JSACE 1/24

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Received 2018/12/11

Accepted after revision 2019/02/07

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http://dx.doi.org/10.5755/j01.sace.24.1.22167

The field measurements of airtightness in Estonian detached and apartment buildings conducted between 2003 – 2017 were combined into a large dataset for further analysis. The buildings were classified based on building structure, number of storeys, year of construction, energy classification and compactness factors. A subset with all wooden buildings (313 in total) was statistically analysed to determine the average (median) air leakage rates at 50 Pa and tested (Kruskal-Wallis test with post-hoc Conover test) for significant differences within the grouping factors. As expected, the median air leakage (q_{50}) of older buildings between 10.7 and 13.9 $m^3/(hm^2)$ has decreased to 1.1 $m^3/(hm^2)$ after the minimum requirements for energy efficiency have taken effect. A more detailed analysis on newer buildings showed that quality of the workmanship combining systematic measurement routines as well as prefabrication, yields significantly lower median air leakages compared to on-site construction. The buildings with better energy classification targets also achieved lower median air leakages compared to buildings designed to meet minimum requirements. Further analysis showed significant differences between buildings with lightweight timber construction and those with log construction. This can be due to fact that the airtightness has been predominantly measured in prefabricated buildings compared to on-site building technology. Surprisingly, the analysis showed no significant difference between buildings with a different compactness factor or a different number of storeys. For use in energy calculations, the base values of air leakage rates for each group are calculated and presented accounting for variation of measurements.

Keywords: airtightness, air leakage, pressurisation test.

Introduction

A well-insulated, airtight and thermal bridge free building envelope is a key factor for nearly zero energy buildings (nZEB) that becomes mandatory from year 2021. Minimising heat losses and combining a thermally optimised building envelope with the passive use of solar energy allows a significant reduction in the heat load and heating energy demand of residential buildings. However, increased insulation thickness in timber constructions creates a serious risk of moisture accumulation inside the construction and deterioration of the building structure if the air leakages are not minimised or avoided. This is especially important in the case of timber construction where the materials are more sensitive to extensive moisture and deterioration.

In Estonia, lightweight timber-frame envelopes are common for single-family detached houses. Today timber structures have become more and more common for apartment buildings and non-res-

Journal of Sustainable Architecture and Civil Engineering

Vol. 1 / No. 24 / 2019

pp. 36-43

DOI 10.5755/j01.sace.24.1.22167

idential buildings. Structures built from timber logs have been historically very common and are still used for some projects. It is expected that the air-tightness of the building envelope has been improved over the years, especially after the minimum requirements for energy efficiency have been set by legislation. However, several publications seem to conclude that the overall air leakage of the building envelope, even in modern buildings, depends mostly on the building quality and on subsequent factors that affect the building quality (Mortensen and Bergsøe 2017, Colijn *et.al* 2017, Kalamees 2007). For example, the number of storeys, compactness of the building volume etc has been shown to increase the complexity of the work needed to achieve the necessary air-tightness. There have been attempts to estimate the air-tightness of the building envelope without measuring, based on component measurements and subsequent calculations, but no reliable method for estimation has been found (Relander *et.al* 2012). This means that in the design phase, or when calculating the energy use of existent buildings with no means of direct measurements, the statistical average values for different building techniques, construction types and different time frames have to be used. The average air-tightness of existing building stock and the variation within subgroups can be different in different countries as the building process and quality assurance measures are different. In this study a large number of air tightness measurements of Estonian wooden buildings are statistically analysed to determine the average (median) air leakage rates at 50 Pa and tested for significant differences within the grouping factors related to building complexity and quality assurance. Additionally, the base values of air leakage are calculated including the effect of variation within the measured groups.

Methods

Studied buildings

The database of air leakages was combined based on the results of different measurements carried out between 2003 and 2017 (in total 522 buildings). The subset of all wooden buildings (in total 313 buildings) were used for further analysis. The buildings were classified based on building structure (log houses versus lightweight timber frame), the number of storeys (single-storey versus multi-storey), year of construction (built before 1945, built between 1946-1994, built between 1995-2008, built since 2009), energy classification (energy classes A and B versus minimum requirements) and compactness factors (envelope area ratio to volume and envelope area ratio to floor area). Additionally, those companies (producers or building companies) with 5 or more measurements were grouped to analyse the effect of systematic measurements on them.

For all buildings built since 2009 an additional grouping based on production technology was described to compare on-site building practice to prefabrication for lightweight timber construction, and hand-made building logs to prefabricated building logs for log-houses. The prefabrication level for lightweight timber construction differs between different companies. For volumetric modules the building envelope is typically finished internally and externally and air-tightness is controlled with vapour control membranes separately for each module. Prefabricated separate roof and wall elements are typically structurally complete but the internal finishing layers and external cladding are completed on-site allowing for additional taping to connect the vapour control membranes between the separate elements. For both production types the vapour control layer (polyethylene sheet) is used on the interior side of the load bearing structures (Fig. 1).

For log houses the prefabricated glulam timber logs are assembled on-site and typically no additional insulation nor separate air tightness layers are used. The energy performance requirements of those buildings are fulfilled through more efficient heating system and well insulated lightweight roof structure with similar vapour control membrane for air tightness. For glulam log structures with thickness less than 200mm an additional external insulation layer with timber frame in combination with wind-barrier layer, ventilated cavity and cladding is used for better energy performance.

Measurements

The air leakage measurements were carried out using a standardised pressurisation test according to method B (the test of the building envelope where all the intentional openings (for natu-

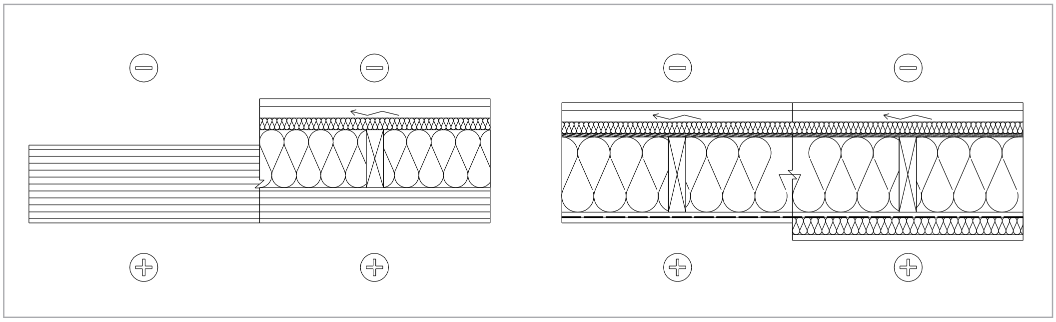

Fig. 1

A typical solution for prefabricated glulam timber log structures (left) and lightweight external wall timber structure with and without additional installation layer (right) for better air tightness and moisture safety used in Estonia. The air tightness layer is marked with black dashed line

ral and mechanical ventilation) shall be sealed, the doors, windows and trapdoors being closed) described in EN ISO 9972:2015 and EN 13829:2001. The air tightness of the building envelope was tested in a range of pressure differences between 10 Pa and 60 Pa and reported with a standardised pressure of 50 Pa. At an air flow rate of 50 Pa the pressure difference (V_{50}), the air leakage rate (q_{50}), and air change rate (n_{50}) were calculated by dividing the measured air flow rate by the external envelope area or by the internal volume of the building respectively.

For all buildings, a depressurisation test was carried out to test the airtightness of the building envelope. For some buildings an additional pressurisation test was carried out to measure air leakage in reversed pressure conditions. For these buildings, the average leakage rate and other relevant test results were calculated as arithmetic means.

Statistical analysis

The preliminary analysis of the data showed that the distribution of the measured air leakage (q50) data is non-normal. Because of this, the median value and 0.16 / 0.84 quantiles were used to describe the distribution within the different subsets of the data and the non-parametric Kruskal-Wallis rank test was used to determine statistical differences between different groups of the measured data. In case of significant difference, a subsequent pairwise comparison of subsets was carried out using a post-hoc Conover test. For the analysis, the statistical analysis software R (version 3.5.1) was used with several add-on packages to allow non-parametric analysis and visualisation.

Along with median values, the mean value of air leakage rate ($q_{50,mean}$) and standard deviation (σ_{q50}) of all groups were calculated to allow the estimation of base value of air leakage rate ($q_{50,base}$) for different groups of buildings.

Calculation of the base value

The base value of air leakage rate was calculated according to the method described in the Finnish quality assurance manual for airtightness of building envelope [RT 80-10974, 2009]. The calculated base value depends on the group size and the variation within the group, so that 75 percent of the measured buildings will be below the base value with a confidence interval of 84 percent in the case of normal distribution of the means. The base value is calculated according to equation 1 as follows.

$$q_{50,base} = q_{50,mean} + 0.674 \cdot \sigma_{q50} + \sigma_{q50} \ : \sqrt{n} \qquad (1)$$

where: $q_{50,base}$ – estimated base value of air leakage rate ($m^3/(hm^2)$); $q_{50,mean}$ – measured value of mean air leakage rate of the group considered ($m^3/(hm^2)$); σ_{q50} – standard deviation of mean air leakage rate of the group considered ($m^3/(hm^2)$); n – number of measured buildings in the group considered.

Results

As expected, the median air leakage (q_{50}) of older buildings between 10.7 and 13.9 $m^3/(hm^2)$ has decreased to 1.1 $m^3/(hm^2)$ after the minimum requirements for energy efficiency have taken effect (Fig. 2). A more detailed analysis on buildings (137 in total) built since 2009 described the effect of different factors on air leakage (Table 1).

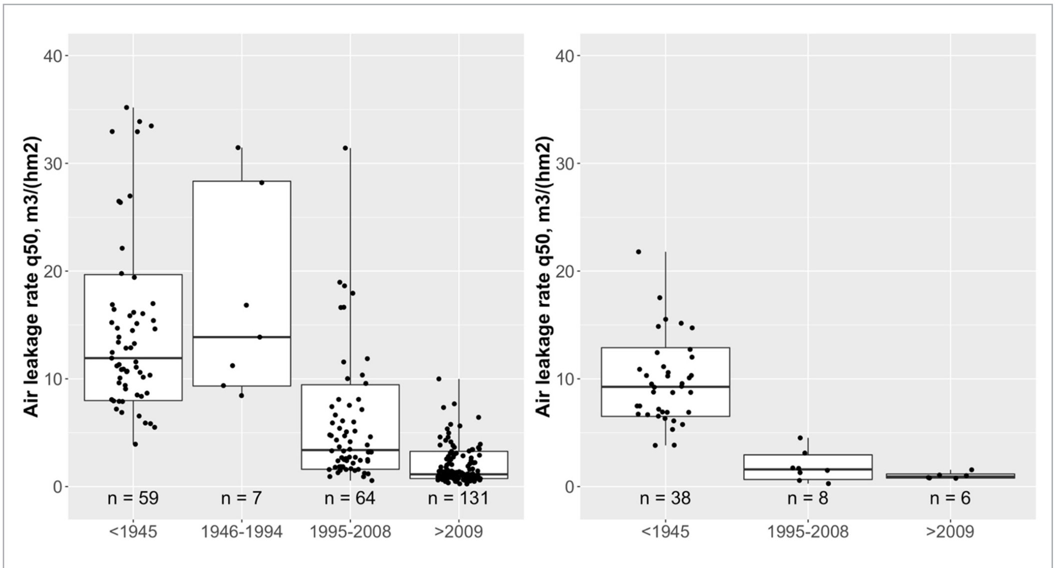

Fig. 2

Air leakage rates of detached (left) and apartment buildings (right) based on year of construction. The median values with 0.16 / 0.84 quantiles are marked

Table 1

Effect of different factors on air leakage rate and its distribution

	Number of buildings median	Air leakage rate q_{50}, m³/(h·m²)					
		median	16% percentile	84% percentile	mean	σ_{q50}	$q_{50,base}$
All wooden buildings							
<1945	97	10.7	6.9	16.4	12.5	6.9	17.8
1946-1994	7	13.9	9.3	28.3	17.1	9.2	26.8
1995-2008	72	3.2	1.5	8.1	5.2	5.5	9.5
>2009	137	1.1	0.8	3.1	1.8	1.6	3.0
Wooden buildings 2009+							
1-storey	34	1.1	0.8	3.1	1.9	1.9	3.4
multi-storey	103	1.1	0.7	3.2	1.8	1.5	3.0
Energy class A	6	0.5	0.3	1.5	0.9	1.0	2.0
Energy class B	10	0.7	0.4	1.4	1.0	1.1	2.1
Energy class C (minimum)	121	1.2	0.8	3.3	1.9	1.7	3.2
Log-building	46	2.2	1.0	3.9	2.5	1.7	3.9
Lightweight timber	91	0.9	0.7	1.6	1.4	1.5	2.6
irregular measurements	35	2.8	0.9	5.5	3.1	2.4	5.1
systematic measurements (>5)	102	1.0	0.7	2.1	1.3	0.9	2.0

The energy classification A or B contributed to slightly lower median air leakage (0.5 / 0.7 m³/(hm²)) than buildings designed to meet minimum requirements (1.2 m³/(hm²)). The lightweight timber construction (0.9 m³/(hm²)) had significantly lower air leakage compared to log houses (2.2 m3/(hm²)). This can be due to fact that the airtightness has been predominantly measured in prefabricated buildings compared to on-site building. The companies which are systematically conducting air leakage measurements (5 or more measurements in dataset) have significantly lower air leakage rates in those buildings (1.0 m³/(hm²)) compared to buildings in the irregular measurement group (2.8 m³/(hm²)). All those differences were statistically significant with p-value < 0.05.

As can be seen from the Table 1, the number of storeys did not have an effect on air leakage of the building envelope. Both groups have equal air leakage (1.1 $m^3/(hm^2)$). Surprisingly, the analysis showed no significant difference between buildings with different compactness factors or different number of storeys (Fig. 3) although a lower air leakage rate was expected for buildings with better compactness through favourable ratio of the external envelope area to internal volume and a generally smaller number of junctions related to a more simple form factor.

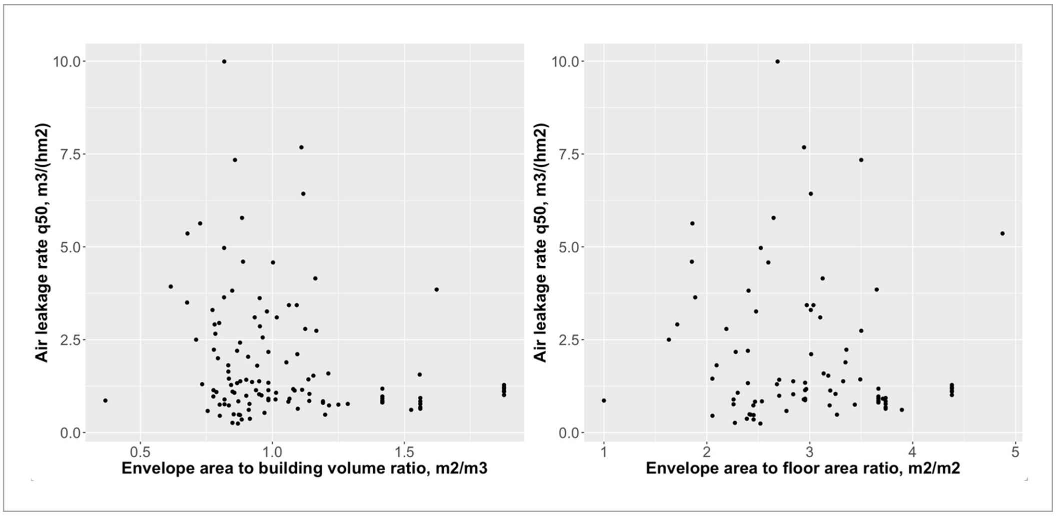

Fig. 3
The correlation of air leakage rate (q50) and building compactness for buildings built since 2009. The envelope area to volume ratio (left) and envelope area to floor area ratio (right) are given

As the construction technique had a great effect on an average air leakage, both groups (log-buildings and lightweight buildings) were further analysed to see if prefabrication has a significant effect as expected. As can be seen from Table 2, the prefabricated log-buildings (1.6 $m^3/(hm^2)$) are 55% more airtight than hand-made log-buildings (3.6 $m^3/(hm^2)$). In the case of lightweight timber buildings, the prefabrication has even larger effect and prefabricated buildings (0.9 $m^3/(hm^2)$) have 74% lower air leakage rate compared to on-site building (3.4 $m^3/(hm^2)$).

Table 2
The effect of prefabrication on air leakage rate and its distribution for sub-construction types

	Number of buildings median	Air leakage rate q_{50}, $m^3/(h\cdot m^2)$					
		median	16% percentile	84% percentile	mean	σ_{q50}	$q_{50,base}$
All log buildings 2009+							
Handmade logs	13	3.6	2.7	5.8	4.2	1.9	5.9
Prefabricated logs	33	1.6	0.9	3.1	1.9	1.1	2.8
All lightweight timber buildings 2009+							
Prefabricated elements	80	0.9	0.7	1.3	1.1	0.7	1.6
On-site building	11	3.4	1.4	6.0	4.0	2.7	6.7

The effect of systematic measurement practice within manufacturing or building companies were further analysed separately for log-buildings and lightweight timber construction. Similarly to the full dataset, the effect of systematic measurements in both groups of different construction technologies was significant, but the differences were smaller (Table 3). Within log-buildings the systematic measurements showed 37% lower air leakage rates. Within lightweight timber buildings the systematic measurements showed 47% lower air leakage rates. This means that systematic measurements give good feedback to manufacturers and building companies about the air leakages, with possibilities to improve the air-tightness system used and quality control system used.

	Air leakage rate q_{50}, $m^3/(h \cdot m^2)$						
	n	median	16% percentile	84% percentile	mean	σ_{q50}	$q_{50,base}$
All log buildings 2009+							
irregular measurements	11	3.0	1.9	6.3	3.9	2.3	6.1
systematic measurements (>5)	35	1.9	0.9	3.5	2.1	1.2	3.1
All lightweight timber buildings 2009+							
irregular measurements	24	1.7	0.8	4.6	2.7	2.4	4.8
systematic measurements (>5)	67	0.9	0.7	1.3	1.0	0.4	1.2

Table 3

The effect of systematic measurements on air leakage rate and its distribution for sub-construction types

For visual comparison between different building technologies within companies that conduct systematic measurements on their buildings the average (median) air leakage rates along with 16% and 84% percentiles are given in **Fig. 4**. It can be seen from **Fig. 4** that log-buildings have a significantly higher variation within the same company compared to prefabricated lightweight elements.

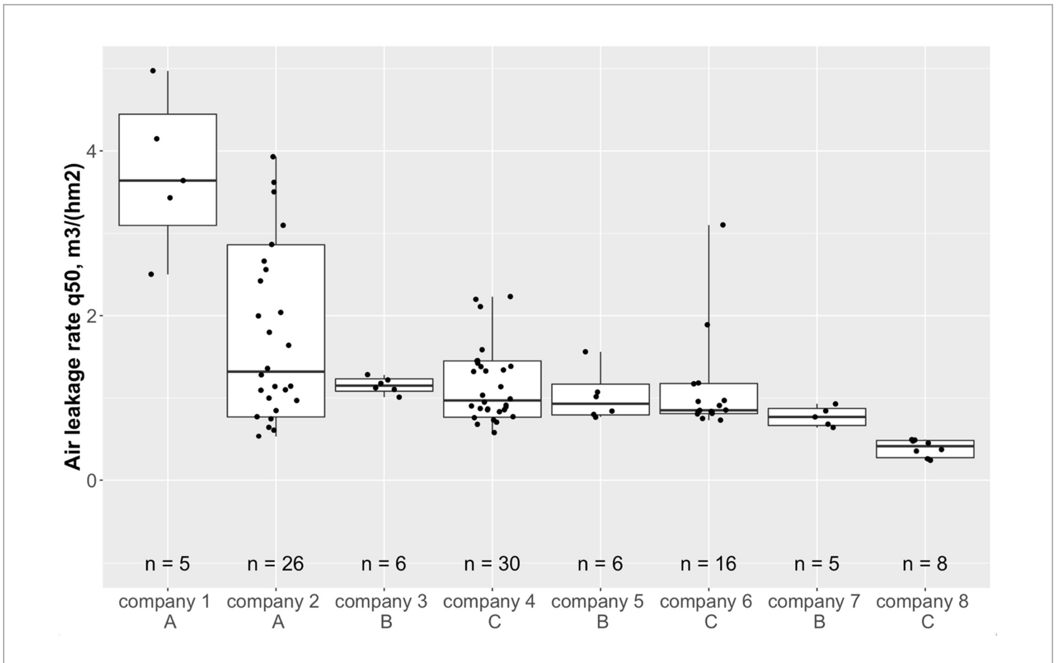

Fig. 4

Comparison of air leakage rates and its distribution between companies that conduct systematic measurements (A – log buildings, B – volumetric prefabricated modules, C – prefabricated wall/roof elements)

The prefabricated volumetric and regular modules have a lower variation and the median values of air leakages are around $q_{50} = 1.0\ m^3/(hm^2)$ or even lower. The higher variation in measurements is significantly affecting the base values of air leakage rates for these construction technologies. For handmade log buildings the base value $q_{50,base} = 5.9\ m^3/(hm^2)$. For prefabricated log buildings the base value of air leakage is 53% lower resulting in $q_{50,base} = 2.8\ m^3/(hm^2)$. Both construction technologies cannot compete with prefabricated modular technology, where base value of air leakage rate $q_{50,base} = 1.6\ m^3/(hm^2)$. For a comparison, the base value of air leakage rate $q_{50,base}$ for all timber buildings built since 2009 is $3.0\ m^3/(hm^2)$.

Discussion

The results confirm that buildings built after the energy performance requirements have taken effect have significantly lower air leakage than older buildings with median q50 of 1.1 ($m^3/(hm^2)$) and range of 0.8 – 3.1 ($m^3/(hm^2)$) corresponding to 16% and 84% quantiles. This corresponds well with other countries where new buildings had similar air leakage rates. In Poland, typical new building construction was characterised by airtightness n_{50} in the range of 1.6 to 2.6 h^{-1} (Górzeński *et.al* 2016). Similar results have been achieved for timber-frame low-energy houses in Norway, where measured apartments had airtightness n_{50} in the range of 0.5 to 1.3 h^{-1} (Relander and Holøs 2018).

According to the previous study of Estonian building stock, the most significant factors affecting the air tightness were the quality of workmanship and supervision, as well the number of storeys of the house, both showing a more than a two-fold effect (Kalamees 2007). This study shows that, for newer buildings, the number of storeys no longer has any effect on air-tightness. This refers to the fact that a systematic approach to designing the air-tight envelope avoids large air leakages related to external wall and intermediate ceiling junctions in older buildings. Furthermore, non-existent correlation between airtightness and compactness of the building envelope refers to the assumption that if systematic quality assurance with a proper air tightness concept in all junctions is used, the geometric and structural complexity of the building envelope is no longer a key factor while achieving air tightness in Estonia. It has to be noted that similar studies in Finland have shown significant differences in building airtightness depending on the number of storeys, with timber-frame multi-storey buildings (4.8 $m^3/(hm^2)$) having higher air-leakage rates than single-storey buildings (3.4 $m^3/(hm^2)$), referring to the fact that these kinds of effects are related to local building technologies and overall quality assurance mechanisms (Vihna *et.al* 2015).

The quality of workmanship through systematic measurements as well as prefabrication showed significant improvement in the full dataset and in both subgroups (log-buildings and lightweight timber buildings) corresponding to a 37% to 74% improvement, depending on the factor and group. The differences in other grouping factors were significantly smaller. For buildings with better air tightness target including buildings with higher designed energy efficiency and quality management similar sealing measures are utilised including systematic use of specialised membranes and sealing tapes with a significant attention to connections between openings and external wall.

The results from this study give an overview of average air leakage rates along with the variation for different grouping factors related to building geometry and construction technology. Assuming consistency in construction technologies and in quality assurance mechanisms, these average values with appropriate safety margins can be used for energy calculation in Estonian conditions for new buildings, or buildings in respective age groups. The base values calculated and stated in Tables 1, 2 and 3 take into account the variation of the measured results and try to give estimates for each grouping factor with a 75% margin and 84% confidence interval. Due to the high variation in measured values, the base values are much higher than median or mean air leakage rates. The base values for buildings built since 2009 are in a range of 1.6 to 3.9 $m^3/(hm^2)$ with a value of 3.0 $m^3/(hm^2)$ for all buildings. The lowest base value of air leakage rate is for a group of prefabricated lightweight timber buildings with a value of $q_{50,base}$ = 1.6 $m^3/(hm^2)$. The groups with an energy classification target of A or B energy class, or systematic measurement practice within a single company achieved a base value $q_{50,base}$ around 2.0 $m^3/(hm^2)$, while on-site construction along with handmade log-buildings achieved a base value $q_{50,base}$ 6.7 $m^3/(hm^2)$ and 5.9 $m^3/(hm^2)$ respectively.

Conclusions

The air-tightness of Estonian wooden buildings has improved by a factor of 10 since the minimum requirements for energy efficiency have taken effect. Buildings with a higher energy efficiency target also have a slightly better air leakage rate. Prefabrication with light-weight timber construction technology seems to be superior to traditional log-wood building and notably, prefabrication improves air-tightness even within log-wood building or lightweight building groups, meaning that on-site building or the use of handmade logs corresponds to significantly higher air leakages. The compactness factor and number of storeys did not have a significant effect on air leakage referring to the fact that if systematic quality assurance with a proper air tightness concept is used, the geometric and structural complexity of the building envelope is no longer a key factor while achieving air tightness.

Acknowledgment

This research was supported by the Estonian Research Council with Personal research funding PRG483 "Moisture safety of interior insulation, constructional moisture and thermally efficient building envelope", Institutional research funding grant IUT1-15, Estonian Centre of Excellence in Zero Energy and Resource Efficient Smart Buildings and Districts, ZEBE, grant TK146 funded by the European Regional Development Fund and H2020 project No 754177: "NERO - Cost reduction of new Nearly Zero-Energy Wooden buildings in the Northern Climatic Conditions".

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