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Relationships between air-tightness and its influencing factors of post-2006 new-build dwellings in the UK

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A B S T R A C T

Addressing air leakage of dwellings is important to improving energy efficiency and thermal comfort. This paper reports on the air permeability test results of 287 post-2006 new-build dwellings in the UK. The paper explores the relationships between air-tightness and its influencing factors including build method, dwelling type, management context, design target, season, number of significant penetrations, and envelope and floor area. One-way ANOVA analysis was utilised to compare means of air permeability in relation to the individual factors, and two- and three-way ANOVA analyses were applied for examining the interactions between them. The air-tightness of the dwellings averaged 5.97 $m^3/(h\,m^2)$ at 50 Pa, which has improved from UK historic data. Dwellings built using precast concrete panels were significantly air-tighter than those built using timber frame, whilst those masonry and reinforced concrete frame dwellings were most leaky. Greater extent of innovative practice and 'self-build' procurement led to achieving superior air-tightness. Interaction was observed between 'build method' and 'dwelling type' and between 'dwelling type' and 'management context'. A modest positive correlation was noticed between air permeability and design target, which became weak in relation to the number of significant penetrations and envelope area. Applying the linear regression technique a predictive model is developed for estimating air permeability of dwellings. This model integrates the influencing factors and their significant interactions. The findings should contribute to future research in predicting impacts of controlling the influencing factors on achieving air-tightness of dwellings more consistently.

1. Introduction

The domestic housing sector accounts for over a quarter (27%) of overall energy consumption in the UK [1]. More than half (53%) of the carbon emissions associated with that energy use is contributed by space heating [2]. Addressing air leakage of dwellings has been claimed to be important to improving energy efficiency and thermal comfort and reducing associated carbon emissions and health risks [3–5]. With fabric insulation levels being raised, air-tightness of the building envelope is expected to play an increasingly important role in achieving carbon emissions targets for new-build homes [6]. In the UK, important changes were introduced to the 2006 version of Building Regulations Approved Document Part L1a [7] in order to help achieve the national targets on reducing carbon emissions and implement the European Union's Energy Performance of Buildings Directive. In this revised version of Part L1a, sample air leakage testing of dwellings on completion became required on all sites and the worst possible air permeability allowable is 10 $m^3/(h\,m^2)$ at 50 Pa. Such 'baseline' air-tightness requirement will likely be raised in the new version of Part L that is being planned to come into force in 2010 [8]. Furthermore, the sites with commitment to higher environmental standards may have a requirement for lower air permeability rates and will require additional measures to achieve the standards. Failure to comply with required air-tightness standards will generate significant additional costs because of rectification, and will also introduce considerable risks to business due to potential delays and increased dwelling sample size for testing [7]. Nevertheless, too low built air permeability will require rethinking ventilation strategy for ensuring good indoor air quality [8]. It is important to strike a balance between air-tightness and ventilation and to achieve designed air permeability in a consistent manner.

Previous research in air-tightness of dwellings suggests two schools of studies, which can be termed 'experimental' and 'correlational' research [9]. 'Experimental' research is where true experiments are carried out under experimental controlled conditions with the purpose to measure the causal effect of independent variables upon the dependent one. Examples in the first school include the studies of air-tightness of dry-lined masonry dwellings

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by Roberts et al. [10] and Johnston and Lowe [11] and the three case studies of air-tightness of dwellings built by structural insulated panel, timber frame and modern masonry methods [4]. 'Correlational' research is under statistical control with the purpose to understand the correlations between variables. Examples of this include the studies of air-tightness of dwellings in Estonia by Kalamees [5], in Greece by Sfakianaki et al. [12], in the US by Sherman and Dickerhoff [13] and Chan et al. [14], and in the UK by Johnston et al. [15] and the Building Research Establishment (BRE) [16,17]. In parallel with these empirical studies there have been a number of practical guidelines in the literature for achieving and improving air-tightness, e.g. by the Energy Saving Trust (EST) [3,4] and BRE [18]. However, there appears to be a lack of empirical study of air-tightness of dwellings built in the UK after the revised Part L1a came into effect in 2006. Although sample air testing of dwellings on completion has since been required, very few results of measurement have been reported in the literature. There exist perceptions in practice that air-tightness of dwellings has been improved [8]. However, those perceptions lack substantiation from empirical quantitative analysis. Also, beyond the Part L1a 'baseline' requirement there exist a range of superior standards of air permeability [4,19]. The use of these superior standards is being increasingly encouraged. Many designers, developers and house-builders in the UK are aware of the importance of achieving air-tight dwellings, but such aspiration appears to be achieved, if so, on a 'hit-and-miss' manner.

This paper reports on a study of Part L1a field air-tightness tests of 287 post-2006 new-build dwellings on completion. The paper compares the measured air permeability of these dwellings with that revealed in previous research. It then examines the relationships between air-tightness and its influencing factors including build method, dwelling type, management, season, design target, number of significant penetrations through the building envelope, and floor and envelope area. It also explores the interactions between the critical influencing factors. Drawing on these exploratory analyses and a regression technique, the paper develops a predictive model which best describes the data available for this research. The model may be utilised for estimating air permeability of new-build dwellings in a more consistent manner.

2. Literature review

2.1. Air permeability and air-tightness standards

Air permeability is the physical property used to measure air-tightness of the building fabric. It is defined in Part L1a as 'air leakage rate per envelope area at the test reference pressure differential across the building envelope of 50 Pa' [7]. Air permeability appears similar to 'air leakage index' as used up to the introduction of Part L 2002, e.g. in the BRE study [16]. However, it is different from 'air change rate' calculated by air flow rate at 50 Pa divided by the internal volume of the dwelling (ach at 50 Pa) [5] or 'normalised leakage' used by, e.g. Sherman and Dickerhoff [13] and Chan et al. [14]. Air permeability, measured in $m^3/(h\,m^2)$ at 50 Pa, is used in this paper in order to keep alignment with the current building regulations and most practical guides in the UK. There exist a wide range of air-tightness standards for new-build dwellings. Table 1 compares a number of these standards in the UK and other countries.

The comparison suggests a variety of air-tightness levels, ranging from $10\,m^3/(h\,m^2)$ to less than $1\,m^3/(h\,m^2)$ at 50 Pa, representing Part L1a (2006 Edition), and the PassivHaus Standard and the Association for Environment Conscious Building (AECB) Carbon Lite Middle and Gold Standard, respectively. The EST Energy Practice levels and the others sit between. The regulatory air-tightness standards in the UK appear to be much less stringent compared with the others.

Table 1
Air-tightness standards for dwellings.

Air-tightness standards	Max air permeability $m^3/(h.m^2)$ at 50 Pa	Max air change rate (ach at 50 Pa)
Building Regulations Part L1a (2006 Edition) [7]	10	
Part L1a Indicative Standard for SAP 2005 [7]	7	
Part L1a 2010 Target [8]	5	
Energy Saving Trust (EST) Good Practice [4]	5	
EST Best Practice [4]	3	
EST Advanced Practice [19]	1	
ATTMA Best Practice [20]	3	
AECB Carbon Lite Silver Standard [19]	3	
AECB Carbon Lite Middle Standard [19]		0.6
AECB Carbon Lite Gold Standard [19]	0.75	
PassivHaus Standard [19]		0.6
Netherlands [21]		6
Switzerland [21]		3.6
Germany [21]		1.8–3.6
Denmark [22]		2.8
Estonian [5]	3	
Belgium [23]		1 or 3[a]
Super E (Canada) [4]	1.5	
Finland [24]		1

[a] 1 1/h for dwellings with balanced mechanical ventilation with heat recovery; 3 1/h for dwellings with mechanical ventilation.

2.2. Air-tightness of dwellings

In the international context, many air-tightness surveys have been carried out. For example, Hamlin and Gusdorf [25] reported on air-tightness of 47 special energy efficient R-2000 houses and 222 new conventional houses in Canada, which averaged 1.23 1/h and 3.06 1/h, respectively, at 50 Pa. Jokisalo et al. [26] reported an average leakage rate of 3.7ach from a study of 170 detached houses in Finland. They also claimed that the particular type of construction used has an effect on air-tightness, because the average building leakage rate of the massive (concrete, brick, and light weight block houses) was 2.3ach, while the average of the timber frame and the log houses were 3.9ach and 5.8ach. Granum and Haugen [27] studied the air-tightness of 10 detached houses in Norway built in 1980, averaged 3.9ach at 50 Pa. Kalamees [5] examined 32 detached houses built more recently in Estonia and found their average air leakage rate to be 4.9ach. Sfakianaki et al. [12] measured the air-tightness of 20 lightweight detached houses in Greece, which averaged 6.79ach but with a wide spread (1.87, 11.3). Sherman and Dickerhoff [13] quoted a mean air leakage rate of 29.7ach at 50 Pa for over 12902 dwellings in the US, which was however associated with a significant Standard Deviation (SD) of 14.5. This quoted mean air leakage rate appears very high, and Stephen [16] warned that data samples for some air-tightness surveys may have been biased by special dwellings used for research. Also, the locations, climate conditions, and the use of different construction methods and air-tightness standards, associated with the dwellings studied in these surveys, may have contributed to the diversity of air-tightness of dwellings in the international context.

In the UK context, the BRE database [16] shows that pre-1994 UK dwellings were very leaky with an average of around 13ach at 50 Pa, about three times in Scandinavia as reported previously. BRE and the National Energy Services inspected air-tightness of 99 new dwellings constructed to Part L1 2002 and revealed an average air permeability of 9.2 $m^3/(h\,m^2)$ at 50 Pa [17]. However, none of these dwellings achieved the EST Best Practice standard of 3 $m^3/(h\,m^2)$. Around a third failed to achieve the maximum air permeability allowed in Part L1a, i.e. 10 $m^3/(h\,m^2)$. Less than 20% of these dwellings tested met the EST Good Practice standard of 7 $m^3/(h\,m^2)$ and only two dwellings achieved 5 $m^3/(h\,m^2)$ or better [17]. During the same period, Johnston et al. [15] reported a mean air permeability of 6.89 $m^3/(h\,m^2)$ of four timber frame terrace and three masonry detached houses. However, these reports do not provide detailed analysis of air-tightness in relation to different dwelling types or build methods. The size of the samples might have constrained quantitative analysis on a more detailed level. Also, the samples studied included a range of dwelling types in both social and private sectors at a number of geographical locations. All these variables would have rendered any correlational analysis less effective. According to the recent UK Part L and F consultation paper, a large number of pressure tests were carried out, which showed that around 5% of the dwellings tested had an air permeability lower than 3 $m^3/(h\,m^2)$ and 30% lower than 5 $m^3/(h\,m^2)$ [8]. However, there were no details of these results or the sampling available in public domains because of the confidential and commercial nature of those tests. Also, it remains publically unknown how these results represent the air-tightness of new-build homes in typical UK housebuilding practice, given the background that Part F 2006 provides guidance on ventilation for new-build dwellings with an assumed air leakage of 3–4 $m^3/(h\,m^2)$ at 50 Pa.

The review of air-tightness of dwellings above suggests that the dwellings in the UK were leakier than in many other countries, particularly Canada and Scandinavia. Evidence shows that air-tightness of UK dwellings has improved following the revision of Part L1a and the introduction of compulsory air tests. However, the test results of more recent new-build UK dwellings remain anecdotal and fragmented, and largely exist in commercial entities.

2.3. *Factors influencing air-tightness*

The literature of air-tightness suggests a wide range of influencing factors which can be grouped under design, specification, construction, and testing [3,4]. Each group can be broken down further. For example, design factors include build method, location and type of openings, interaction between the structure and air-tight layer, and specification covers components and systems that make up the envelope and materials used to form the air barrier [4]. Montoya et al. [28] identified that variables including structure type, floor area, age of the building, number of storeys and insulation type have the greatest influence on air-tightness. Stephen [16] studied the relationship between air-tightness of pre-1994 UK dwellings and age of dwelling, type of wall construction, ground floor type, season and drying out process. Sifakianaki et al. [12] noticed a linear correlation between air tightness measurements at a 50 Pa pressure difference and the total windows frame length, mainly at the 'low air tightness' houses. Roberts et al. [10] examined the positive effects of applying parging coat and improving workmanship on air test results. Johnston and Lowe [11] revealed that sealing the external walls with expanding polyurethane foam reduced air permeability of the dwellings by more than 8 $m^3/(h\,m^2)$ and sealing the loft hatch and the electrical sockets reduced air permeability by approximately 0.1 $m^3/(h\,m^2)$ at 50 Pa each. Despite the increasing research efforts in recent years to improve understanding of air-tightness, previous studies of UK dwellings present fairly generic quantitative analyses of the relationships between air-tightness and its many constituent factors. Given the continuing emphasis on building air-tight dwellings [8], it is important to develop knowledge of how air-tightness correlates with design, specification and construction factors. Such knowledge will need to be made further available to policy-makers, designers, housebuilders and developers.

3. Methodology

This research was focused on the quantitative analysis of the field air-tightness test results of 287 recent dwellings in the UK built to Part L1a 2006 or more strict standards in relation to air permeability. This study was correlational in nature.

3.1. *Sampling air-tightness tests*

The field air-tightness test results were collected from three housebuilding companies in the UK (Table 2). These companies operated in the regions of Great London, Northwest, Midlands, East, and Southeast of England. These companies, although financially independent, were all associated with a national developing group which built circa 2500 new homes per annum with an annual turnover of £550million before the 'credit crunch'. The companies also shared some technical and managerial knowledge of the group in relation to energy efficiency design and construction. The selection of these companies for this study aimed to provide a reasonable geographical coverage of housebuilding practice in England, but also to minimise any skewed analysis which might be generated from including test results from other companies which may be associated with drastically different management context.

All the dwellings tested were proposed by the housebuilders and approved by building controls, in compliance with the sampling requirements of Part L1a [7]. The homes studied represented all the dwelling types specified in Part L1a, including detached, semi-detached, end-terrace, mid-terrace, mid-floor flat, ground-floor flat and top-floor flat. The selection of the air-tightness test results for analysis in this paper utilised a 'convenience sampling' strategy [29], i.e. utilising the test results available from the companies' internal technical database at the time of this study.

Table 2
Companies from which air-tightness test results were collected.

	Company A	Company B	Company C
Region	Northern England and West Midland	Southern England, Eastern England and Great London	Same as Company B
Nature of business	Private developer	Same as Company A	Social housing contractor
Nature of projects	Mixed private-for-sale and social housing	Same as Company A	Social housing
Procurement route	Self-build (i.e. the developer also took the role of a main contractor)	Mixed self-build and 'design & build' (i.e. employing a main contractor)	Contracting only
Extent of innovation	Pioneering in the design and use of innovative and modern methods of construction, particularly precast concrete panel systems	Trailing and utilising innovation to an extent but arguably associated with comparatively more conventional construction	Utilising innovative methods but much less involved in design due to its nature of business as social housing contractor

3.2. Selecting air-tightness influencing factors

The factors of build method, dwelling type and season have been studied in previous research [4,10,11,16,26], and are verified in this paper. Other factors including design target, number of significant penetrations, and floor and envelope area appear largely overlooked in the literature, and are examined in this study. Workmanship has been claimed critical to improving air-tightness [4,10], whilst this factor only addresses site-based construction practice. The relationships, if any, between air-tightness and ‘soft’ management issues like procurement and innovation are under-researched. This paper uses the term ‘management context’ to denote ‘soft’ management issues covering design, procurement, innovation and construction, and explores its relationship with air-tightness of dwellings. Such management context of the three housebuilding companies is described in Table 2, which shows the most direct procurement management control and greatest extent of innovation in design and construction practice in Company A, followed by Company B and then Company C.

However, testing factors, including test standards and procedures, technicians, test equipment, and timing of tests, were not included in this study for the following reasons. The building preparation and test standards and procedures utilised for all the tests analysed in this research complied with the relevant accredited and accepted requirements specified in BS EN 13829 (Method B: Test of the Building Envelope), CIBSE Technical Memorandum 23, and/or ATTMA Technical Standard 1. Intentional openings in the building envelope were temporarily sealed or closed. Weather conditions, e.g. winds and temperature differences inside to outside the dwelling, were addressed in accordance with the standards and procedures. The test technicians involved were all qualified and certified professionals. All test equipment was UKAS certificated and calibrated at regular intervals, complying with the required measurements and tolerances. Test timings were managed in alignment with the build process, and the dwellings needed to be largely completed for test, with the envelope sealed as required to create an air-barrier, albeit carpets or other floor coverings no need to be in place. Therefore, all these testing factors were considered to be controlled conditions in this study and would less likely skew the analysis presented in this paper. Any implications of the specific building fabric physical properties, e.g. mass of the envelope, core density, cavity insulation and finish, were not studied in this paper, due to the nature of this research to be correlational. Measuring influence of these details on air-tightness more relies on experimental research under controlled conditions [10,11].

3.3. Methods of analysis

Microsoft Excel was used for storing, analysing and illustrating the original air-tightness test data and relevant supportive information. The software package SPSS16 [9,29,30] was used for more advanced statistical analysis and illustrations where necessary. The quantitative data analysis involved a combined use of the methods of univariate and bivariate analysis [29]. Three measures of central tendency, i.e. the mean, median and mode, and SD for dispersion, were used to avoid unexpected effect on results of extreme scores. For bivariate analysis, the measure Pearson’s r was used for representing correlations between variables according to their nature. One-way Analysis of Variance (ANOVA) was utilised to compare the means of air permeability in relation to the influencing factors, on an individual basis. Two- and three-way ANOVA were applied for examining the interactions between the factors, in order to disentangle the cross relationships between air-tightness and multi factors. A range of statistical and analytical techniques provided in SPSS16, e.g. bar chart, boxplot, scatter plot, histogram, were used to illustrate the results.

The predictive model for estimating air permeability was developed from examining the influencing factors by applying linear regressions using the ‘enter’ method [9,30]. Firstly, an initial regression with the potential most significant factors observed from the exploratory and ANOVA analyses were carried out. Additional factors were then incorporated in the model, from which the resulting adjusted R-square and the significance of the factor regression coefficients (the p value) were observed. In principle, the factors were kept if the adjusted R-square increased significantly, or disregarded if the adjusted R-square remained similar. This process led to the development of the linear regression model which appeared to be the best statistical approximation for estimating air permeability of the dwellings studied.

4. Analysis and results

The air-tightness test results of 287 dwellings (Table 3) were used for the analysis which addresses the overall air-tightness of the dwellings, the relationships between air-tightness and the individual influencing factors, and the interactions between the critical factors.

4.1. Overall air-tightness of dwellings

All of the results averaged 5.97 $m^3/(h\,m^2)$ at 50 Pa (SD = 2.29). The results present a general normal distribution, with one extreme case of 17.46 $m^3/(h\,m^2)$ (Fig. 1).

The test results show that almost all the dwellings studied (97.9%) achieved the air permeability standard in Part L1a 2006, i.e. 10 $m^3/(h\,m^2)$, and the majority (71.1%) achieved the Part L1a Indicative Standard for the Standard Assessment Procedure 2005, i.e. 7 $m^3/(h\,m^2)$ [7]. Over a third (34.8%) complied with the EST Good Practice (5 $m^3/(h\,m^2)$), whilst only 10.5% were acceptable to the EST Best Practice or the AECB Carbon Lite Silver Standard

Table 3
Dwellings included in this study.

	Company A			Company B			Company C			Total
	House	Flat	Sub-total	House	Flat	Sub-total	House	Flat	Sub-total	
Traditional masonry[a]	6	27	33	33	26	59	32	5	37	129
RC frame[b]	0	0	0	0	17	17	0	42	42	59
Timber frame[c]	27	22	49	2	1	3	10	7	17	69
PCC panels[d]	0	30	30	0	0	0	0	0	0	30
Total	33	79	112	35	44	79	42	54	96	287

[a] Traditional masonry: the internal loadbearing leaf of the wall to be masonry tied to an outer leaf of either block or brick, typically with beam and block floors and timber trussed roof.

[b] Reinforced concrete (RC) frame: with the internal leaf to be prefabricated walling or masonry tied to the outer leaf, with insitu concrete floors and prefabricated roof.

[c] Timber frame: to be covered internally by plasterboard, insulated, and with the outer leaf typically to be brick, stone, render or timber.

[d] Precast concrete (PCC) panel systems: PCC external and internal party walls and floor planks with on-top screeding.

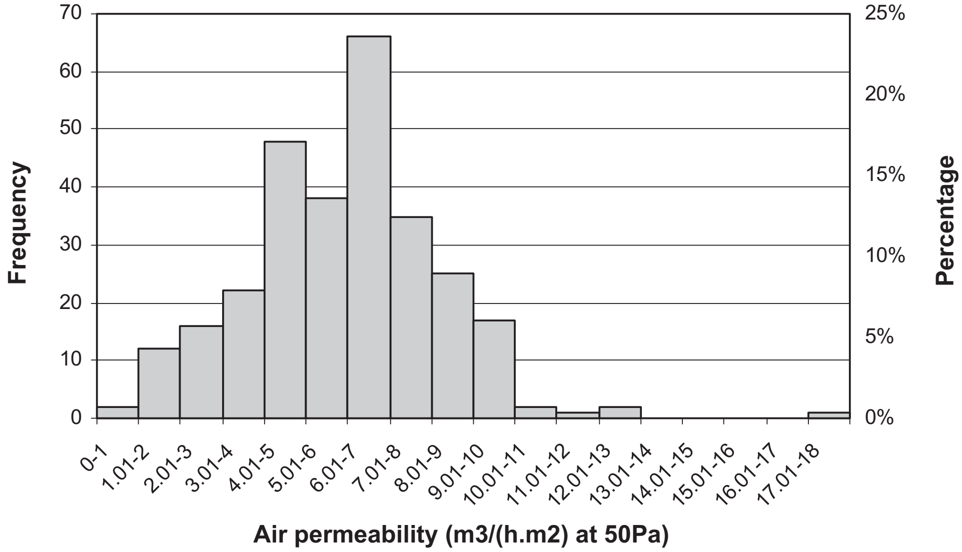

Fig. 1. Air permeability of all dwellings studied; $n = 287$, mean = 5.97 m^3/(h m^2), SD = 2.29, max = 17.46 m^3/(h m^2), min = 0.72 m^3/(h m^2).

(3 m^3/(h m^2)). Very few cases demonstrated compliance with the EST Advanced Practice (0.7%) (1 m^3/(hom^2)) or the AECB Carbon Lite Gold Standard (0.3%) (0.75 m^3/(h m^2)). The varied air-tightness standards are detailed in Table 1.

4.2. Air-tightness and build method

The dwellings studied were constructed using four types of build methods: traditional masonry, reinforced concrete (RC) frame, timber frame, and precast concrete (PCC) panel systems (detailed in Table 3). The mean of measured air permeability of the dwellings built using PCC panel systems (2.21 m^3/(h m^2)) were dramatically lower than those built using the other build methods including timber frame (6.04 m^3/(h m^2)), traditional masonry (6.51 m^3/(h m^2)) and then RC frame (6.64 m^3/(h m^2)) (Fig. 2).

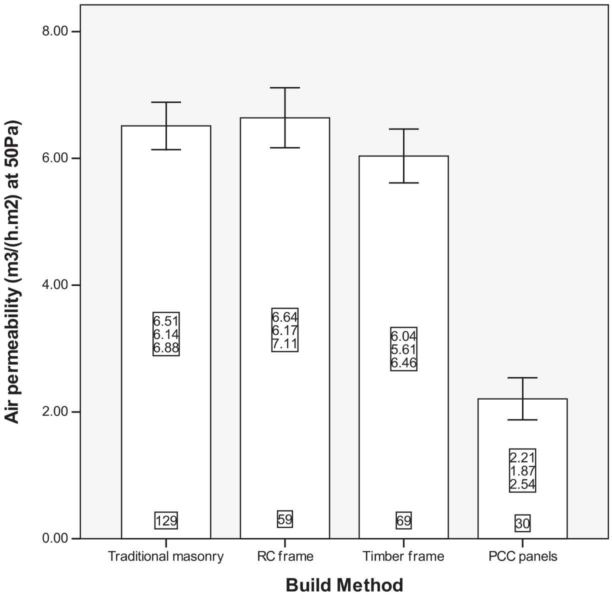

Fig. 2. Measured air permeability and build method; $n = 287$; in the bars first are means, then ranges within 95% confidence interval, then numbers of cases.

The spread of the results within 95% confidence interval suggests typical distribution for all the four groups. The ratio of the between-groups mean square divided by the within-groups one ($F = 45.6$, $p < 0.01$) implies that the differences between the means of air permeability of the dwellings built using the four different construction methods were statistically significant, unlikely to be due to chance. The test of homogeneity of variances (Levene Statistic 5.88, $p < 0.01$) suggests that the variances for the four groups also differed significantly. As Bryman and Cramer [30] suggested, the F test only tells whether there is a significant difference between the groups whilst it does not inform where this difference lies. Therefore, a post-hoc Scheffe test [30] was run to compare the means between each pair of the groups, which suggests significant difference between the means of all the pairs ($p < 0.05$) except 'traditional masonry' & 'RC frame'. This might be partly attributed to the primary on-site wet-trade feature shared by these two types of build method. These results, together, indicate that very air-tight fabric was more likely to have been achieved by using PCC panel systems whilst more site-based labour-intensive construction led to inferior air-tightness. Nevertheless, such relationship may be complicated by interactions from other factors, which is continually examined in this paper.

4.3. Air-tightness and dwelling type

The mean of measured air permeability of the flat dwellings (5.25 m^3/(h m^2)) was considerably lower than that of the house dwellings (7.14 m^3/(h m^2)) (Fig. 3). This mean difference was tested as statistically significant using Levene's test [9,30] ($p < 0.05$) and the t value of 7.44 ($p < 0.01$, 2-tailed).

The mean air permeability of mid-floor flats (4.50 m^3/(h m^2)) was the lowest, followed by ground-floor flats (5.41 m^3/(h m^2)), top-floor flats (5.94 m^3/(h m^2)), mid-terrace (7.07 m^3/(h m^2)), detached (7.12 m^3/(h m^2)), end-terrace (7.16 m^3/(h m^2)), and then semi-detached houses (7.83 m^3/(h m^2)) (Fig. 4). The spread of the test results within 95% confidence interval suggests typical distributions for all the seven groups, whilst the ranges for detached (5.84, 8.40) and semi-detached dwellings (6.44, 9.22) were much wider than for the rest (Fig. 4).

The F ratio of 10.35 ($p < 0.01$) implies that the differences between the means of air permeability of the seven different types of dwellings were significant. However, the test of homogeneity of

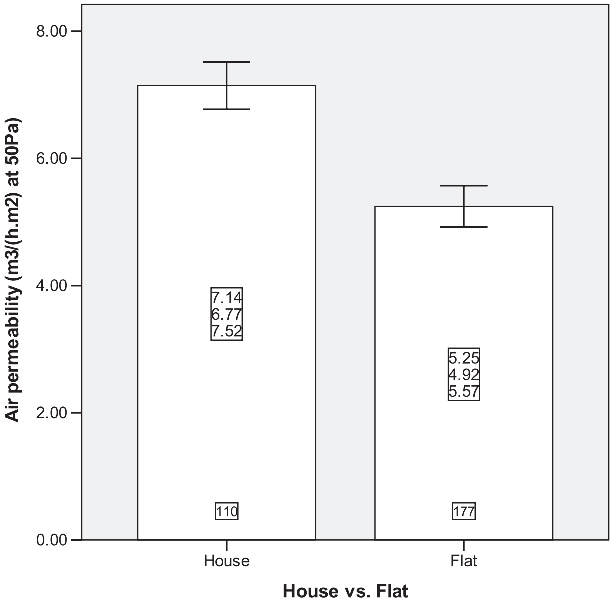

Fig. 3. Measured air permeability (House vs. Flat); $n = 287$; in the bars first are means, then ranges within 95% confidence interval, then numbers of cases.

variances (Levene Statistic 1.21, $p = 0.30$) suggests that the variances among the seven groups were not significant. A post-hoc Scheffe test was therefore run to compare the means between each pair of the groups. The results suggest that statistically significant difference in mean air permeability ($p < 0.05$) only existed between mid-floor flats and each of the four house types, and between ground-floor flats and semi-detached houses, but not between the four house types, between the three flat types, or between top-floor fats and all house types. These results, together, indicate that new-build flats were generally considerably air-tighter than houses while air-tightness of specific types of dwellings was affected by some other factors.

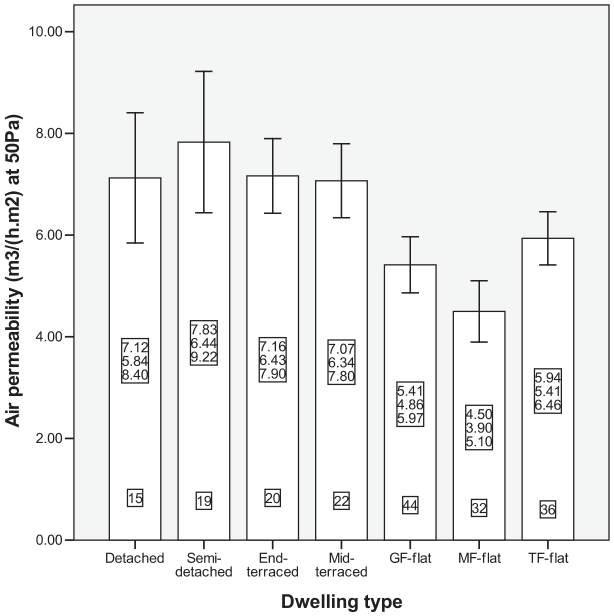

Fig. 4. Measured air permeability and dwelling type; $n = 188$; in the bars first are means, then ranges within 95% confidence interval, then numbers of cases.

4.4. Air-tightness and management context

The mean air permeability of the dwellings built by Company A ($4.45\ m^3/(h\ m^2)$) was considerably lower than those by Company B ($6.74\ m^3/(h\ m^2)$) and Company C ($7.12\ m^3/(h\ m^2)$) (Fig. 5). The spread of the test results within 95% confidence interval suggests typical distribution for all the three groups, whilst the range of the results from Company B (6.23, 7.24) was wider than from Company A (4.10, 4.80) and Company C (6.78, 7.47). The F ratio of 57.4 ($p < 0.01$) implies that the differences between the means of air permeability of the dwellings built by these three companies were significant, which, however, is conflicting with the suggestion from the test of homogeneity of variances (Levene's Statistic 1.1, $p = 0.336$) that the variances among the three groups did not differ significantly. Therefore, a post hoc Scheffe test was run again to compare the means between each pair of the groups, which indicates significant difference between the means of the results from Company A and Company B or C ($p < 0.01$) but not between the results from Company B and C.

These statistics suggest significant influence, on air-tightness of dwellings, of management context which is interpreted in this paper to denote 'soft' management issues such as procurement, innovation, design, and construction management (Table 2). Nevertheless, the complexity of these 'soft' issues and possible interactions between management context and other factors may complicate their influence on air-tightness, which is further analysed using two and three-way ANOVA methods later in the paper.

4.5. Air-tightness and season

One-way ANOVA analysis was carried out to compare the means of air permeability in relation to the categories of 12 months in which the air-tightness tests were carried out. No statistically significant difference was found at the $p < 0.05$ level ($F = 1.778$; $p = 0.058$). The same analysis was also carried out in relation to the categories of four seasons, as defined by the Met Office (the UK's National Weather Service) [31], i.e. Spring (March–May), Summer (June–August), Autumn (September–November) and Winter (December–February). The results show a virtual pattern of

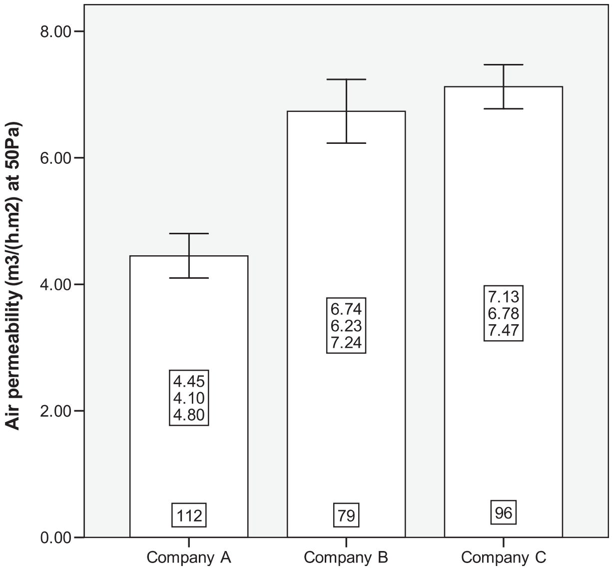

Fig. 5. Measured air permeability and management context; 50 Pa; $n = 287$; in the bars first are means, then ranges with 95% confidence interval, then numbers of cases.

decreasing mean air permeability from Summer (6.27 $m^3/(h\,m^2)$ at 50 Pa), Autumn (6.11), Spring (5.81) to Winter (5.21). However, this difference was found not statistically significant at the $p < 0.05$ level ($F = 2.592$; $p = 0.053$).

4.6. *Air-tightness and design target*

Less than half of the dwellings tested (44%) were associated with the air-tightness design target of 10 $m^3/(h\,m^2)$ at 50 Pa as required in Part L1a. For many dwellings (40%) a more stringent design target, 8 $m^3/(h\,m^2)$, was used. The other dwellings were with a design target between 8 and 10 $m^3/(h\,m^2)$ or below 8 but no less than 5 $m^3/(h\,m^2)$. The vast majority of the dwellings (95.1%) achieved the designed or lower air permeability rate. The scatter diagram (Fig. 6) shows a modest positive correlation between the measured air permeability rates and the design targets ($r = 0.367$, $p < 0.01$, 2-tailed).

However, such correlation hardly suggests any causality between setting the design targets and built air-tightness, as the design targets were set according to the design and specification of the dwellings and the management context (Table 2) of the housebuilding companies. In many cases, the design targets were the air permeability values presumed at the design stage for use in the calculation of the dwelling emission rate. Also, dwellings with too low air permeability, e.g. lower than 5 $m^3/(h\,m^2)$, are required in UK building regulations to provide mechanical ventilation [8] which leads to financial concerns. Nevertheless, this correlation suggests a favourable implication of the practice of setting appropriate reasonable design targets on achieving built air-tightness. The high consistent achievement rate of the designed air-tightness indicates minimised rectification work and re-test, which improved business efficiency of the housebuilding organisations.

4.7. *Air-tightness and number of significant penetrations*

A weak positive correlation was observed between the measured air permeability and the number of significant penetrations through the dwelling envelope, i.e. doors, windows and flues ($r = 0.297$, $p < 0.05$, 2-tailed). However, this analysis is based on 69 cases only for which information on penetrations was available. The number of significant penetrations per dwelling averaged 10 with a SD of 6, while these 69 dwellings had a mean air permeability of 7 $m^3/(h\,m^2)$ with a SD of 2.27.

4.8. *Air-tightness and floor and envelope area*

Analysis was also carried out of the correlations between measured air permeability and floor and envelope area. Results suggest no significant correlation between air permeability and floor area ($n = 109$, $r = -0.077$, $p = 0.426$) and a weak correlation with envelope area ($n = 166$, $r = 0.158$, $p < 0.05$, 2-tailed).

4.9. *Two-way ANOVA analysis*

The analysis above suggests that build method, dwelling type and management context were significant to air-tightness and their influences may interact with each other. For achieving effective two-way ANOVA analyses all the ‘extreme cases’ and ‘outliers’ [30] in the dataset as revealed in the boxplot were removed in order to symmetricise the distribution. The boxplot for the two-way analysis ‘build method’ × ‘dwelling type’ is provided as an example (Fig. 7).

The results suggest a significant ‘build method’ × ‘dwelling type’ interaction: $F(1, 272) = 12.28$; $p < 0.01$. Partial eta squared = 0.04, a ‘small’ effect (Fig. 8a). As explained in the SPSS software, Partial eta-squared is the ratio of the variation accounted for by an individual independent variable to the sum of the variation accounted for by the independent variable and the variation unaccounted for by the model as a whole. This suggestion of interaction indicates that the influences of these two factors on air-tightness were not homogeneous.

However, for the pair of factors, ‘build method’ × ‘management context’, no significant interaction was observed: $F(2, 268) = 2.27$; $p = 0.11$. Partial eta squared = 0.02 (Fig. 8b). This result suggests that the influences of these two factors on air-tightness, although critical on an individual basis as revealed in the one-way ANOVA analysis, were homogeneous to some extent. Such suggestion

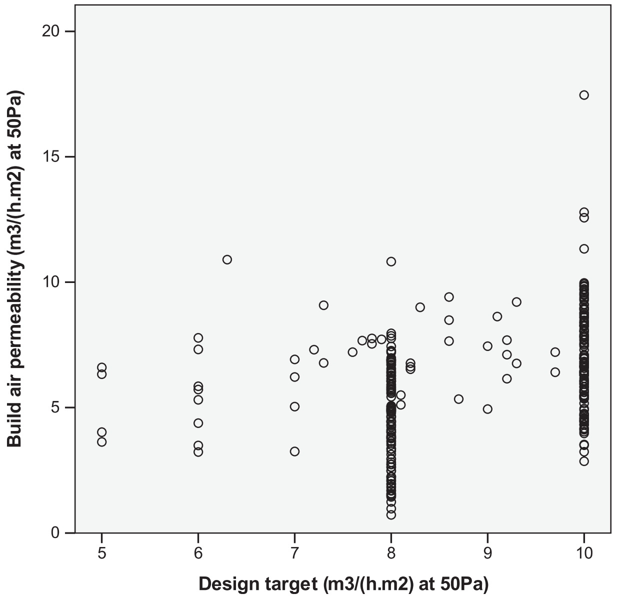

Fig. 6. Correlation between air permeability and design target: $n = 287$, Pearson's $r = 0.367$, $r^2 = 13.5\%$, $p < 0.01$ (2-tailed).

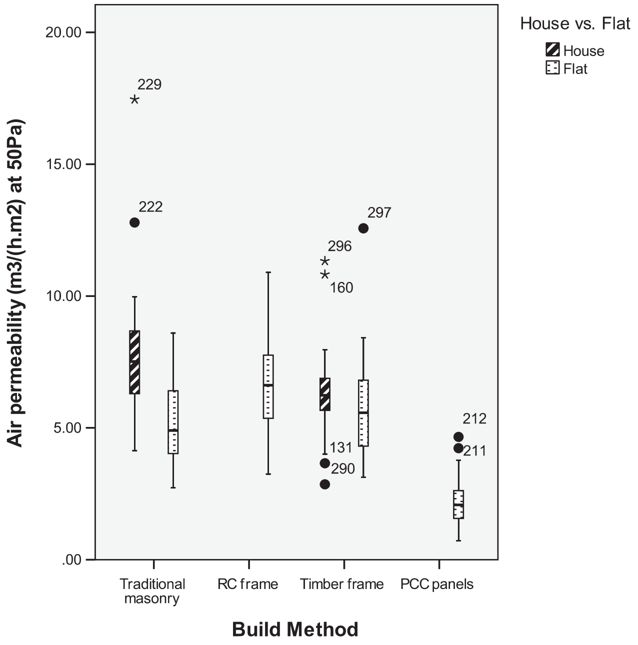

Fig. 7. Extreme cases and outliers in the dataset.

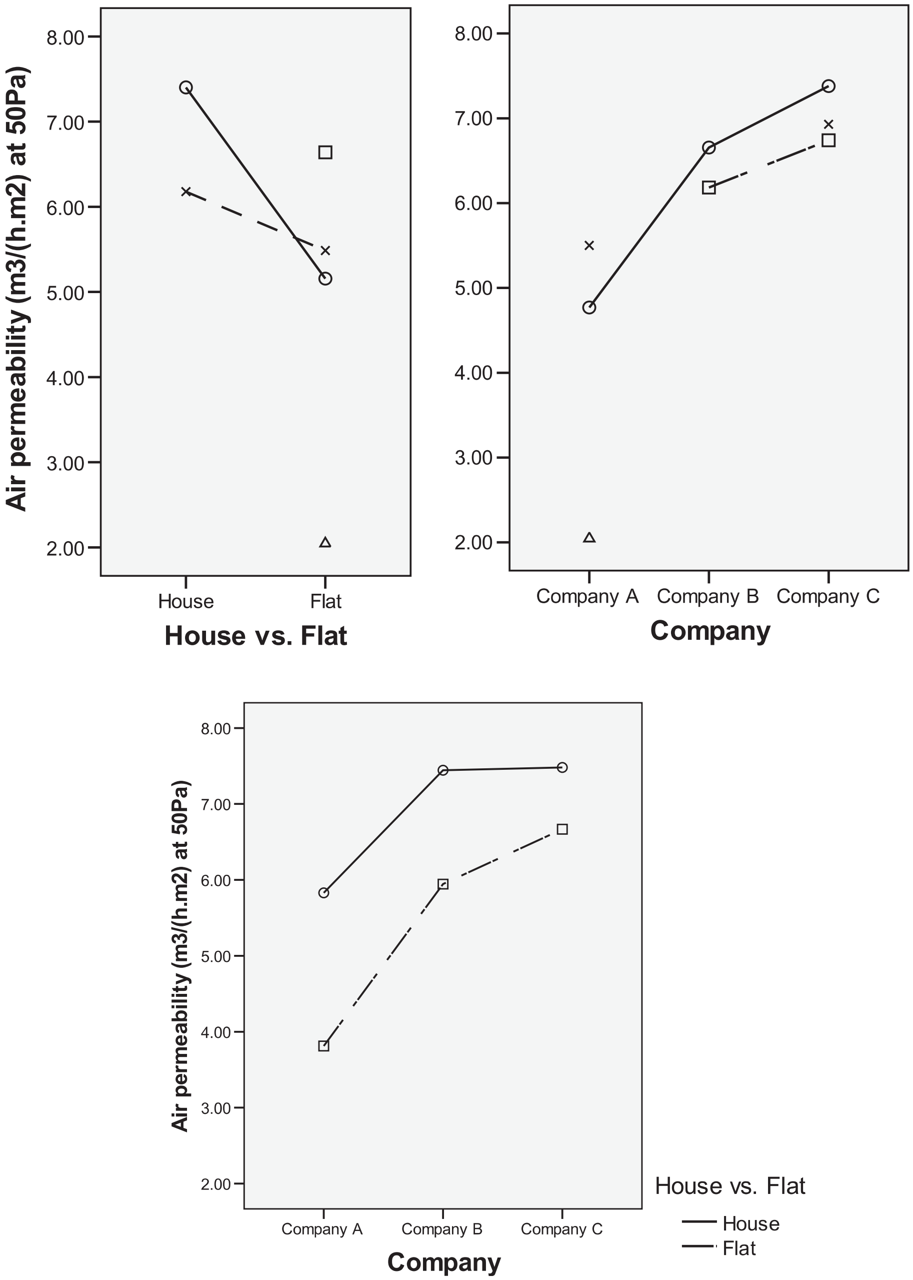

Fig. 8. Two-way ANOVA analyses, (a) 'build method' × 'dwelling type'; (b) 'build method' × 'management context'; and (c) 'dwelling type' × 'management context'. ○————○: Traditional masonry, ×- - - - - -×: Timber frame; □-·-·-·-□: RC frame; △————△: PCC panels.

reflects the utilisation of build methods and management context in the three companies (Tables 2 and 3). A typical phenomenon was that Company A contributed all the PCC dwellings and more than two thirds of the timber frame dwellings while it utilised 'self-build' procurement for more direct management control and endorsed greater extent of modern methods of construction.

In terms of the pair of factors, 'dwelling type' × 'management context', a significant interaction was found: $F(2, 277) = 3.25$; $p < 0.05$. Partial eta squared = 0.02, a 'small' effect (Fig. 8c). Therefore, the influences of these two factors on air-tightness were believed not homogeneous either.

4.10. Three-way ANOVA analysis

The result from the three-way ANOVA analysis indicates no statistically significant three-way interactions among the factors of 'build method', 'dwelling type' and 'management context': $F(1, 262) = 0.98$; $p = 0.32$. Partial eta squared = 0.00 (Fig. 9). This result implies that the two-way interaction observed between 'build method' and 'dwelling type' was homogeneous in the three management contexts, and also that the interaction observed between 'dwelling type' and 'management context' was homogeneous in the four build methods. Such homogeneous three-way relationship is believed to be partly attributed to the utilisation of build methods and management context in the three companies as explained early.

4.11. Regression analysis

The results of the exploratory analyses above, summarised in Table 4, suggest the following most significant influencing factors

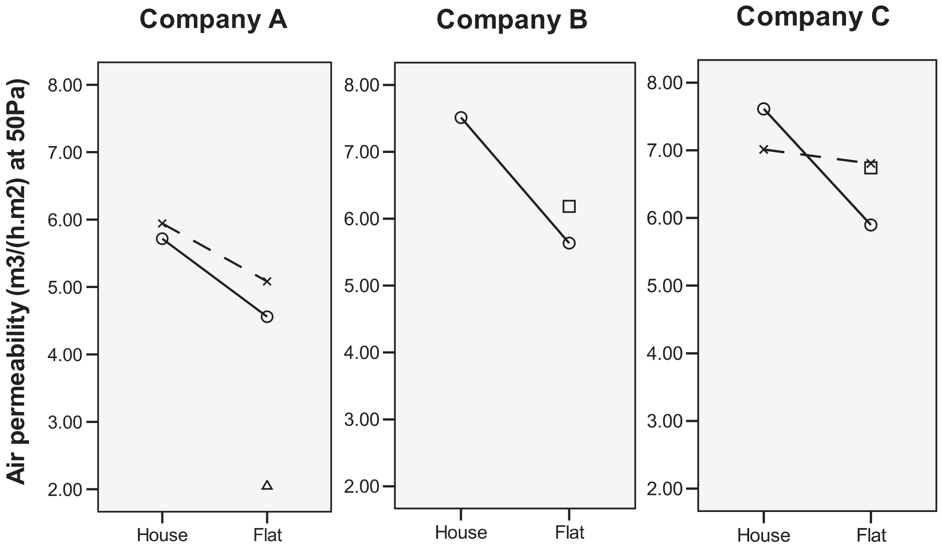

Fig. 9. Three-way ANOVA analysis. ○————○: Traditional masonry, ×- - - - - -×: timber frame; □-·-·-·-□: RC frame; △————△: PCC panels.

to air permeability: management context (MC), build method (BM), dwelling type (DT).

These three most significant factors were considered in the initial model (Eq. 1).

$$\text{Air Permeability} = \alpha + \beta_{\text{DT}} \cdot \text{DT} + (\beta_{\text{MC}-B} \cdot \text{MC}_B + \beta_{\text{MC}-C} \cdot \text{MC}_C) + (\beta_{\text{BM}-2} \cdot \text{BM}_2 + \beta_{\text{BM}-3} \cdot \text{BM}_3 + \beta_{\text{BM}-4} \cdot \text{BM}_4) \quad (1)$$

The parameter β_{DT} represents the coefficient for dwelling type. The factor DT takes the value of 0 for houses and 1 for flats. The factors MC and BM were qualitative variables, including more than two categories, which were called by Montgomery et al. [32] as ‘dummy variables’. These factors were converted to combinations of the values of 0 and 1 to enable effective regression analysis (Table 4). β_{MC-B} and β_{MC-C} represent the coefficients for management context B and C, and $\beta_{\text{BM}-2}$, $\beta_{\text{BM}-3}$ and $\beta_{\text{BM}-4}$ for the coefficients for build method: RC frame, timber frame and PCC panels, respectively.

The regression results (Table 5) are generally consistent with the findings of the exploratory analysis. All the variables, except build method 2 (RC frame) and build method 3 (timber frame), were statistically significant ($p < 0.01$). The adjusted *R*-Square (0.480) shows that 48% of the variability could be explained by this model.

The factor ‘design target’ was then added to the first model. Results show a very minor decrease of the adjusted *R*-Square to 0.478. No statistical significance was found for the design target coefficient ($p = 0.722$), while the other factor coefficient remained similar. Therefore, the factor design target was disregarded from the model.

The second model, on the first model basis, added one more factor ‘BM×DT interaction’ which would theoretically include three variables: BM2×DT, BM3×DT and BM4×DT. However, the parameters $\beta_{\text{BM}-2\times\text{DT}}$ and $\beta_{\text{BM}-4\times\text{DT}}$ were not applicable to this study because of the feature of the dataset available that the build methods RC frame and PCC panels only applied to flats but not to houses. Therefore, only the parameter $\beta_{\text{BM}-3\times\text{DT}}$ was added to the second model (Eq. 2).

$$\text{Air Permeability} = \alpha + \beta_{\text{DT}} \cdot \text{DT} + (\beta_{\text{MC}-B} \cdot \text{MC}_B + \beta_{\text{MC}-C} \cdot \text{MC}_C) + (\beta_{\text{BM}-2} \cdot \text{BM}_2 + \beta_{\text{BM}-3} \cdot \text{BM}_3 + \beta_{\text{BM}-4} \cdot \text{BM}_4) + \beta_{\text{BM}-3\times\text{DT}} \cdot \text{BM}_{3\times\text{DT}} \quad (2)$$

The regression results (Table 5) show an increase of the adjusted *R* Square from 0.480 to 0.492, which suggests that the second model could explain slightly more variability of the data. Also, the variables which were statistically significant in the first model remained similar while the added variable $\text{BM}_3 \times \text{DT}$ was also statistically significant. Furthermore, the variable BM_2 (RC frame) became statistically significant, and only the variable BM_3 (timber frame) was still not statistically significant ($p = 0.17$). Considering all these results, therefore, the variable $\text{BM}_3 \times \text{DT}$ was kept and the second model (Eq. (2)) was perceived to better describe the data than the first model (Eq. (1)).

After that, the factor ‘number of significant penetrations’ was added to the second model. The regression results show a dramatic decrease of the adjusted *R*-Square to 0.153. This factor was not found statistically significant ($p = 0.762$). Also, the variables of MC_B, MC_C, BM_3, BM_4 and $\text{BM}_3 \times \text{DT}$ became constants or had missing correlations and therefore were removed from the analysis. These results were probably because of the shortage of data for this factor (24% usage). Apparently, the model with ‘significant penetrations’ included does not effectively describe the data, and therefore this factor was disregarded from the model.

And then, the factor ‘MC × DT interaction’ was added. This factor includes three variables: $\text{MC}_A \times \text{DT}$, $\text{MC}_B \times \text{DT}$ and $\text{MC}_C \times \text{DT}$. The regression results show that the adjusted R-Square (0.491) remained almost the same as that without including this factor, whilst the *F* value dropped from 40.554 to 31.637. The added variables $\text{MC}_B \times \text{DT}$ and $\text{MC}_C \times \text{DT}$ were not found statistically significant ($p = 0.939$ and 0.391, respectively). Also, the variable BM_2 (RC frame) became not statistically significant again ($p = 0.154$). The coefficients for the other variables remained similar. Considering all these results, the variables representing the factor ‘MC × DT interaction’ were disregarded as well.

The third model (Eq. (3)) is developed from the second one, but removing the variable BM_3 which was not statistically significant ($p = 0.17$).

$$\text{Air Permeability} = \alpha + \beta_{\text{DT}} \cdot \text{DT} + (\beta_{\text{MC}-B} \cdot \text{MC}_B + \beta_{\text{MC}-C} \cdot \text{MC}_C) + (\beta_{\text{BM}-2} \cdot \text{BM}_2 + \beta_{\text{BM}-4} \cdot \text{BM}_4) + \beta_{\text{BM}-3\times\text{DT}} \cdot \text{BM3} \times \text{DT} \quad (3)$$

Table 4
Summary of results of exploratory analyses.

Factors	Variables		*F*-test[a]	Pearson's *r*	*p* value [a]	Partial eta squared
Management context (MC)	Company A	(0,0)	57.408		0.000	
	Company B	(1,0)				
	Company C	(0,1)				
Build method (BM)	BM1 (Trad' masonry)	(0,0,0)	45.553		0.000	
	BM2 (RC frame)	(1,0,0)				
	BM3 (Timber frame)	(0,1,0)				
	BM4 (PCC panels)	(0,0,1)				
Dwelling type (DT)	House	0	10.345		0.000	
	Flat	1				
BM × DT interaction (two-way)	BM1 × DT	(0,0,0)	12.281		0.001	0.043
	BM2 × DT	(1,0,0)				
	BM3 × DT	(0,1,0)				
	BM4 × DT	(0,0,1)				
MC × DT interaction (two-way)	MC_A × DT	(0,0)	3.254		0.040	0.023
	MC_B × DT	(1,0)				
	MC_C × DT	(0,1)				
MC × BM interaction (two-way)			2.273		0.105	0.017
MC × BM × DT interaction (three-way)			0.982		0.323	0.004
Design target				0.367	0.000	
Number of significant penetrations				0.297	0.013	
Envelope area				0.158	0.042	
Season	S1 (Spring)	(0,0,0)	2.592		0.053	
	S2 (Summer)	(1,0,0)				
	S3 (Autumn)	(0,1,0)				
	S4 (Winter)	(0,0,1)				
Floor area				−0.077	0.426	

[a] *F*-test and *p* values were generated from the analysis of the factors/variables and their interactions, on an individual basis, as provided in the early sections of the paper.

The regression results (Table 5) show that the adjusted R-Square remained similar (0.490) while there was a considerable increase of the *F* value from 40.554 to 46.849. The variable BM$_2$ (RC frame) became arguably statistically significant ($p = 0.051$). Also, all the variables included in the third model were associated with less standard errors than in the second model. These results, together, suggest that the third model (Eq. (3)) better describes the data than the second model does.

Furthermore, the factors 'envelope area and floor area' were added to the third model. The regression results show a dramatic drop of the adjusted R-Square to 0.148. These two added factors were not found statistically significant ($p = 0.754$ and 0.658, respectively). The factors MC$_B$ and BM$_4$ became constants or had missing correlations and therefore were removed from the analysis. All the other variables were found not statistically significant. These results were believed due to the shortage of data for these factors (32% usage). Apparently, this model with 'envelope area and floor area' included would not effectively describe the data. Therefore, these two factors were disregarded from the model.

Finally, given the virtual pattern of changing mean air permeability with season, this factor was added to the third model. The factor season is 'dummy variable' and therefore was converted to three variables: S1, S2 and S3 (Table 4). The regression results show that the adjusted *R*-Square remained similar (0.489) while there was a drop of the *F* value to 31.446 ($p = 0.000$). The three added variables were found not statistically significant ($p = 0.128$, 0.718 and 0.582, respectively). Therefore, the factor season was disregarded.

Amalgamating all the regression analysis results, the third model (Eq. (3)) appeared to be the best statistical approximation for estimating air permeability of the dwellings studied.

5. Discussion

5.1. Overall air-tightness performance

The results of this study suggest that the air-tightness of post-2006 new-build dwellings in the UK (averaged 5.97 m^3/(h m^2)) has improved from those investigated in previous research, which reported mean values of 6.89 m^3/(h m^2) by Johnston et al. [15], 9.2 m^3/(h m^2) by Grigg [17], and 11.5 m^3/(h m^2) by Stephen [16]. The cross comparison of reported air-tightness suggests an increasing air-tightness of UK dwellings, overall, from pre-1994 through post-2006 (Table 6). This phenomenon provides evidence to support the increasingly stringent air permeability standards in use for new-build homes in the UK, primarily marked by the regulatory

Table 5
Coefficients and adjusted *R*-Squares from the models.

Coefficient	Regression 1 (Eq. (1))	*t*	*p* value	Regression 2 (Eq. (2))	*t*	*p* value	Regression 3 (Eq. (3))	*t*	*p* value
α	5.989 ± 0.300	19.940	0.000	6.330 ± 0.321	19.692	0.000	6.027 ± 0.234	25.728	0.000
β_{DT}	−1.360 ± 0.249	−5.453	0.000	−1.887 ± 0.312	−6.054	0.000	−1.684 ± 0.275	−6.125	0.000
β_{MC-B}	1.413 ± 0.310	4.553	0.000	1.299 ± 0.310	4.198	0.000	1.491 ± 0.277	5.390	0.000
β_{MC-C}	1.701 ± 0.306	5.559	0.000	1.522 ± 0.309	4.921	0.000	1.685 ± 0.286	5.893	0.000
β_{BM-2}	0.392 ± 0.325	1.207	0.229	0.740 ± 0.345	2.144	0.033	0.668 ± 0.342	1.956	0.051
β_{BM-3}	0.159 ± 0.282	0.563	0.574	−0.507 ± 0.369	−1.375	0.170			
β_{BM-4}	−2.424 ± 0.399	−6.080	0.000	−2.237 ± 0.400	−5.595	0.000	−2.137 ± 0.394	−5.427	0.000
$\beta_{BM-3\times DT}$				1.388 ± 0.502	2.763	0.006	0.937 ± 0.381	2.460	0.014
Adjusted *R*-Square	0.480			0.492			0.490		
F	44.974		0.000	40.554		0.000	46.849		0.000

Part L 2002 and 2006 versions and the recent introduction of a number of voluntary standards (Table 1). In the international context, the air-tightness of UK dwellings studied in this paper was superior to that in some other countries like Greece [12] and US [13]. However, the UK dwellings studied were still significantly leakier than that reported from Canada [25], Estonia [5] and Scandinavian countries, e.g. Finland [26], Norway [27] and Denmark [22] (Table 6). The variety of air-tightness of dwellings across the different countries, however, can be attributed to many factors such as locations, climate conditions, the use of different air-tightness standards (Table 1), the use of different construction methods [26], and also the data samples surveyed [16].

5.2. Air-tightness and individual influencing factors

In relation to 'build method', the results reveal that the dwellings built using PCC panels were dramatically air-tighter than those built using timber frame, whilst those masonry and RC frame dwellings (dry-lined internally) were associated with the worst air-tightness. These results are consistent with the findings in the BRE study [16] that dwellings with cavity masonry walls were two times leakier than dwellings with brick-cladding timber framed walls or large panel system (LPS). Dwellings with solid masonry walls were less leaky than those with cavity masonry walls, but still about 50% more leaky than the other two types. Stephen [16] explained that LPS dwellings were more air-tight, attributing to the very air-tight panels, and most leakage occurred at joints between panels, service entries and window/door openings instead. The results from this study are also supported by Kalamees' [5] analysis of air-tightness in different building technology. Kalamees claimed that lightweight timber frame detached houses in Estonia constructed in-situ (averaged 5.3 $m^3/(h\,m^2)$) were nearly twice leakier than those built with prefabricated wall or room elements that were made in factory conditions and mounted on the building site (averaged 2.9 $m^3/(h\,m^2)$). However, Jokisalo et al. [26], according to their measurement results, argued that the type of construction has only a minor effect on building leakage rate. Apparently, the influence of build method on air-tightness, although being critical, is subject to interaction by other important factors.

Regarding 'dwelling type', the results from this study verify the general perception of superior air-tightness of flats to houses [4,17]. The results also suggest significant improvement of air-tightness of both flats (averaged 5.25 $m^3/(h\,m^2)$) and houses (averaged 7.14 $m^3/(h\,m^2)$) built to Part L 2006 or better standards, compared to their counterparts built to Part L 2002, i.e. flats (averaged 8.0 $m^3/(h\,m^2)$) and houses (averaged 9.8 $m^3/(h\,m^2)$) [17]. In relation to the specific dwelling types, the results also confirmed the general perception that mid-floor flats are air-tighter than ground-floor and then top-floor ones. However, the results show that the semi-detached houses studied were leakier than the end-terrace and detached houses, albeit such difference not being significant. The discrepancy between this result and the general perception of air-tightness of semi-detached similar to end-terrace but superior to detached, again, verifies the interactions between the influencing factors.

As for 'management context', the analysis reveals significant difference between the air-tightness of dwellings built in the three companies. However, the interpretation of these results may not be straightforward because of the typical ambiguous concept of management context. The descriptions of such context considered in this study (Table 1) suggest that the procurement route and the extent of innovative construction methods utilised by the companies dominated the influence of their management context on air-tightness. Hence the results indicate that superior air-tightness was associated with the use of the 'self-build' procurement route

Table 6
Comparison of air-tightness of dwellings.

Country	Study/source	Air permeability ($m^3/(h\,m^2)$) at 50 Pa (mean (SD; range))	Air change rate (1/h) at 50 Pa (mean (SD; range))	Dwellings studied	Notes
UK	Current study	5.97 (2.29)		110 houses and 177 flats	Built post-2006
	Johnston et al. [15]	6.89 (3.8, 9.46)		4 timber frame terrace and 3 masonry detached	Built in 2003-04
	Grigg [17]	9.2 (3.2, 16.9)		36 flats, 60 houses and 3 bungalows	Built to Part L 2002 (2002–04)
	Stephen [16]	11.48 (2, 29)		384 dwellings	Built pre-1994
Canada	Hamlin and Gusdorf [25]		1.23 (0.13, 2.63)	47 R-2000 houses	Built in 1983–95
			3.06 (0.4, 10.8)	222 new conventional houses	Built 1990–96
Denmark	Tommerup et al. [22]		1.5	3 detached one-storey single-family houses	2 by concrete block and 1 by steel frame with prefab lightweight ext' walls
Finland	Jokisalo et al. [26]		3.7 (2.2)	170 detached houses	100 built by timber frame, 20 by log, and 50 by concrete/break/block
Norway	Granum and Haugen [27]		3.9 (3.3, 5.4)	10 detached houses	Built in 1980
Estonia	Kalamees [5]	4.2 (3.3)	4.9 (3.5)	32 detached houses	Built in 2003–05
Greece	Sfakianaki et al. [12]		6.79 (1.87, 11.3)	20 houses	Measured in 2005
US	Sherman and Dickerhoff [13]		29.7 (14.5; 0.47, 83.6)	12902 houses	Built in 1850–1993

and greater extent of innovative construction methods. However, the relationships between air-tightness and soft management issues like procurement and innovation appear under-researched. Future research should explore appropriate methodologies to quantify these relationships and therefore guide the improvement of air-tightness in these areas in future practice.

No statistically significant difference was found between air permeability test results obtained in different 'months' or 'seasons'. This result is inconsistent with the finding of previous research [16] that there was an increase in air leakage rate of both an unoccupied test house and occupied dwellings during the winter compared with the summer. This inconsistency is probably attributed to the possible interactions between the influences of season and other relevant variables like climate zone and geography. This study itself did not enable analysis of air-tightness in relation to 'age of dwelling' as it was focused on dwellings built from 2006 to 2008. A widely held belief in the UK is that older dwellings are less air-tight than modern dwellings [16].

A modest positive correlation was noticed between the measured air permeability and 'design targets'. This finding is consistent with two observations of general air-tightness practice. One is that air permeability standards in the UK are being made increasingly stringent (Table 1) while air-tightness of UK new-build dwellings is continuously improving (Table 4). The other is that regulatory air permeability standards in the UK are still lower than in Scandinavia and Canada (Table 1) while air-tightness of UK dwellings is generally inferior to that in those countries (Table 6).

5.3. Air-tightness and multiple influencing factors

The two-way interaction observed between 'dwelling type' and 'build method' suggests that the influences of these two factors on measured air permeability were not synchronous but interactive. This interaction might be more complicated as the build methods RC frame and PCC panels were only applicable to flats but not to houses in the dataset available. Similar interaction was also noticed between 'dwelling type' and 'management context', but to a slightly less extent. In comparison, no significant interaction was observed between 'build method' and 'management context'. However, this observed 'no significant interaction' might be affected by another limitation of the dataset available that the air test results for dwellings built using PCC panels were only applicable to Company A, while the results for dwellings built using RC frame were only applicable to Company B and C, but not to A. Nevertheless, these limitations were not build-in data 'errors', but reflected the typical UK housing industry practice that traditional masonry and timber frame methods dominate the housing construction market and the level of usage of PCC panel systems is very low [33].

No statistically significant three-way interaction was observed among the factors of build method, dwelling type and management context. However, this paper acknowledges that this observation may not be robust enough because of the limitations of the dataset explained above. With the results from the exploratory analysis, it is believed that there existed a significant three-way interaction among the critical influencing factors to air-tightness. However, this is yet to be tested in future research. Kalamees [5] observed similar levels of statistically significant difference ($p < 0.02$) in air leakage between houses in relation to 'workmanship quality and supervision' and 'building technology' (prefabricated or built insitu). Nevertheless, Kalamees, taking into account 'cross dependence effect of different variables', perceived that workmanship quality and supervision as well as number of storeys of the house had stronger effect than building technology. However, there appears to be a general lack of research into two- and three-way interactions between the factors influencing air-tightness, which limits the further discussion of the results in this regard.

5.4. The predictive model

The developed predictive model integrates the critical influencing factors to air permeability of the dwellings studied in this paper, which include management context, build method, dwelling type, and 'build method' x 'dwelling type' interaction. However, four important caveats should be taken when interpreting the results and utilising the model. Firstly, this model best describes the dataset available for this study and it may change, subject to the features of the dataset although it is believed to represent post-2006 new-build homes across England. Secondly, the relationships revealed do not necessarily imply causality due to the correlational nature of this study. Thirdly, the variables, including design target, number of significant penetrations, envelope area, season, and MC × DT interaction, although tested to be of trivial influence to the predictive model, were observed to be in relationship with air permeability. Finally, there are also many other factors and variables to air-tightness of dwellings, such as window frame length [12], age of building [16, 28], number of storeys [5,28], insulation type [28]. McWilliams and Jung [34], using data maintained at Lawrence Berkeley National Laboratory, developed a mathematical model using statistical regression techniques to relate residential building shell leakage to variables including building height, floor area, floor leakage, duct leakage and age of house. Montoya et al. [28] applied the multiple linear regression technique for estimating air-tightness of single-family dwellings in Spain and France. Clearly, the factors and variables studied in previous research, as well as this paper, were subject to the specifics of the research and the data sample. How to interpret (measurements available) or predict (measurements unavailable) the influences on air-tightness of the many factors and variables in a holistic manner should be further explored in future research.

6. Conclusions

The air permeability test results of the 287 post-2006 new-build UK dwellings studied in this paper averaged 5.97 $m^3/(h\,m^2)$ at 50 Pa, which shows a considerable improvement over those built in history and investigated in previous research [15–17]. There is evidence suggesting an increasing air-tightness of dwellings in the UK from pre-1994 through post-2006. Such increase in air-tightness features a positive correlation with the improvement on air permeability standards introduced to UK new home building. Comparing to the international context, the more recent new-build UK dwellings studied in this paper were air-tighter than those in some other countries like Greece and US, but were still significantly air leakier than those in Canada and Scandinavia, as reported in previous research. Nevertheless, interpreting results from such cross comparison requires appreciation of locations, climate conditions, the use of different air-tightness standards and construction methods in different countries, which may attract interest for future research.

Air-tightness of dwellings was subject to wide-ranging design, specification, construction and testing factors. The factors of management context, build method, dwelling type and their interactions were observed to be critical in this study. The use of PCC panel systems enabled the achievement of very air-tight flats, whilst the dwellings, particularly houses, built by using more site-based labour-intensive construction methods were much more air leaky. The use of 'self-build' procurement route and greater extent of innovative building practice of the housebuilder led to achieving superior air-tightness of dwellings.

Two-way interaction was identified between the influences of the factors ‘build method’ and ‘dwelling type’ and between those of ‘dwelling type’ and ‘management context’. It is also believed that three-way interaction existed among the critical influencing factors, although it was observed not statistically significant due to the features and limitations of the dataset available. The predictive model best describes the measured air permeability of post-2006 new-build UK dwellings studied in this paper. However, to achieve consistent air-tightness of dwellings effectively, the other influencing factors such as design target, number of significant penetrations and envelope area should also be taken into account given the observed correlations between them and measured air permeability. Future research may lead to interpretation of the influences of all the factors on air-tightness in a more holistic manner.

This paper addresses the lack of research in air-tightness of dwellings built in the UK post-2006. The knowledge contributed should help developers, housebuilders, and their designers and environmental consultants to make more informed design decisions for achieving consistent air-tightness of dwellings. The evidence provided should also be of use for policy-makers and legislators to review the application of air permeability standards. The regression model developed should contribute to future research in predicting potential impacts of controlling the influencing factors on addressing air leakage of dwellings and achieving energy efficiency.

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