Airtightness Measurements of Wood Frame Low Energy Row Houses

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ABSTRACT

Airtightness is a key component of energy efficient buildings. The blower door method can be used to quantify the airtightness. The requirements for airtightness in Norway have become stricter. This leads to a growing interest for airtight constructions and methods.

Jåtten Øst in Stavanger is a development of low-energy row houses. There are a total of 73 apartments with 3 different types of configurations. The row houses were planned to have an air change rate at 50 Pa, n_{50} lower than 1.0 h^{-1}. None of the craftsmen involved had previous experience in building low-energy houses with specific airtightness requirements. Common materials and constructions for timber-frame buildings were used.

The airtightness of all the apartments was measured. Pressurization and depressurization tests were carried out both when the wind-barrier was finished and before takeover. The air change rate at 50 Pa pressure difference, n_{50} varied between **0.70 and 1.63** after finishing the wind-barrier, and between **0.48 and 1.29** before takeover.

The results demonstrate that skilled craftsmen without specific training or experience in airtight building were able to produce dwellings with n_{50} better than **1.0 h^{-1}** with common materials. Improved airtightness beyond the national required level of n_{50} <2.5 h^{-1} is thus an achievable and probably cost-efficient way of reducing energy demand. Polyurethane-based expanding foam was used more extensively than in typical projects.

INTRODUCTION

General

Energy for heating and cooling buildings is of great significance in large parts of the world, and studies have shown that reducing energy demand in buildings are among the most cost-effective means to reduce emission of greenhouse gases (McKinsey 2009). Heat recovery from ventilation air can be very effective if infiltration is low, thus good airtightness is a prerequisite to achieve energy efficient buildings.

In Norway the allowed air change rate at 50 Pa pressure difference (n_{50}) for small residential buildings was reduced from 4,0h^{-1} to 2,5 h^{-1} in 2007, effective from 2009. This, and an increasing demand for "low-energy" or "passive " dwellings with even stricter demands on airtightness, has lead to a growing interest for airtight constructions and methods. Airtightness measurements during construction is becoming more common, in order to increase the contractor's chances of reaching the final n_{50} requirement, n_{50f}. The airtightness is often

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measured when the wind barrier is mounted, n_{50w}. If the n_{50} requirement is reached for n_{50w}, contractors often find this to be a good basis for the achievement of the n_{50f} requirement. The airtightness can be measured at over- and underpressure. All values in this paper are reported as averages of over- and underpressure.

Earlier Work

Brunsell and Uvsløkk (1980) studied airtightness in Norwegian single-family detached houses. The n_{50} of 61 houses was measured to 4,7 h^{-1} with a standard deviation of 1,5 h^{-1}. The houses were 1-5 years old and represented typical Norwegian wood-frame houses. We are unaware of any newer systematic studies of typical wood-frame houses in Norway.

Bassett (1985) found that increased complexity is influential on the airtightness. He defined the complexity as length of joints per external surface area. This should be as low as possible to increase the airtightness.

When airtightness is studied in a broad range of buildings, it is commonly observed that airtightness varies greatly. Sherman & Matson (2002) found the standard deviation to be almost the size of the mean when comparing normalized leakage of a great number of U.S. residential buildings.

Myhre and Aurlien (2005) measured wood-frame houses when wind tightened only, n_{50w}, and when finished, n_{50f}, and concluded that the air leakage of wood-frame houses could be significantly reduced by improving the airtightness of the wind barrier.

According to Sandberg and Sikander (2005), the two most important factors for poor airtightness are poor drawings and lack of motivation and knowledge. It is argued that increasing the knowledge of all the involved participants will be favourable for the airtightness. Further it was found a need to make construction details clear and with explicit indication of how to make it airtight, not only that it is supposed to be airtight.

Development of Row Houses at Jåtten Øst

Jåtten Øst B7 in Stavanger, as depicted in Figure 1, is a development of row houses, based on the winning contribution in the “Europan 7” architectural competition. The theme of the competition was “Sub-urban challenge, housing intensity and diversity”. Late in the development of the design, the ambition of a net energy demand of 106 kWh/m² year was set. A standard project at the time would have a net energy demand of 152 kWh/m² year.

As one means to achieve this reduction in energy demand, the maximum air change rate at 50 Pa (n_{50}) was set to 1,0 h^{-1}. Two local companies were commissioned to document achieved airtightness.

Figure 1. Exterior of two of the row houses at Jåtten.

Jåtten Øst B7 consists of 73 apartments of two different sizes, A and B. Common materials and constructions for timber-frame buildings were used. Some basic features of the buildings are given in Table 1. Variation within each type was minimal, and the same craftsmen were involved in most of the critical processes for airtightness in all apartments.

Table 1. Basic features of the buildings

Feature	**Type A**	**Type B**	**Note**
Floor area	137 m^2	157m^2	Net floor area as defined in national standard NS 3940 (Standard Norway 2007)
Internal volume	318-323 m^3	385-396 m^3	Apartments in middle of a row have larger volumes, as external walls are thicker.
Surface area	428-441 m^2	409-419 m^2	Given as surface of wind barrier, including surface against other apartments. Apartments in middle of a row have smaller surface.
Number of floors	4	3	
Ground floor	Concrete slab		With LDPE radon membrane.
Dividing floors	Wood		
Ground floor walls	Concrete/EPS/Concrete		
Other walls	Wood frame		External walls have wooden cladding, spunbonded polyethylene and gypsum board as wind-barrier, 248 mm mineral wool, 0,15 mm unsealed PE foil as vapour barrier, and gypsum board.

The building project was developed by the Municipality of Stavanger with separate contracting of groundwork, carpentry, plumbing, electrical work and ventilation work. Concrete work was done by the future owners.

METHODS

Blue-prints, descriptions, bids and contracts were examined. As-built details and process experiences were collected via qualitative interviews. Representatives for the commissioner Stavanger municipality, (2), architect (1), carpentry contractor (4), electrical contractor (1) and airtightness surveyor (1) were interviewed.

Representative apartments were examined after completing the wind- and vapour barriers, and solutions compared with descriptions and blue-prints.

Airtightness was measured by independent commissioned companies after completion of the wind barrier and again after completion of building and installation work. At the first measurements all windows and doors, penetrations in the ground floor (electric supply, water supply, sewer pipes) and preparation for ventilation duct penetrations were installed. Before the second measurements ventilation ducts, cables for outdoor lights, doorbells, pipes for outdoor water tap were installed. Ventilation ducts and sewage pipes were sealed prior to the measurements.

Measurements were made with the aid of a Minneapolis Blower Door, following standard EN 13829 (SN 2002). Apartments were measured individually, without pressurizing or depressurizing adjacent apartments. The air leakage rate at 50 Pa q_{50} [m^3/h] calculated as described in the standard was used as the primary measure. In some cases the original test files were unavailable, and q_{50} was then calculated from reported air change rates (n_{50}) and reported volume. Air change rate (n_{50}) was calculated as q_{50}/V where the internal volume V was given as the air volume inside the vapour barrier (floors and dividing walls excluded.)

RESULTS

Air leakage measurements

Measurements for 70 apartments were available. One apartment was excluded from further measurements after the first tests, because of extensive modifications by the future owner. The n_{50w} for two apartments, and n_{50f} for five apartments are missing due to lack of coordination.

Table 2 gives descriptive statistics for air leakage measurements. Taking the area of the wind barrier as envelope area, the corresponding mean air permeability, q_{a50} was 0.87 m^3/m^2h and 0.78 m^3/m^2h for the two apartment types respectively.

Table 2. Descriptive statistics for the n_{50w} and n_{50f} measurements. From the left: the mean value, the standard error of the mean, the standard deviation SD, the minimum value, the lower quartile or 25 % percentile Q1, the median, the upper quartile or 75 % percentile Q3, maximum, the interquartile range (Q3-Q1) and the number of measurements.

Variable	Mean	$SD/\sqrt{n}$	SD	Minimum	Q1	Median	Q3	Maximum	IQ	n
n_{50w}	1,08	0,02	0,20	0,70	0,93	1,10	1,23	1,63	0,30	68
n_{50f}	0,96	0,02	0,18	0,48	0,84	0,92	1,09	1,29	0,25	64

Values for individual apartments are shown in Figure 2. The figure shows a scatter plot in the middle with n_{50f} vs. n_{50w}. In the top and right of the figure, histograms for the data are provided.

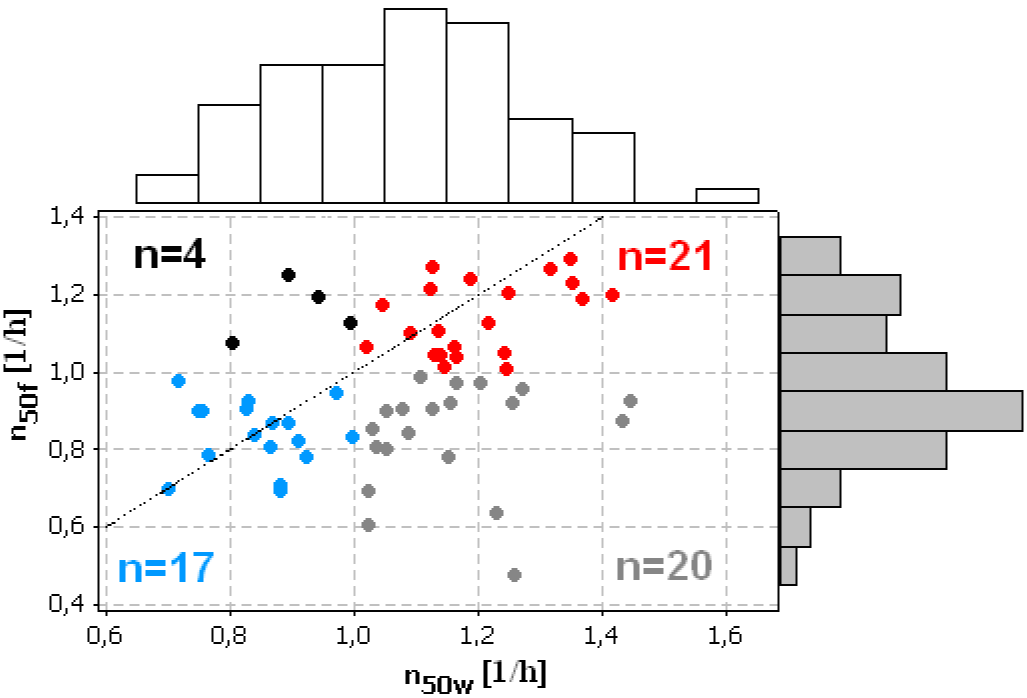

Figure 2 Average air change rate with wind-barrier only (n50w) and finished (n50f) for individual apartments. The dotted line is n50f = n50w. The colors of the dots refer to the 4 groups bound by the limits of 1 h-1 for n50w and n50f. The number inside each of the 4 groups is denoted by n.

The relation between the n_{50f} and n_{50w} can be further investigated. Figure 3 shows a plot of the difference between the achieved n_{50f} and n_{50w} as a function of the n_{50w} for each apartment. Positive values on the y-axis correspond to apartments having increased their air leakage from n_{50w} to n_{50f}. Of the total 62, 18 turned out to be positive. Over and below the regression line are 95 % confidence bounds for the regression line. By tilting the regression line inside the confidence bounds it is seen that with 95 % confidence the regression line covers the x-values from about 0,8 to 0,95. It is also seen that the slope inside the confidence bounds is always negative. R^2 shows that 33.6 % of the variation is explained by the regression. S denotes the standard deviation of the individual measurements.

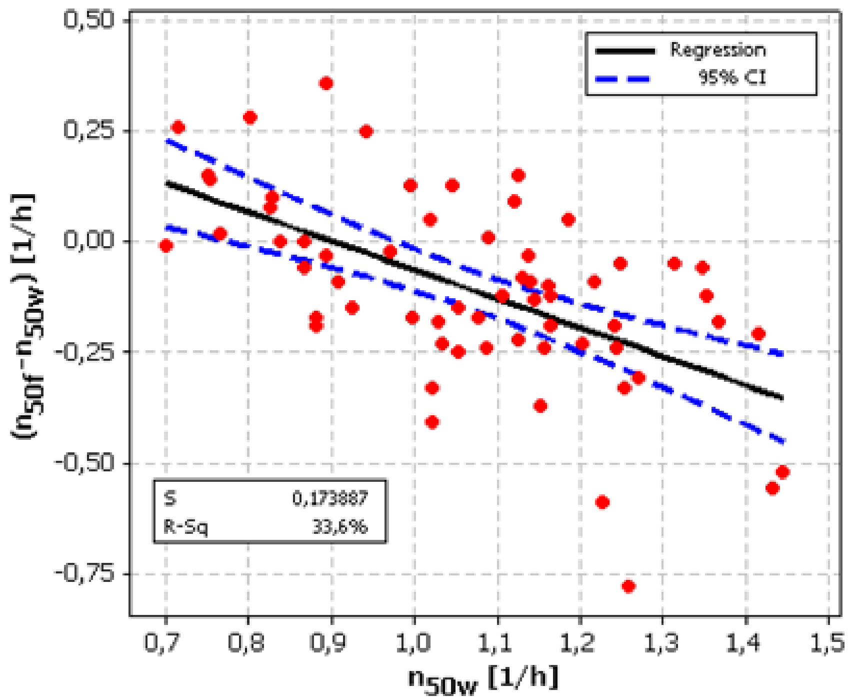

Figure 3 The difference between n_{50w} and n_{50f} as function of n_{50w}. The linear regression curve *n_{50f} - n_{50w} = 0,5904-0,6535n_{50w} in black.*

The blower door data can be subdivided into groups of apartments with different geometry. Figure 4 shows a combination of a box plot and individual value plot of the subgroups.

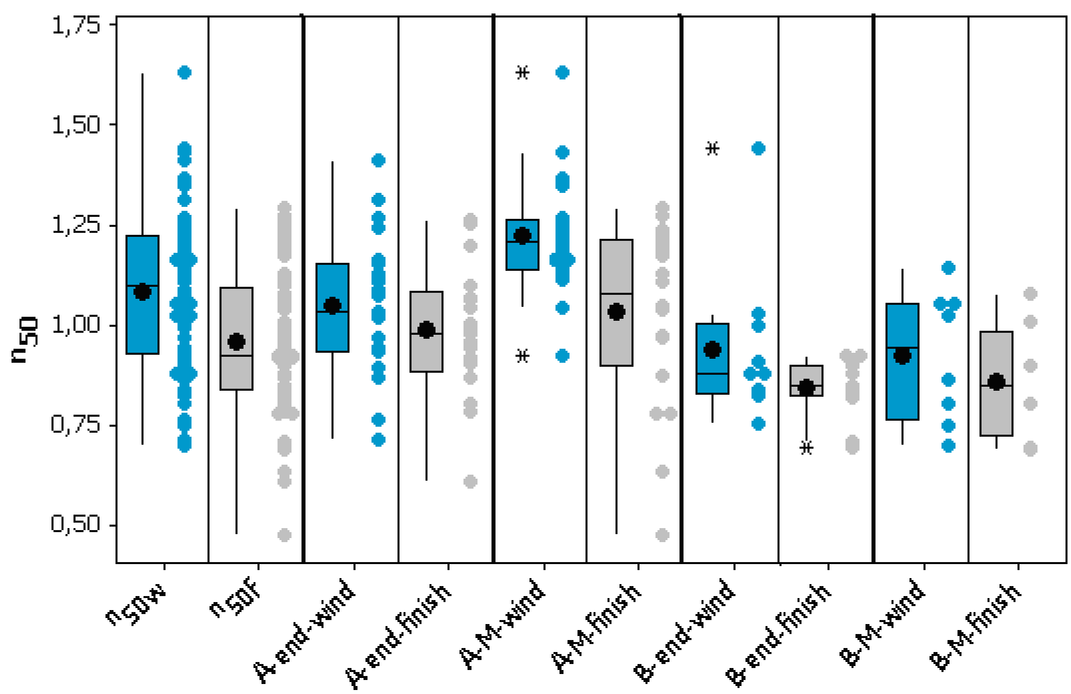

Figure 4. Box-plot and individual value plot of n_{50w}, n_{50f} and the subgroups of different apartment types and configurations. The dots inside the boxes indicate mean values. Outliers are indicated by *.

The different configuration of apartments had only slight differences in n_{50w} and n_{50f} as shown in Figure 4. Notably, there is no indication that apartments in the end of a row are leakier than similar apartments in the middle. This is consistent with a hypothesis that division walls are at least as leaky as external walls.

Interviews and Document Examination

Design and details. As the target for energy demand was set late in the design process, changes were restricted to details like insulation thickness and component quality, while building form, size and number of windows etc, were left unchanged. Airtightness details were in general only loosely described by the architects, however double wind-barrier (gypsum board and a spunbonded polyethylene wind barrier), and a radon barrier under the concrete floor was described.

Due to environmental considerations, the use of insulation foam and caulking was originally very restricted, but these restrictions were loosened considerably during the building period. Construction details of joints and penetrations were inadequate or lacking in the tender documents, thus were to a large extent left to the builders.

Building process. As a rather unusual feature, the ground floor was to a large extent built by the future owners. The clerk of the works, architect, and craftsmen did not report any previous experience with building projects with airtightness measurements, or with specific targets for airtightness. A three-hour seminar focusing on low energy demand and airtightness, involving all craftsmen was arranged. The reactions on this was somewhat mixed; the interviewed representatives of the carpentry contractor found this more worthwhile than electricians and plumbers.

Since the airtightness had received limited attention in the design phase, details for air tightening of joints and penetrations had to be specified in the building phase. The carpentry contractor was responsible for overall airtightness, but several of the details considered important for airtightness involved two contractors.

The representatives of the carpentry contractor reported the following points as particularly demanding to make sufficiently airtight:

- The joints between ground floor wall (concrete / EPS sandwich) and bottom sill of timber wall. To correct for uneven surface, these were grinded smooth with diamond wheels on angle grinders. To correct for deviations of level or direction, an extra sill was used, and the gap between this and the foundation sill was filled with expanding polyurethane foam.
- Joints between windows and the ground floor walls. Polyurethane foam was used.
- Joints between cables and pipes and the wind barrier. Caulking between pipes and gypsum boards was time-consuming.

Estimated costs. The estimated extra labour and cost for air tightening based on the interviews is summarized in Table 3. Cost of extra materials is not included.

Table 3. Identified cost-driving operations to achieve specified airtightness.

Operation	*Estimated cost*	*Note*
Extra design work	*" a few hours"*	*Very few descriptions of details adding to airtightness.*
Information seminar	*80 man-hours*	*Approx. 2 hours of 3 hour seminar with 40 participants*
"Tricky carpentry details"	*"Significanly more than usual"*	*Informants had great trouble separating airtightness-related issues from other issues (extra insulation, unusual geometry, etc.)*
Airtightening of floor	*No extra cost*	*1-2 days work per apartment. Necessary for radon protection.*
Grinding of concrete wallheads	*1-2 days per apartment*	*Performed by future owners*
Notches in external retaining walls	*Unknown*	*Only necessary for the first houses.*
Double wind barrier	*No extra cost*	*Preferred solution to protect from driving rain.*
Preparation for penetrations of ventilation ducts	*1 hour per apartment*	*Extra work, carpenters.*
Cable penetrations	*1-2 hours per apartment*	*Extra work, electricians.*
Measurements	*NOK 5.800 [US$ 928] per apartment*	*2 separate tests per apartment. 1NOK = 0,16 USD or 0,12 EUR at paper preparation.*
Caulking during depressurization	*1-3 hours per apartment*	

DISCUSSION

Overall Results

When calculating n_{50f} with corrected net internal air volumes, the target value of 1,0 h^{-1} was not achieved for all apartments. As apartments were tested individually, and some internal leakages between apartments were observed, the average n_{50} for individual apartments represents an overestimate of n_{50} for the whole buildings. Thus the average n_{50f} of 0.96h^{-1} fulfilled the target value based on energy considerations.

There is currently some discussion nationally on whether internal volume should include the volume of internal walls or not. In the apartments in this study the exclusion of internal walls from the volume increased n_{50} with approximately 5 %.

Variability of Airtightness

The standard deviations of n_{50w} and n_{50f} of 0.20 and 0.18, respectively, shows that when design, construction details and involved craftsmen are very similar, the variability of airtightness is much smaller than when random samples are considered.

As some air tightening was done while measuring airtightness in "cruise-mode" to achieve the target airtightness value, the standard deviation is lower than what would be expected if airtightness results were unknown to the carpenters responsible for airtightness. Initial values of airtightness before this final tightening work were not collected systematically, but reductions of 0,1-0,3h $^{-1}$ after 0,5-1,5 hours of tightening work were recorded for some of the apartments.

Even if this low variability to some extent depends on tightening during measurements, it still indicates that a prediction of airtightness based on project characteristics could be meaningful, given that the most important air leakage factors could be identified.

As depicted by Figure 2, 37/62 (≈ 60%) of the buildings managed the n_{50f} requirement. However, when reporting n_{50} calculated with the original and larger estimated volume, all but one apartment fulfilled the requirement. This is largely an effect of an approach of tightening during depressurization until just below the airtightness target. It is unknown how much extra effort would be required to reach the stricter requirement had this been known during the measurements.

When inspecting Figure 2 further, it is seen that a total of 21 apartments managed the n_{50W} "requirement". 17 of these 21 (≈ 81 %) apartments also managed the final official requirement of n_{50f}. Thus, the results indicate that good airtightness of the wind barrier increased the likelihood of a good final result. But the airtightness can be significantly decreased following the installation of e.g. pipes, cables and ducts.

The overall tendency was that the airtightness increased from n_{50w} to n_{50f}. Figure 3 shows that the values of (n_{50w}-n_{50f}) vary over a great range, and that increased airtightness is more likely for the apartments with high n_{50w}. If the wind barrier is mounted very tight, the effect of another tight layer is not likely to increase the airtightness that much, since many of the leakages probably occurs in junctions. A less perfectly mounted wind-barrier is more likely to benefit from a vapour barrier. An effect of the carpenters knowing the result from the first measurement can not be ruled out.

Factors Contributing to Airtightness

The houses at Jåtten Øst are not particularly compact see Figure 1. The complexity as defined by Basset (1985) is not particularly low compared to more typical Norwegian row-houses. As the houses studied by Bassett (1985) mainly were very much leakier than the houses at Jåtten, no direct comparison with his results were made.

Also, the drawings and description of air tightening details were not complete. Thus one of the risk factors for poor airtightness according to Sandberg and Sikander (2005) was to some extent present.

Still the average n_{50} at Jåtten was 81% lower than the average Norwegian house as reported by Brunsell and Uvsløkk (1980). Several factors have contributed to the acquired airtightness. The demand for airtightness was very clearly stated by Stavanger municipality, and the responsibility was clearly defined in the contract. The information meeting contributed to the understanding and focus on airtightness during the process. The systematic measurements of all apartments probably contributed as a constant reminder of the issue as well as a feedback on quality of the various details. On a construction level, a double wind-barrier, concrete ground floor walls, and a

PE vapour barrier comes to mind as important differences from many of the houses examined by Brunsell and Uvsløkk (1980).

Cost Efficiency of Airtightness

Attempts to separate operations contributing to the improved airtightness from other project-specific issues like overall design and extra insulation were not generally successful. Estimates of total extra costs based on information from the interviews are thus not given. As some of the major cost-driving operations were identified after the bidding, the bids were not suitable for estimating costs either. The major costs that were directly related to airtightness in table 2 were related to an estimated extra work of 12 -22 hours, and a fixed price for measurements of 5,800 NOK per apartment. Using an average hourly labour cost of NOK 340 this gives a roughly estimated direct cost of 10 -13 KNOK [US$ 1,600 – 2,000] for information, caulking, foaming, preparing penetrations, grinding concrete walls and measuring airtightness.

It is our opinion that some of the leakage paths that proved time-consuming to seal, e.g. joint between foundation wall and the bottom sill, could be solved much more efficiently if airtightness was targeted systematically as described by Sandberg and Sikander (2005) in the design process, and previously described solutions had been used. Other details could probably be solved cost-effectively by using available products, e.g. adhesive gaskets adapted to the most common cable and pipe diameters, instead of caulking.

Calculating net energy demands following national standards for n_{50} = 1,0 and 4,0 gives a mean difference of 20 kWh/m^2y, corresponding to yearly reduced energy demands of 2858 to 3306 kWh / apartment * year, depending on size and configuration. This clearly indicates that payback times of the airtightness effort may be short with realistic energy prices.

CONCLUSIONS

- Air change rates in the order of 1,0 h^{-1} were achieved by inexperienced craftsmen using largely conventional materials and construction practices.
- Some costly operations to achieve airtightness could be avoided by a stronger focus on airtightness in the design phase.
- Satisfactory airtightness can be achieved by a continuous wind barrier, but airtightness cannot be assumed to automatically be better in the finished building than after completion of the wind-barrier.
- Ad-hoc solutions to improve airtightness may conflict with environmental considerations.

Acknowledgments

The Norwegian State Housing Bank financed the original work. Hans Ananiassen of Trykktesteren as has provided the air leakage data as well as additional information and valuable discussions. All the informants are thanked for their time and support.

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