Wet plastered masonry cavity apartments (Developer E)	5.8

Table 6 Mean air permeability of the Phase 3 dwellings by construction type.

29 The results from Phase 3 (Figure 8) indicate that light steel frame is presenting greater difficulties in terms of airtightness than masonry cavity construction. To what extent this is a function of the current level of experience with this construction form or of a greater level of technical difficulty is uncertain. However, the results indicate that much more thought is required to the airtightness aspects of design and construction if reliably airtight steel frame dwellings are to be constructed. Only one of the steel frame dwellings achieved an air permeability of less than 10 m^3/(h.m^2) @ 50Pa and this result was only obtained after considerable efforts had been made on site to ensure that the primary air barrier (in this case the wall insulation fixed to the exterior of the frame) was made as airtight as possible. This involved extra taping around all junctions and openings, and sealing around the ground floor slab/external wall junction. Indeed, the best performing steel frame dwelling tested in Phase 3 was still less airtight than 11 out of the 17 masonry cavity dwellings tested in this phase of the project.

30 As the light steel frame dwellings for both phases were built using accredited construction details as a means for Part L compliance, the primary air barrier consisted of rigid insulation panels butt-jointed and sealed with an approved tape as recommended in the Robust Details document (DEFRA, 2001). These results suggest that with considerable additional attention to detail, a number of minor design alterations, and extreme care on site, an air permeability of below 10 m^3/(h.m^2) @ 50Pa can be achieved with this type of construction, but the achievement of levels of

airtightness significantly below 10 $m^3/(h.m^2)$ @ 50Pa may be difficult to achieve without a fundamental rethink of the airtightness aspects of this form of construction.

Complexity of design

31 Complexity of design is also known to influence airtightness. All things being equal, the more complex the form and the techniques used to construct a building, the greater the potential for air leakage (see Johnston, Wingfield and Bell, 2004). The effect that complex designs can have on air permeability was observed in the Phase 1 dwellings constructed by developer C. In this phase, the results for the end-terraced and semi-detached dwellings tested returned lower air permeability than the mid-terraced dwellings by some 3 to 4 $m^3/(h.m^2)$ (see Figure 8). Despite differences in dwelling form, notable differences in the complexity of detailing were observed and this was thought likely to have been a significant factor in the results.

32 Three of the dwellings (C238, C239 and C240) were similar in size and design, only differing in form (one was an end-terrace whilst the other two were semi-detached), the two remaining dwellings (C236 and C237) were virtually identical mid-terraced dwellings; all were constructed by the same team on site (Figure 9). The measured air permeability of the mid-terraced dwellings was 16.5 and 14.0 $m^3/(h.m^2)$ @ 50Pa, and 11.1, 12.2 and 11.7 $m^3/(h.m^2)$ @ 50Pa for the end-terrace/ semi-detached dwellings. The higher air permeability of the mid-terraced dwellings could be partly attributable to the fact that mid-terraced properties tend to have low exposed internal surface areas and a greater proportion of openings on the external walls than other dwelling forms of equivalent floor area. Although this may explain some of the difference in air permeability between the dwellings, a greater part of the difference is likely to be attributable to a number of complex details that had been incorporated within the mid-terraced properties in particular the extending of the first floor bathrooms over the ground floor passage way (see Figure 10).

Figure 9 Front elevations of developer C mid-terrace and end-terrace properties.

33 As a direct result of the Phase 2 feedback session held with developer C it was decided to explore the issue of complexity a little further.[18] In order to do this a detached dwelling on the same site containing many of the more complex design detailing issues as in the mid-terrace dwellings was selected (C194 — Figure 11) and constructed by the same site team using the same standard-build approach as in Phase 1 and its construction observed. The pressure test result of this detached property was 14.96 $m^3/(h.m^2)$ @ 50Pa, which was similar to the mid-terrace dwellings in Phase 1. Figure 12 compares the pressure test results for the Phase 1 dwellings with that obtained for the detached dwelling.

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[18] We are of course aware that this trial cannot be seen as having any statistical significance but in a qualitative and exploratory study such as the one being reported it was considered a useful exercise for the insights and explanatory power it provides. To address this issue directly would require a much more complex and expensive study involving many more dwellings and a complex control framework.

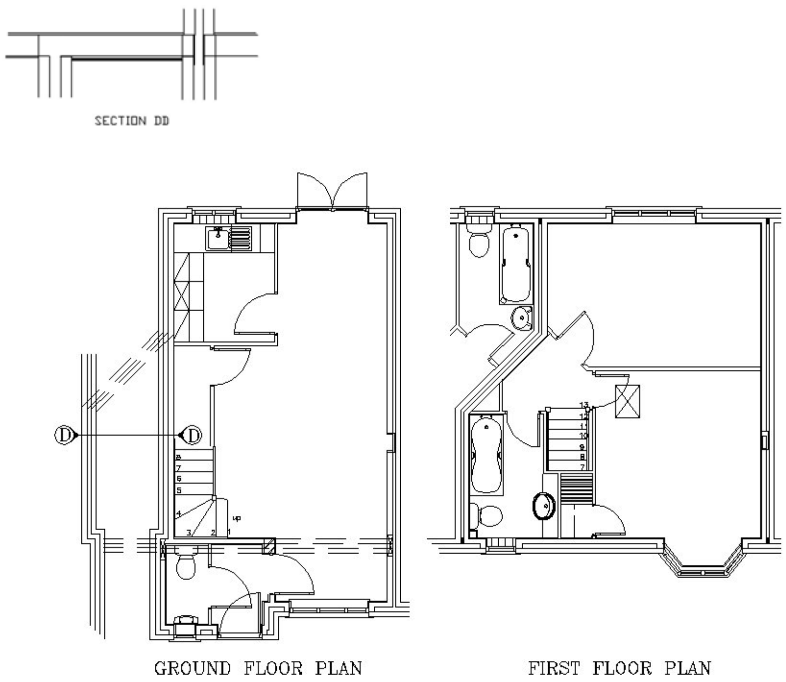

Figure 10 Ground and first floor plans of developer C's mid-terrace property.

Figure 11 Developer C's detached property, C194, and internal view of partially constructed first floor bay.

34 Complexity of geometry and structure tend to add a degree of uncertainty as to what actually constitutes the primary air barrier, and how its continuity was maintained. In the end-terraced/semi-detached dwellings some uncertainty occurred around the roof of the front porch, but the mid-terrace properties displayed a greater degree of complexity with significant changes in the plane of the primary air barrier, including extended ground floors, timber framed first floor bay windows, angled separating wall junctions and bathrooms constructed over passageways (see Figures 9 and 10). The detached property (C194 — Figure 11) displayed similar complex detailing to the mid-terrace housing; in both house types there appeared to be confusion over what constituted the air barrier directly above semi-exposed areas (in the cases of the integral garage in C194, and the bathrooms over the passageway in C236/C237). Also substantial air leakage into areas around the roof space over the extended ground floor was observed in both house types particularly around the first floor bays (Figure 11). Since site observations indicated that the quality of materials, workmanship and supervision were constant throughout this site, these results suggest that the

additional complex detailing in C194, C236 and C237 was likely to have been influential in the different air permeability test results obtained.

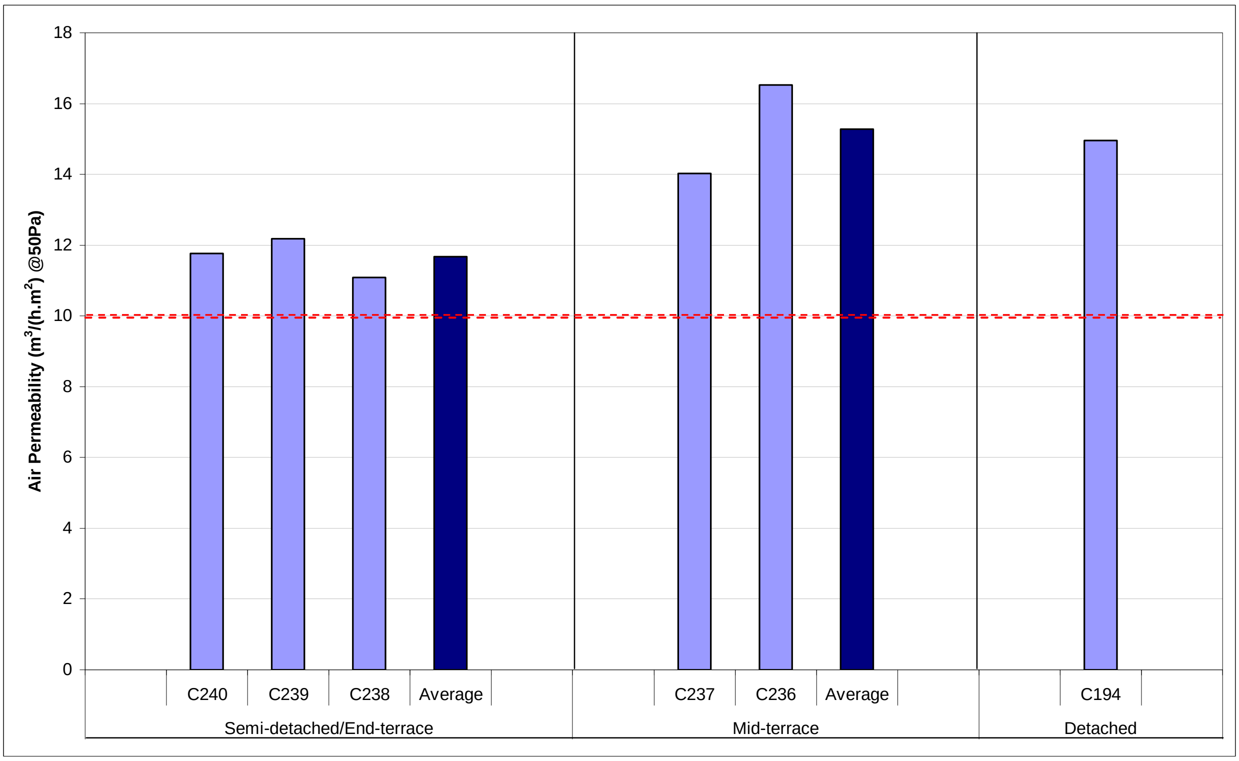

Figure 12 Developer C's test results for Phase 1 dwellings and C194 (Phase 3).

35 In multi-dwelling buildings, different dwellings within the same block may contain varying degrees of complexity and even different construction types. The summary of the Phase 1 air permeability test results for developer E, contained within Table 7 and Figure 13, indicate the variation in dwelling performance based on the boundary conditions for these apartments. The L1A (2006) definition of dwelling type distinguishes between ground, mid and top-floor apartments. The results obtained for developer E support this approach, with the two top-floor apartments producing higher air permeability test results than the ground and mid-floor apartments. Another factor that appeared to have an effect on the air permeability was that of location of the apartment on its specific floor (Figure 14), with the three apartments situated on the external edge of the apartment block being less airtight than their internal equivalents. The traditional timber roof construction of the top-floor apartments (EC301 and EC302) contained loft hatches and had recessed lights backing into a ventilated loft void rather than the enclosed suspended void observed in the other apartments; apartments with a greater number of external walls (ECG01, EC201 and EC301) also had at least two additional windows.

Dwelling	**Boundary condition**	**Air permeability ($m^3/(h.m^2)$)**
ECG01	Concrete ground and intermediate floors, 3 external walls	5.01
ECG02	Concrete ground and intermediate floors, 2 external walls	4.35
EC201	Concrete intermediate floors, 3 external walls	4.61
EC202	Concrete intermediate floors, 2 external walls	3.95
EC301	Concrete intermediate floor, traditional timber roof, 3 external walls	7.42
EC302	Concrete intermediate floor, traditional timber roof, 2 external walls	5.25

Table 7 Air permeability of the dwellings tested for developer E.

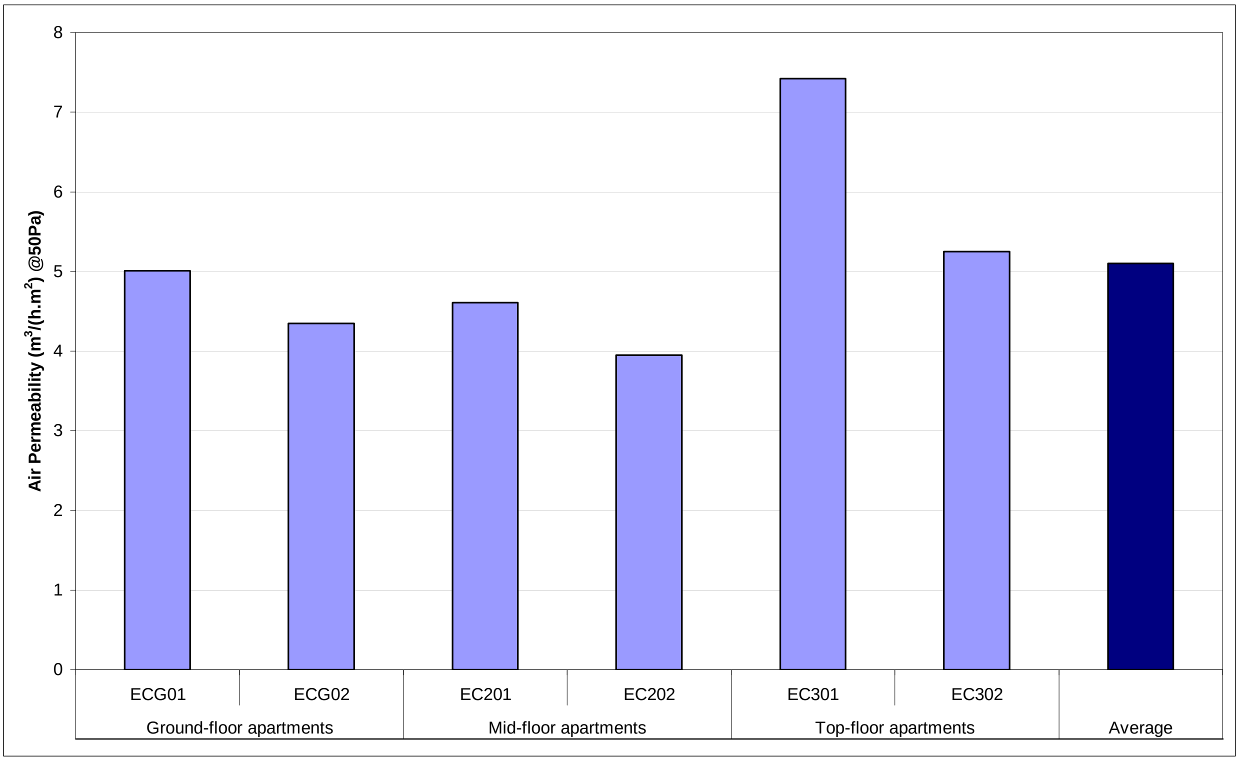

Figure 13 Developer E, Phase 1 pressure test results.

36 The test result for EC301 still exceeds what would be expected for the slight increases in complexity outlined above, this can be explained by the introduction of a mezzanine storage deck across the entire width of the apartment (Figure 14) and an additional high-level window, neither of which is present in EC302 or in any of the other apartments tested. Leakage detection performed in conjunction with the pressure tests showed similar leakage paths present in all the apartments but in the case of EC301 an additional and significant amount of air leakage was observed in the area of the mezzanine storage deck, indicating the influence of the more complicated detailing around this feature.

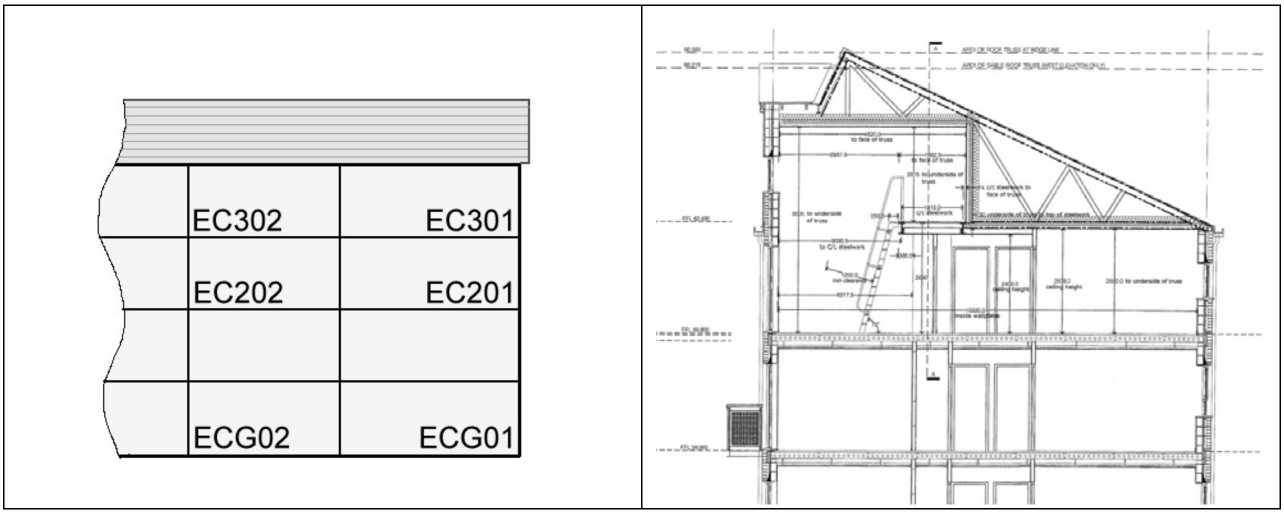

Figure 14 Developer E's apartment locations within the block, and the mezzanine storage deck in EC301.

37 The discussion of complexity is not intended to imply that such complexity should be avoided as a matter of principle. Clearly where complexity serves no purpose there are benefits to be gained in all aspects of design by simplification, but where there are clear aesthetic or other reasons we do not advocate the avoidance of complex details. However, designers and constructors need to understand the airtightness problems that are introduced and devise robust solutions.

Approach

38 The Phase 3 results have been analysed in terms of the different approaches to improving performance taken by each developer. Table 8 and Figures 15 and 16 show, for the three general approaches adopted, the percentage improvement (on a plot by plot comparison) together with the Phase 3 test result. This provides an indication of the sort of reductions that can be achieved by the different strategies.

Action taken	**Plot**	**Construction type**	**Test result ($m^3/(h.m^2)$ @ 50Pa)**	**Developer Phase 1 equivalent ($m^3/(h.m^2)$ @ 50Pa)**	**Plot % improvement over Phase 1 equivalent**
1. General feedback only	C194	Full-Fill Masonry	14.96	15.28	2.1
	D73	Light Steel Frame	13.31	13.47	1.2
	D74	Light Steel Frame	12.71	13.47	5.6
	Average		13.66		2.97
2: Detailed site quality control and feedback from Leeds Met research team	A64	Partial-Fill Masonry	10.44	14.23	26.6
	A65	Partial-Fill Masonry	8.01	14.23	43.7
	A66	Partial-Fill Masonry	7.98	14.23	43.9
	B14	Full-Fill Masonry	8.74	10.54	17.1
	B21	Full-Fill Masonry	7.29	10.54	30.8
	B22	Full-Fill Masonry	7.37	10.54	30.1
	C18	Full-Fill Masonry	9.41	14.28	47.0
	C20	Full-Fill Masonry	10.45	11.68	10.5
	C21	Full-Fill Masonry	10.00	11.68	14.4
	C193	Full-Fill Masonry	9.64	15.28	36.9
	D75	Light Steel Frame	10.6	13.47	21.3
	D96	Light Steel Frame	11.14	13.47	17.3
	Average		9.26		28.3
3: Additional sealing to primary air barrier	A79	Partial-Fill Masonry	6.62	14.32	54.5
	A80	Partial-Fill Masonry	5.59	11.79	52.6
	B16	Full-Fill Masonry	5.59	10.54	47
	B17	Full-Fill Masonry	5.69	10.54	46
	C17	Full-Fill Masonry	6.06	11.68	48.1
	C19	Full-Fill Masonry	7.30	14.28	48.9
	D76	Light Steel Frame	8.89	13.47	34
	Average		6.52		47.3

Table 8 Phase 3 results by approach, showing improvement over Phase 1 mean.

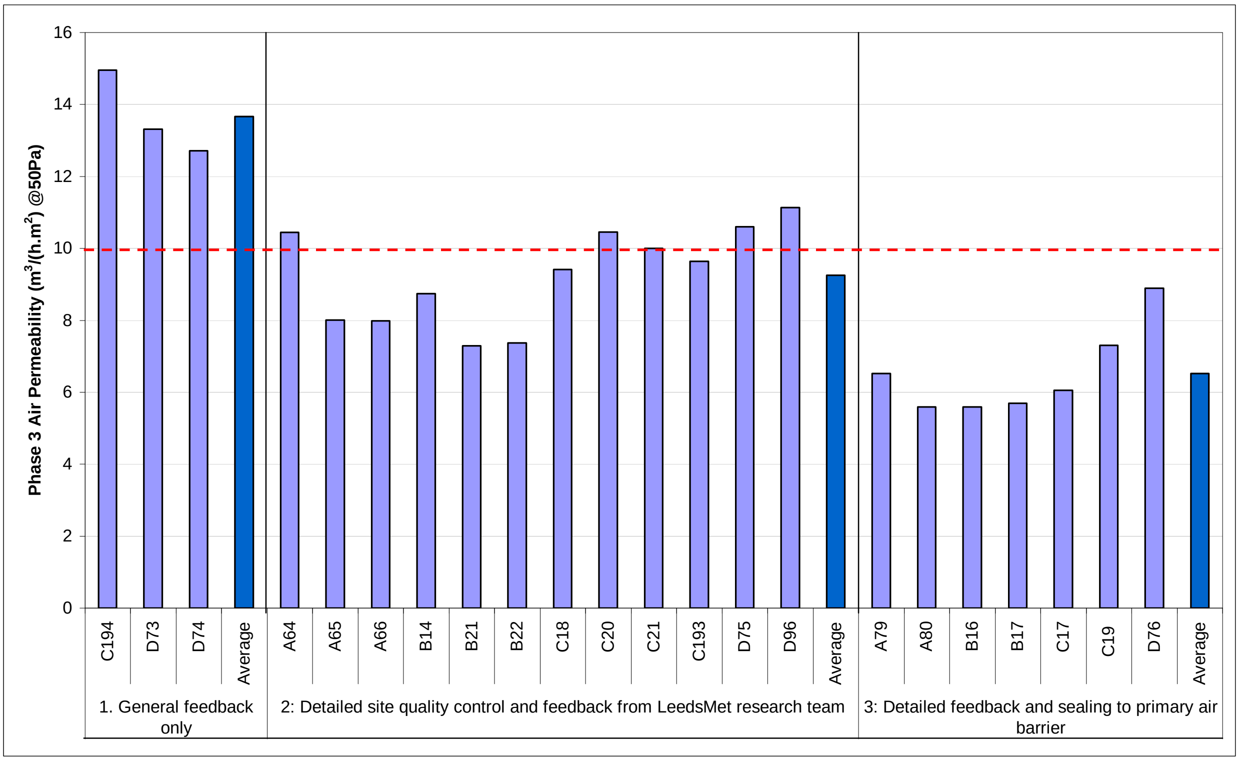

Figure 15 Phase 3 air permeability test results.

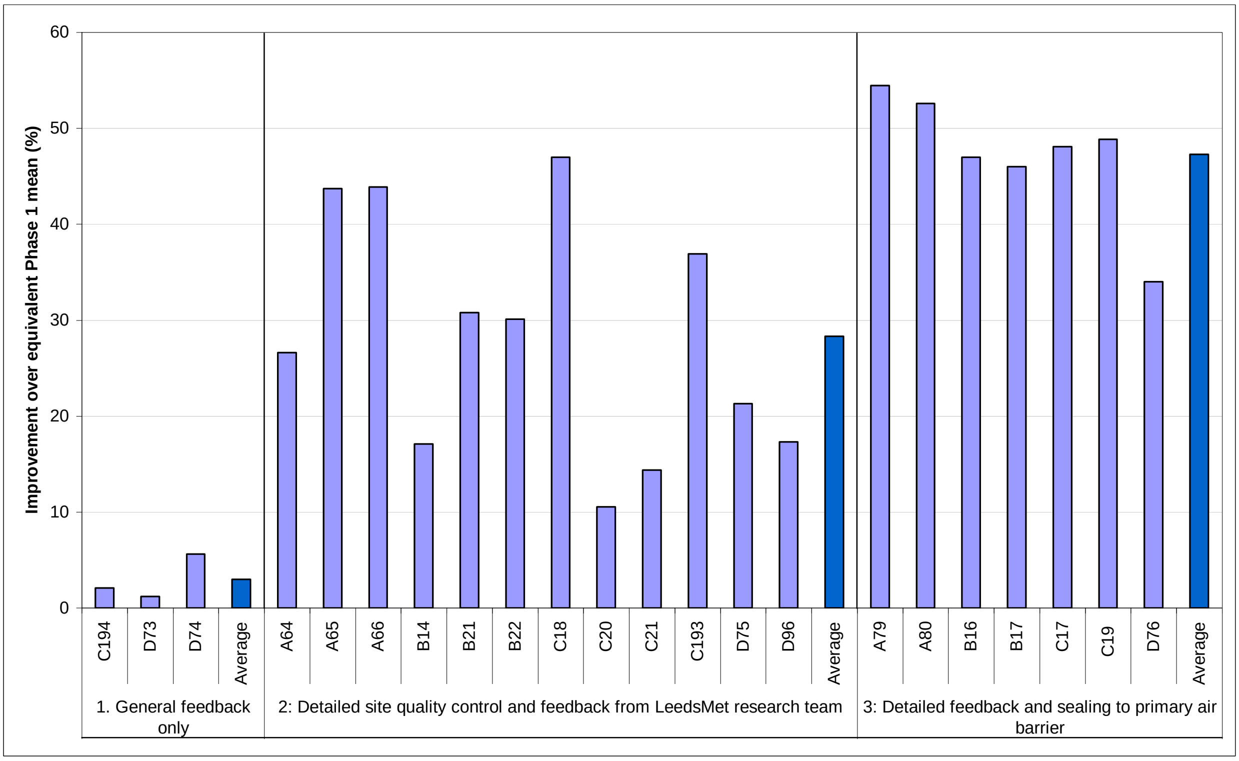

Figure 16 Improvement of Phase 3 air permeability test results over equivalent Phase 1 mean.

39 As Figures 15 and 16 illustrate, the least effective approach was to seek to respond to the general feedback provided in Phase 2 by tightening up in a general way, but with no specific design measures or any detailed site control measures. This resulted in a negligible reduction in the mean air permeability of the dwellings constructed. The second approach was to maintain existing detailed design, but to seek to address the site quality issues. An approach that could be labelled

’doing what we do now but with improved and detailed quality control‘. This approach also entailed responding to detailed feedback from the Leeds Met research team following each site visit. Typically this would result in additional sealing and rectification works done as construction progressed. Adopting this measure produced air permeability values ranging from 7.3 to 11.1 $m^3/(h.m^2)$ @ 50Pa (with an average of 9.3 $m^3/(h.m^2)$ @ 50Pa) with reductions of between 11% and 47%. The greatest reductions in air permeability were observed when design-led changes were introduced focusing attention on the air barrier, its identification and its continuity. This approach resulted in air permeabilities of between 5.6 and 8.9 $m^3/(h.m^2)$ @ 50Pa (average 6.5 $m^3/(h.m^2)$ @ 50Pa), with reductions over the equivalent Phase 1 dwellings of between 34% and 55%.

40 As indicated above, where no specific action had been taken to improve the airtightness of the dwellings for Phase 3, besides the general Phase 2 feedback, no significant improvement in airtightness was observed. In the case of C194 this was expected, as it was only chosen for Phase 3 to provide a comparison with developer C’s different house types included in Phase 1. However in the cases of D73 and D74 (light steel frame), the developer had introduced new house designs and detailing to comply with the 2002 Building Regulations, their dwellings examined in Phase 1 had been manufactured to older designs adapted for 2002 compliance. The design assessments carried out on D73 and D74 (Johnston, Miles-Shenton and Bell 2005b) indicated only one airtightness modification was made for these Phase 3 dwellings; the use of a temporary course of blockwork as a sacrificial slab former, to improve the junction of the slab, frame and insulation (see Figures 17 and 18). The remaining Phase 3 dwellings (D75, 96 and 76) built by developer D received much more attention with commensurate improvements in airtightness.

Figure 17 Developer D, Phase 1, the use of removable polystyrene formers created an inconsistent and uneven slab edge, with potential for air leakage at the junction of slab, steel frame and insulation.

41 Developers A, B, C and D have all had Phase 3 properties tested where secondary sealing measures have occurred as a result of detailed feedback from the Leeds Met research team. This has involved tightening up on existing detailing due to information received in the Phase 2 individual developer feedback sessions and additional measures taken as a reaction to continuous on-site feedback from the research team, who visited the sites at critical stages throughout the Phase 3 construction programme. In all cases this resulted in improved supervision of operatives via a more informed site management team and many minor changes were introduced which did not incur any significant additional cost; this has been reflected in the results.

Figure 18 Developer D, Phase 3, using sacrificial blockwork to form the slab; after the blockwork is removed a straighter and more uniform slab edge reduces the potential for air leakage at this junction.

42 Three of developer A's Phase 3 dwellings (A64, A65 and A66) displayed no apparent difference in quality or methodology between their construction process and level of feedback received, yet the pressure tests yielded results of 8 $m^3/(h.m^2)$ @ 50Pa for two of the Phase 3 properties (A66 and A65) and 10.4 $m^3/(h.m^2)$ for the other one (A64). Leakage identification performed with the pressure tests revealed similar leakage paths in all three dwellings. These Phase 3 results for developer A suggest that this approach of improved supervision and site feedback can reduce air leakage in traditional-build cavity masonry partial fill dwellings, but this alone cannot be relied upon to guarantee compliance with the new Part L limit of 10 $m^3/(h.m^2)$ @ 50Pa. The two dwellings where developer A introduced additional sealing to the primary air barrier (A79 and A80) both provided test results well below this limit, at 6.5 and 5.6 $m^3/(h.m^2)$ @ 50Pa.

43 The Phase 3 results for developer B suggest that increased knowledge and awareness of airtightness issues alone can reduce air permeability, as shown with Plot B14. With the additional on-site feedback from the Leeds Met research team the airtightness was reduced further, with both Plots B21 and B22 producing test results of below 7.5 $m^3/(h.m^2)$ @ 50Pa. The additional internal secondary sealing performed on B22 (e.g. mastic sealant around electrical pattress boxes and light fixings), but not on B21, did not appear to have any significant additional effect as the test results for both properties were very similar (7.4 and 7.3 $m^3/(h.m^2)$ @ 50Pa, respectively).

44 The most significant reductions in air permeability, and lowest test results for each developer, occurred where improvements to the primary air barrier were introduced. Establishing exactly what constituted the primary air barrier was essential in this approach. The solid ground floor and top-floor ceiling were identified as the primary air barrier in all dwellings. In the cavity masonry construction of developers A, B and C the primary air barrier for walls was identified as the inner leaf blockwork, whilst for developer D's light steel frame dwellings it was the polyurethane foam external insulation system. Developer A introduced additional sealing to the primary air barrier in dwellings A79 and A80. This was achieved using tape, mastic and expanding foam to seal junctions, penetrations and the loft boundary at a pre-plaster stage, and was coupled with increased site supervision and quality control. Developer B sought to test two approaches to improving the airtightness of the inner leaf. In the case of B16 all internal blockwork and junctions were inspected at the pre-plaster dry-lining stage and additional pointing work undertaken to remedy any defects. In contrast, B17 had a 3~6 mm thick full parging layer applied to the blockwork prior to dry-lining. Developer C adopted a similar approach in the case of C17, with a 6~12 mm coarse render applied to party walls (for Part E compliance) also being applied to all external walls. Developer D improved their primary air barrier with a combination of additional sealing (with tape, mastic and expanding polyurethane foam) and a minor design change at the intermediate floor perimeter. For developers B, C and D the cost of this action was approximately one man-day per dwelling plus marginal material costs. In the case of developer A, the work undertaken was more

labour intensive, approximately 2 man-days per dwelling, and involved much greater material costs (approximately £500 per dwelling). Of the design-led approaches, the most significant reductions were achieved by developer A in dwellings A79 and A80, which achieved an air permeability of 5.6 and 6.5 $m^3/(h.m^2)$ @ 50Pa, respectively, representing a reduction in excess of 50% compared with their equivalent Phase 1 dwellings. However, the approach used to achieve these reductions was not only labour and material intensive but relied on assiduous site supervision and sealing of the loft boundary junction. However, the effort involved is likely to make such an approach unsustainable in the long term. Similar and more robust reductions in air permeability are likely to be achievable by adopting an alternative approach to providing continuity of the air barrier at the loft boundary junction, such as the use of membrane materials. B16 and B17 achieved similar figures for air permeability of 5.6 and 5.7 $m^3/(h.m^2)$ @ 50Pa, representing reductions of 47% and 46% from the Phase 1 equivalent. Plots C17 and C19 displayed pressurisation test results of 6.1 and 7.3 $m^3/(h.m^2)$ @ 50Pa when tested on completion, representing 48% and 49% reductions on their equivalent Phase 1 mean. The smallest reduction of the design-led approach was seen in the case of steel frame construction, with D76 providing a final air permeability measured at 8.9 $m^3/(h.m^2)$ @ 50Pa, a reduction of 34%. This was only achieved after considerable effort by both the site staff and the Leeds Met research team to identify potential leakage paths and perform the necessary remedial action, suggesting that much more thought is required in the design of the air barrier for light steel frame designs (warm frame) that rely on the external insulation layer as an air barrier.[19]

Feedback and guidance

45 An important aspect of the project was the feedback and guidance given by the Leeds Met research team. During Phase 1 of the project, the research team's role was purely observational and no feedback or guidance on airtightness was given to the developers during the construction of the Phase 1 dwellings. Following completion of these dwellings, a feedback seminar was organised with each of the developers where the observations from site, the air permeability results and the leakage identification work was presented to the developers and general advice and guidance was given on airtightness. Further details of these seminars can be found within Johnston, Miles-Shenton and Bell (2005a).

46 A two-way dialogue was then facilitated between the Leeds Met research team and the developers during Phase 3, enabling any observations from site on the airtightness performance of each of the selected dwellings to be fed back to the developers. In practice, the feedback took the form of a short written report, supplemented by photographs, highlighting any potential areas or issues that may have an influence on the eventual airtightness performance of the dwellings in question. These reports were sent to the respective sites by mail or electronically to allow action to be taken as soon as possible, and in most cases were supplemented with discussions with the site team prior to the next site visit. By providing continuous detailed (site specific) feedback to the developers, it gave them the opportunity to identify and rectify any issues relating to airtightness on site, prior to the dwellings being completed and tested. The provision of such feedback also raised the awareness levels of airtightness on site.

47 With respect to the effect of feedback and guidance on airtightness, the Phase 3 results suggest that for those dwellings where the only difference between Phases 1 and 3 was the general feedback provided at the Phase 2 seminar (C194, D73 and D74), very little reduction in air permeability was observed. This suggests that there appears to be little immediate benefit in providing general feedback on airtightness to developers. Although how much information from the Phase 2 seminar had filtered down to site operative level at the time of completion of these dwellings is unclear. The results would suggest that very little had reached site level.

48 It has not been possible to separate out the effect that the detailed feedback alone had on the Phase 3 results. Nevertheless, in those dwellings where constant detailed feedback was given to the developers, reductions in air permeability from the Phase 1 mean were observed. Although it is difficult to say how much of this reduction was attributable to the detailed feedback and how much was attributable to the measures that were adopted, it is felt that feedback alone is unlikely to result in significant reductions in air permeability.

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[19] The adoption of a hybrid form of steel frame (see DEFRA, 2001 section 7) in which insulation is placed between studs as well as externally together with an internal vapour control layer (as is common in timber frame) may present fewer airtightness problems.

49 It is also important to note that providing continuous detailed feedback on airtightness during the construction of a dwelling, at the same level as discussed above, is onerous and labour intensive.

Robustness of approach

50 Observations from site suggest that there are likely to be differences in the robustness of the approach adopted to improve airtightness. The observations from this project suggest that the adoption of an approach which involves no change to design relying instead on assiduous site supervision and remedial sealing where necessary is unlikely to be robust. In most cases such an approach tends to rely upon the sealing of gaps, such as service penetrations through intermediate floors, skirting boards at floor/wall junctions and the sealing of entries into internal service ducts. Practically, it is almost impossible to seal all of these gaps. The difficulties are compounded by the fact that many of the spaces within the construction communicate with each other resulting in a very complex pattern of air flows both within and through the building envelope. Thus to concentrate on this type of sealing works, which often takes place after key areas have been covered up, is not a very efficient approach. To ensure acceptable airtightness through this route requires a very high level of workmanship and site supervision to ensure that all of the gaps are properly sealed. A much more robust approach would be to adopt a design-led primary sealing approach, where the effort in both design and construction is concentrated on ensuring that there is an effective and continuous air barrier.

51 The results for dwellings B16 and B17 also highlight another aspect of robustness. Although both dwellings adopted a primary sealing approach for Phase 3, the measures that were incorporated within each dwelling were quite different. Both dwellings achieved similar air permeability results (5.6 $m^3/(h.m^2)$ @ 50Pa), suggesting that pointing and parging can have a similar impact on airtightness. However, from a quality control perspective, it is much simpler and quicker to check that the parging layer has been applied correctly rather than checking to see if all of the apertures and joints have been pointed. Although both methods achieved similar results, it is felt that parging is likely to provide greater consistency.

Repeatability

52 During the inspection work on the individual dwellings, attempts were made, in some cases, to observe in a general way the construction of other dwellings not featured in the research project. Casual observations from the sites suggest that the knowledge and experience of airtightness gained throughout this project does not appear to be filtering through to the construction of other dwellings on site. A way of establishing whether this is actually the case would be to measure the air permeability of a number of other dwellings, from the same production phase as the test dwellings, that were not directly involved in this project. Although a number of the developers have been approached regarding this, to date, no agreements have been given by the developers to test such dwellings on site.

53 A possible explanation for why this knowledge and experience may not be filtering through may simply be that there is no current requirement to do so, as all of the dwellings currently under construction are meeting the airtightness requirements by the adoption of Robust Construction Details. This situation is unlikely to change significantly, even after the introduction of Part L1A 2006 (ODPM, 2006a), as the current pressure testing regime only requires a limited number of dwelling types[20] to be tested per development. It is also difficult to say how the experience of airtightness gained from one particular site will transfer to other sites that are being constructed by the same developer.

54 The results from developer A highlight that it also likely to be difficult to achieve consistent air permeability results even when dwellings of the same size, construction type and form are being constructed on the same site by the same workforce. As previously mentioned, the Phase 3 dwellings constructed by developer A displayed no apparent difference in quality or methodology between the dwellings. Despite this, the air permeability of the two identical mid-terraced dwellings (A64 and A65) varied bv over 2 $m^3/(h.m^2)$ @ 50Pa, with dwelling A64 achieving an air permeability of 10.4 $m^3/(h.m^2)$ @ 50Pa whilst dwelling A65 achieved an air permeability of 8.0 $m^3/(h.m^2)$ @ 50Pa.

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[20] Dwelling type is defined in Part L1A (2006) as a dwelling of the same generic form, e.g. detached, semi-detached, end-terrace, mid-terrace, ground-floor flat, mid-floor flat, top-floor flat.

55 Another issue that is likely to influence repeatability is the level and consistency of the feedback and guidance that is given on airtightness. The results from Phase 3 suggest that any feedback and guidance given on airtightness should be continuous, detailed, targeted and an integral part of a consistent quality control system if it is to result in a reduction in air permeability. Although general feedback and awareness raising is important, on its own, it is unlikely to result in any improvement in performance. It is also critical that design and construction quality control systems take into account construction processes and sequences since once the dwelling or a particular part of the dwelling is complete, it becomes extremely difficult and expensive to improve airtightness through secondary sealing measures.

Conclusions

56 This paper discusses the results that have been obtained on this project and identifies the levels of air permeability that could be achieved within new UK dwellings using existing technology and construction techniques.

57 Although the size, structure and non-random nature of the sample preclude it being taken as representative, the results obtained from Phase 1 suggest that the impact of the 2002 edition of Approved Document Part L1 on airtightness has been minimal. The failure of the majority of the dry-lined masonry cavity and steel framed dwellings included within this phase to achieve the ADL1 2002 airtightness target also suggests that the adoption of Robust Construction Details, at least in their current form, provides no guarantee that the current regulatory standard will be achieved with any degree of consistency. The results from Phase 3 of the project suggest that an air permeability of less than 6 $m^3/(h.m^2)$ @ 50Pa is genuinely achievable within mass-produced housing in the UK using existing techniques, materials and practices, and without incurring significant cost.[21] However, to achieve such a standard in a consistent and robust way will required a mix of relatively minor modifications to design and a committed and targeted approach to quality control.

58 The results from both phases of the project have highlighted a number of issues that need to be considered when constructing dwellings to meet a particular airtightness target. These issues relate to:

a) **Type of construction** — Certain construction types are intrinsically more airtight than others. The results illustrate that wet/mechanically plastered masonry cavity construction can default to a reasonable level of airtightness by UK standards without much additional attention being given to airtightness. Other construction types, such as dry-lined masonry cavity and steel framed construction appear to require much greater attention to detail if they are to achieve an air permeability below 10 $m^3/(h.m^2)$ @ 50Pa. In the case of masonry the required design changes may be relatively minor. The construction type that presented the greatest difficulty was steel frame construction (warm frame). Air permeability values of below 10 $m^3/(h.m^2)$ @ 50Pa are possible with this type of construction, but with existing design and detailing the effort involved, particularly at site level, is considerable. Given the observations in this project it is difficult to see how an air permeability consistently below 10 $m^3/(h.m^2)$ @ 50Pa can be achieved without a fundamental rethink of airtightness design in this form of construction.

b) **Complexity of design** — Complexity of design is likely to have a significant impact on airtightness. Differences in air permeability of up to 4 $m^3/(h.m^2)$ @ 50Pa from the mean were observed in dwellings of similar size, construction and form that had been constructed with comparable levels of workmanship and site supervision. The main difference observed between the dwellings was the complexity of the detailing. Higher levels of air permeability were consistently observed in those dwellings that contained the most complex detailing. In some instances, this detailing also added a degree of uncertainty as to what actually constituted the primary air barrier. Examples of such detailing included: extended ground floors, timber frame first floor bay windows, angled separating wall junctions, habitable rooms constructed over passageways and mezzanine storage decks.

c) **Airtightness approach adopted** — The approach that is adopted to improve airtightness can influence the eventual levels of air permeability that are achieved. The greatest reductions in air permeability were achieved where improved construction was undertaken in the form of design-led changes with respect to the primary air barrier.

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[21] The exception is light steel frame where much more thought at the design stage is likely to be required.

d) **Feedback and guidance** — The level and consistency of any feedback and guidance that is provided on airtightness is important. The results obtained from this project suggest that the provision of general feedback and guidance to the developer on airtightness, prior to the dwellings construction, is likely to have little or no immediate effect on airtightness. Such guidance does little more than raise awareness and, although a necessary first step, it must lead to a system of quality control that provides continuous detailed feedback and guidance during construction. However, providing this sort of feedback and guidance on a dwelling by dwelling basis is onerous and labour intensive.

e) **Robustness of approach** — The results illustrate that certain approaches to improving airtightness are likely to be more robust than others. Approaches that involve no change to design but instead concentrate efforts on basic workmanship coupled with secondary, remedial, sealing measures during construction are likely to be much less robust than those approaches that are based on an explicit attempt at the design stage to concentrate on ensuring that there is an effective and continuous air barrier. Detail design that recognises the importance of buildability and simplifies the construction process are also likely to be more robust.

f) **Repeatability** — Observations from site suggest that the knowledge and experience gained on airtightness does not appear to be filtering through to other dwellings on the same site. There are concerns that the other dwellings will not achieve the same sorts of levels of airtightness as the dwellings featured in this project. Clearly there remains a considerable amount of training and development work to be done to ensure that the house building industry is capable of producing a consistent standard of airtightness. This will not be a trivial task.

59 All of the above issues will have implications for the development of future regulations and testing regimes. These implications are discussed in detail in milestone D10 of this project (*Discussion Paper 2 — Impacts of Pressure Testing*).

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