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Durability of building airtightness

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international cooperation among the 30 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)

The high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely ‘Objectives’ and ‘Means’. These two groups are distinguished for a better understanding of the different themes.

Objectives: The strategic objectives of the EBC TCP are as follows:

– reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stakeholders and promotion of co-benefits;
– improvement of planning, construction and management processes to reduce the performance gap between design stage assessments and real-world operation;
– the creation of ‘low tech’, robust and affordable technologies;
– the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible;– the creation of holistic solution sets for district level systems taking into account energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means: The strategic objectives of the EBC TCP will be achieved by the means listed below:

– the creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life cycle analysis (LCA);
– benefitting from ‘living labs’ to provide experience of and overcome barriers to adoption of energy efficiency measures;
– improving smart control of building services technical installations, including occupant and operator interfaces;
– addressing data issues in buildings, including non-intrusive and secure data collection;
– the development of building information modelling (BIM) as a game changer, from design and construction through to operations and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the ‘objectives’ themes are final goals or solutions (or part of) for an energy efficient built environment, while the ‘means’ themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019-2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)

Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO_2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO_2 Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (*)
Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems (*)
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Annex 85: Indirect Evaporative Cooling
Annex 86: Energy Efficient Indoor Air Quality Management in Residential Buildings

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group - Cities and Communities
Working Group – Building Energy Codes

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Abstract

Much progress has been made to improve the airtightness level of new buildings. Still, little is known about the durability of building airtightness, or the impact of degradation on airtightness. This report presents a comprehensive review of studies that deal with building airtightness durability. Regarding field measurement studies, the envelope airtightness seems to decrease during the first years after achievement and then stabilize. However, these variations are rarely explained. Key elements that may drive airtightness variations were identified. Regarding laboratory ageing studies, there is actually no standardized protocol to characterize the durability of product assemblies concerning airtightness. This report gives the pros and cons of various alternatives to define a protocol. Finally, this report stresses the importance of implementation conditions on airtightness durability, whose impact can be studied both on site and in laboratory.

1. Introduction

Over the last thirty years, much progress has been made to increase our knowledge about mechanisms driving building airtightness and the impact of air infiltration on energy efficiency (Ng et al., 2015), health effects (Airaksinen et al., 2004; Richieri et al., 2016) and construction quality-related issues (Janssens and Hens, 2003). As regulations require buildings to achieve higher levels of thermal performance, the energy cost associated with air leakage becomes more significant (Leprince et al., 2017). However, having a requirement on building airtightness is relevant only if the airtightness level is durable. Nevertheless, studies have shown that a mandatory level of airtightness can lead to last-minute taping and mastic setting that is most probably not durable (Love et al., 2017).

The durability of airtightness products and assemblies at mid- and long-term scale is, therefore, a pending question. Indeed, this subject remains very complex, since it covers in the meantime:

- the modelling of the mechanisms of buildings and products loads and deformations;
- the accelerated ageing in laboratory-controlled conditions; and
- the performance characterization from field measurements results.

In the past years, several studies have focused on this issue using two different approaches. Some studies seek to characterize the evolution of airtightness over time by field measurements in real buildings. The other studies are based on laboratory measurements in order to test the accelerated ageing of airtightness products.

The objective of this report is to make a critical review and a comparative analysis of research and technical studies that deal with building airtightness durability, covering both field and laboratory studies. First, the report presents the research method including literature retrieval. Then, it reviews the results and discusses the analysis of field studies, followed by laboratory experiments. Finally, the report focuses on the impact of the implementation conditions on airtightness durability.

2. Approach

The aim of this literature review is to identify and discuss the results of studies and existing standards on the characterisation of building airtightness durability across field measurements in real buildings and laboratory experiments in controlled conditions.

Therefore, this review focuses on studies regarding:

- field measurements of building airtightness changes over time and the uncertainty in airtightness testing. When analysing the airtightness evolution, it is important to take into account the variability of test results due to the tester, measurement devices, external conditions, seasonal variations, etc.
- experimental measurements about the air barrier system ageing in controlled conditions, and the physical stresses on the air barrier inducing its deterioration. The knowledge of physical stresses is essential to define the conditions for the experiments.

This review is the result of a thorough literature research through Elsevier and AIVC's Airbase, additional search through Google Scholar and the bibliography available in already found articles. This research focused mostly on peer-reviewed journals (37) and conference (29) publications. Reports from research centers (8), European and international standards (3), a publication from a technical magazine and another one from a foundation are also referenced, bringing the total references to 79.

It seems that long-term performance of building airtightness has been a key subject of research in the second part of the 80's (mostly in the USA and Canada). Very few studies were published during the 90's and 00's but since 2010, this subject has come back into focus in Europe. This review is based mostly on studies published after 1995 for two reasons; first, there were a lot of changes in building construction practices and products in the last 20 years; and second, airtightness measurement devices and protocols have evolved since the 80's.

3. Field studies in real buildings

In this chapter, we present a literature review of field studies testing the airtightness durability on real buildings, with results presentation and discussion, focusing on the uncertainty in airtightness testing. The chapter ends with a list of recommendations for future studies.

3.1. Review of on-site studies testing buildings airtightness durability

Table 1 presents the field measurements studies grouped by country and summarizes their main results (more details about these studies are presented in Annex 1). Airtightness results are converted into n50 (as defined in ISO 9972 (ISO/TC163, 2015)) to ease comparison. However, the wide range of sample sizes (ranging from 2 houses for a German study to 61 houses for a French study), age of the buildings and types of materials make it difficult to do this comparison and draw general conclusions.

Table 1: Summary of field measurement studies

Country	Sample size	Year of construction	Age (years)	Mean air permeability n_{50} (upon completion)	Main material	Air permeability evolution	Reference
Belgium	15 new houses	2010	1-2	0.6 ACH	Concrete blocks	Max: +120% Mean: +36% Min: -3%	(Bracke et al., 2016)
	41 new houses	2007 - 2019	0.5-12	0.94 ACH	? (low-energy houses)	Max: +200% Mean: +38% Min: -35%	(Verbeke and Audenaert, 2020)
Canada	17 new houses	1985	3 / then 11	1.5 ACH	Wood	Max: - / +60% Mean: +6% / +11% Min: - / -16%	(Proskiw, 1998)
Czech Republic	4 new houses	2007	11 (or tested regularly between 3 and 11)	0.57 ACH	Wood	Houses A&B: +35% House C: +137% House D: +103%	(Novák, 2018)
France	30 new houses	2009	5-6	1.8 ACH	Concrete blocks	Max: - Mean: +50% Min: -	(ADEME, 2016)
	61 new houses	2009 - 2016	1-8	1.38 ACH	Hollow brick (36); Concrete blocks (19); Wood (6)	Max: +180% Mean: +20% Min: -38%	(Moujalled et al., 2021)
Germany	2 new houses	1990	25	0.6 ACH	Concrete blocks	1st house: 0% 2nd house +34%	(Feist et al., 2016)
	17 new houses	?	1.4-10.5	0.42 ACH	Wood (9); Composite (4); Concrete (2) solid (2)	“almost always within the measuring accuracy”	(Peper et al., 2017)
	31 new houses	2000	2	0.37 ACH	? (passive houses)	Mean: +24%	(Erhorn-Kluttig et al., 2009)
Sweden	6 new houses	1990	10-20	0.6-4 ACH	Wood	Max: +580% Mean: +162%	(Hansén and Ylmén, 2012)

						Min: -1%%	
UK	23 new houses	2007	1-3	4 ACH	Wood and concrete blocks	Max: +154% Mean: +25% Min: -33%	(Philips et al., 2011)
	5 new houses	2005	1	5 ACH	Concrete blocks	Max: +30% Mean:+4% Min: -22%	(Jez Wingfield et al., 2008)
US	17 new houses	2001-2003	10-13	6 ACH	Wood	Max: +140% Mean: +15% Min: -25%	(Chan et al., 2015)
	17 refurbished houses	2007-2008	5-7	10 ACH	Wood	Max: +150% Mean: 0% Min: -40%	

The min, max and mean change in air permeability for each study are plotted in Figure 1 and Figure 2 against the building age (min, max and average between these two values). The circles' surfaces are proportional to the sample sizes ranging from 4 to 61. In Figure 1, three colours are used to characterize the mean initial air permeability n50: low (between 0.5 and 1 ACH) in green; moderate (between 1 and 2 ACH) in orange and high (> 2 ACH) in red. In Figure 2, four colours are used to differentiate the main material used for construction. From these two graphical summaries, one can draw the following conclusions:

- **Airtightness is not robust.** Significant changes in air permeability with time are observed for at least part of the tested houses in all studies except one (Peper et al., 2017). This is the case regardless the initial airtightness level, building age and building sample size.
- **Airtightness tends to deteriorate after completion.** The mean change in air permeability is positive for all studies. The average of all mean changes weighted by the sample size gives an increase of 24%. Hansén and Ylmén however noted that for the 6 houses tested, air leakage increased for half of the tested houses (up to 6 times) and decreased for the other half (Hansén and Ylmén, 2012).
- **Changes in airtightness are highly variable.** For each study, results differ considerably between the tested houses, with almost always at least one presenting an improved airtightness (by up to 40%) and almost always at least one presenting a very deteriorated airtightness (by up to 580%).
- **Changes in airtightness occur quickly after construction.** The mean change in measured air permeability does not seem to clearly increase with the building age, which would mean that changes occur mostly within the first (1 or 2) year(s) of the building use. This is suggested in the study with the largest sample size (Moujalled et al., 2021) and confirmed by a study with buildings tested regularly where air permeability increased mainly in the first years (Novák, 2018).
- **Changes in airtightness in percentage does not seem to be correlated to the initial air permeability level.** The mean change in measured air permeability is given in percentage and there is no clear difference between the three levels of initial air permeability. This however means that changes in absolute terms are larger for more permeable buildings. In other words, an originally very airtight building tends to have rather small additional air defects (in absolute terms) compared to an originally leaky building.
- **Changes in airtightness do not seem to strongly depend on the main construction material.** Both wooden and concrete constructions were sometimes found to have a durable airtightness and other times a strongly deteriorated airtightness.

One can note that big databases collecting airtightness test results could be used for the analysis of the airtightness durability. This was done by McWilliams and Jung (McWilliams and Jung, 2006) who analysed 100,000 building airtightness tests and concluded that on average houses get about 1% leakier every year. However, they mentioned that the data did not allow to isolate the effect of durability issues from the fact that older houses were generally built less airtight. This approach is indeed not straightforward and requires detailed and extensive amount of data to estimate the average airtightness level of new houses depending on the construction year and therefore evaluate the ageing effect with tests performed several years after the construction.

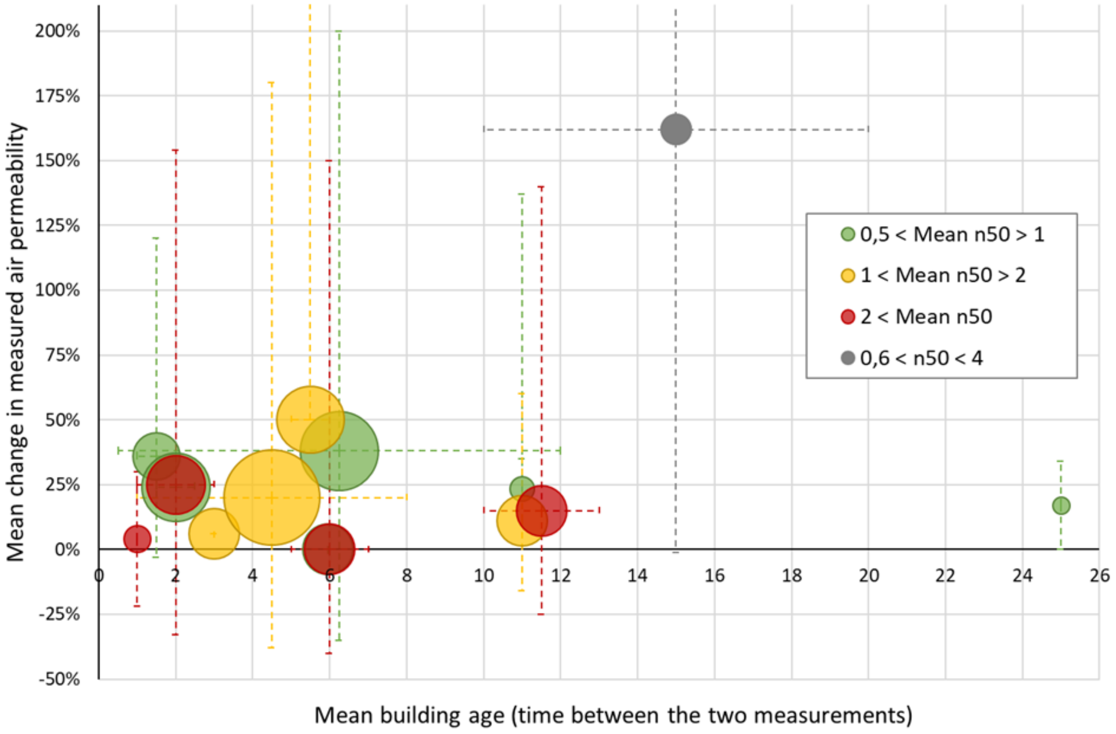

Figure 1: Graphical summary of field measurement studies: (min, max and mean) change in measured air permeability according to the (min, max and corresponding) mean building age; mean initial air permeability in ACH (3 colours) and sample size (circles' size)

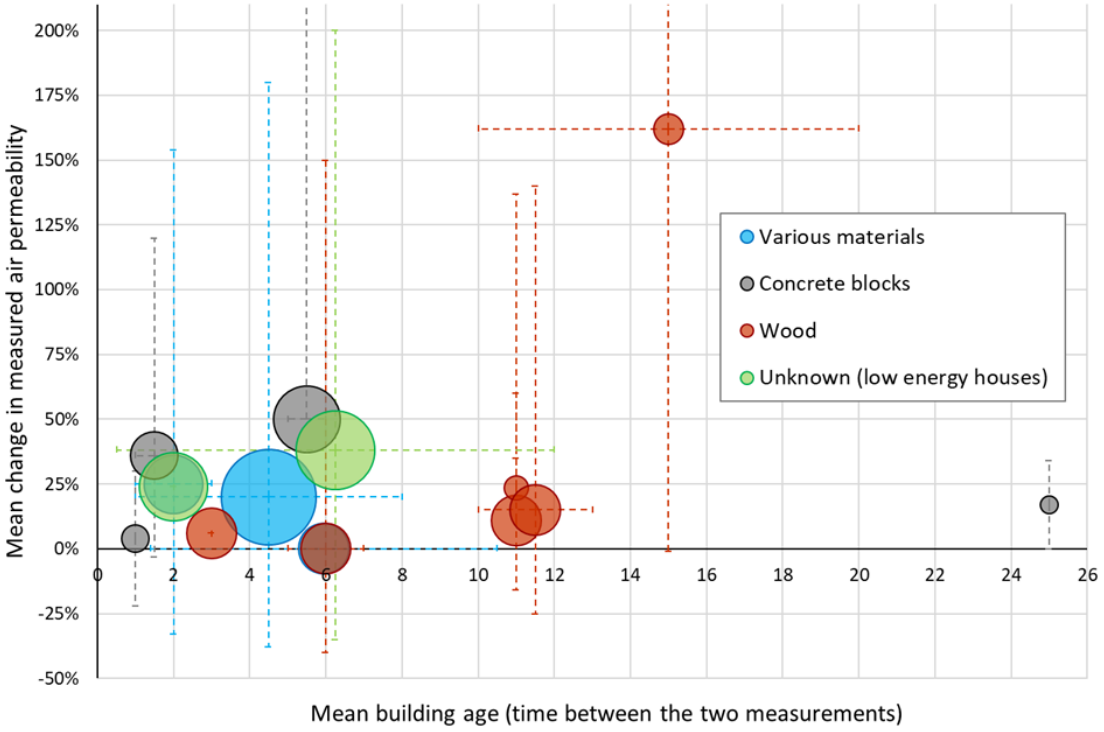

Figure 2: Graphical summary of field measurement studies: min, max and mean change in measured air permeability according to the min, max and mean building age; main construction material (4 colors) and sample size (circles' size)

3.2. Key factors for airtightness change over time

3.2.1. Possible factors of airtightness decrease over time

Based on the results of field studies regarding the evolution of air permeability in real buildings, it seems that when air permeability increases, it increases in the first years and then stabilises. Different factors have been identified explaining this increase over short and long term. These factors- over short term- mentioned in the literature and sometimes contradicting each other are:

- **Buildings' natural "movements":**
    - Heating houses for the first time may induce the shrinkage of mastics and/or structural timber. Hence, if the first test was performed before the heating of the house, the impact of shrinkage is not reported (Jez Wingfield et al., 2008).
    - Shrinkage of mastic when a backer rod is not used (Feist et al., 2016; Jez Wingfield et al., 2008).
    - Structure movements and packing may induce cracking in the junctions between the air barrier and penetrations (eg. carpentry or ductwork and plasterboard) (Chan et al., 2015).
- **External interventions:**
    - Drilling holes into the envelope deteriorates the air barrier system; this occurs during the first years of the life of a building (for kitchen furniture, hoods, wood stoves, etc.) (ADEME, 2016). In (Novák, 2018) the highest increases in air permeability were explained by external interventions affecting the air barrier system.
    - Installation of cables or ductwork after the completion of the building (e.g. rooftop solar panels) (Verbeke and Audenaert, 2020).
- **Specific building materials and construction types:**
    - Uncertain impact of the number of storeys; in (Moujalled et al., 2021) 2-storey houses seem to deteriorate more than 1-storey ones, but this is probably not a predominant factor as according to (Philips et al., 2011) houses generally become leakier than flats
    - Air barriers made of plasterboard seem to deteriorate in average more than air barriers made of polyethylene membrane:
        - The airtightness of houses with polyethene air barriers did not change, but slightly degraded for houses built with the drywall approach in (Proskiw, 1998).
        - Plasterboard-lining as an internal finish can result in very high leakage according to (Johnston and Lowe, 2006) so it is recommended to separate the air barrier function from the plasterboard lining.
        - The airtightness of houses made of concrete blocks (air barrier made by plaster boards) deteriorates more compared to houses made of wood (air barrier made by a membrane) (ADEME, 2016) with, however, heterogeneous results from one house to another.
    - Air barriers made with membranes can also, however, potentially strongly deteriorate: timber frame dwellings showed the largest change in airtightness when compared to plastered masonry (Philips et al., 2011), especially in case of exposed wood frame roofs, which seem to deteriorate more than other roofs according to (Moujalled et al., 2021). The joints between the wooden beams and the plasterboards may be the source of significant leaks, particularly in the case of wood shrinkage.
- **Poor workmanship** (see paragraph 5.1)
- **Unsuitable implementation conditions** for adhesives and mastic such as cold and/or dusty conditions (see paragraph 5.2) (Antonsson, 2015).

In the long-term, it seems that some products do not deteriorate (Feist et al., 2016), however, the durability of assemblies can deteriorate when combining incompatible products. Moreover, Novak has shown that interventions into the building envelope can significantly increase the air permeability unless they are performed with caution on the air barrier system protection (Novák, 2018).

These explanations for short-term ageing are relevant mostly when part of airtightness is made of mastic. When the air barrier is made of a membrane or of plaster on masonry it seems that airtightness durability mostly relies on occupants' behaviour rather than on products (Bracke et al., 2016; Proskiw, 1998).

Airtightness measurement uncertainty (including building preparation) is also a reason for changes observed in air permeability (see paragraph 5.1) (Bracke et al., 2016). When the two tests are not performed by the same person, (Verbeke and Audenaert, 2020) mentioned that biased errors could be caused by commercial entities tempted to be less strict on the guidelines for the initial test.

One can also note that the airtightness durability issue during the first years can hardly be explained by the deterioration of building envelope components. In their extensive literature review on the service life of building envelope elements, Silva and Brito analysed over 100 publications and concluded that apart from painted surfaces with an average of 12 years, no element had an average estimated service life below 20 years (Silva and de Brito, 2021).

3.2.2. Possible factors of airtightness improvment over time

It is interesting to notice that, in many studies, the airtightness of some of the tested dwellings had improved. There are a few explanations, but apart from measurement uncertainty, this could be due to:

- the settlement: the installation of carpets and floor finishes after the original test, the presence of plugs in electrical sockets (Philips et al., 2011)
- the user reducing the air inlets to decrease the heating load (but also the indoor air quality) (Ramos et al., 2013)
- wood expansion with humidity (Moujalled et al., 2021): the airtightness of wood-frame houses with airtightness obtained by an air-vapor barrier tends to stabilise or even improve over the years (possibly due to this factor)

Nevertheless, none of the studies allows to quantify the impact of each factor, both for airtightness decrease and improvement over time, as they just present particular observations. Only the repeatability and reproducibility of airtightness tests is well described in the literature and detailed below.

3.3. Uncertainties in airtightness testing

Part of the differences between test results may not be due to the airtightness change over time but due to test uncertainty. Deviations in airtightness testing are consequent to:

- variations in the testing protocol (including building preparation and testing equipment installation);
- wind and thermal draft impacts;
- measurement device uncertainty;
- seasonal variation of airtightness;
- regression model.

To limit the impact of tester behaviour, many countries have developed qualification schemes for testers and specific standards that describe building preparation among other things (Carrié and Leprince, 2014). However, Bracke et al. (Bracke et al., 2016) noticed that small changes in building preparation, such as locking a door or not, may have an important impact on results when it comes to very airtight buildings. The quality of the Blower Door installation for the test can also be critical, and as an alternative to include leakage of the entrance door, the ventilation system can sometimes be used as a source of air. Also, for terraced houses, depending on where the air barrier is set, the status of openings in adjacent dwellings may have an impact on the measurement result.

Various studies on repeatability and reproducibility have been performed in the last decade from which the following conclusions can be drawn:

- The average air leakage rate has a repeatability standard deviation ranging from 3.5% at 4 Pa to 1.4% at 50 Pa (Delmotte and Laverge, 2011), confirmed by (Bracke et al., 2016; Brennan et al., 2013). The average air leakage rate has a reproducibility standard deviation ranging from 5.9% at 4 Pa to 2.4% at 50 Pa under favourable conditions: no wind and low-temperature difference (Delmotte and Laverge, 2011).
- The repeatability and reproducibility improve when tests are performed both in pressurization and depressurization (Bailly et al., 2012; Delmotte and Laverge, 2011).

The impact of wind on the uncertainty in airtightness testing was discussed in a previous publication (Hurel and Leprince, 2021), with a detailed literature review. Carrié and Leprince (Carrié and Leprince, 2016) concluded that the model error due to the wind on the estimated airflow rate is relatively small at the high-pressure point (12% for wind speeds up to 10 m/s at 50 Pa), but it can become very significant with a low-pressure point (up to 60% at 10 Pa).

Therefore, when estimating airtightness at 4 Pa, wind could be responsible for significant errors (in some cases more than 35%) (Bailly et al., 2012).

In addition to wind, stack effect is another obstacle in having homogeneous pressure differences along the building's envelope for high buildings, inducing errors in the airtightness test results. However, for simplicity, durability tests are usually carried out on single dwellings with a non-significant stack effect.

The seasonal variation of building airtightness is yet a pending question which has led to various publications with heterogeneous results. In Sweden, two very tight wooden structure houses were tested 10% tighter in summer than in winter during 2 years (Wahlgren, 2014). A study from the early 80's reported seasonal variations in the order of up to 100% (Kim, A.K.; Shaw, 1986). This is not confirmed in recent studies and one should note that, as most studies were performed on very airtight buildings, even large variations in percentage represent small absolute airflow rates. Studies of the French (Bailly et al., 2015) and British (ATTMA website) database with average results for each month, show no difference between summer and winter. Nevertheless, these two databases mostly contain houses made of concrete blocks and just a few of wooden structures. The seasonal variation was also studied by (Moujalled et al., 2021) with no significant variation over the year observed. As there are a number of causative factors, like internal moisture generation and ventilation, which affect structural moisture content, additional specific research on a large number of buildings would be needed to further investigate seasonal variation and understand the various factors.

Finally, another significant source of uncertainty is the regression method used to derive the C and n coefficients from the experimental pressure and flowrate measurements. As any model, the regression will in practice always induce an error, more or less significant, depending on the chosen model. Standard ISO 9972 requires the use of a least squares technique without giving further guidance. The ordinary least squares (OLS) method is usually used, but a weighted method of least squares (WLS) such as the weighted line of organic correlation (WLOC), reduces the error (Okuyama and Onishi, 2012) (Kölsch and Walker, 2020), especially for low and high pressures (Prignon et al., 2018), (Delmotte, 2013)

3.4. Recommendations for future field studies

Unfortunately, very few studies have tried to isolate one specific factor to investigate its impact on durability. To go beyond these factors, future field studies should include the following:

- Ideally, measurements should be repeated year after year (and even every few months for the first 2-3 years) on large sample sizes.
- Occupants should be asked to answer to questionnaires to identify drillings made in the air barrier after the first test and leakage detection should be performed to evaluate the consequences of drilling; it is also important to check if air inlets have been reduced (for heating load reduction purposes as observed by Ramos et al. (Ramos et al., 2013)).
- Information about construction details, products used for the air barrier (compatibility of products, whether or not backer rod is used under mastics), the period when the air-barrier was laid out (during the heating period or not), and whether the air-barrier was heated prior to the first test.

Performing- at each measurement- a leakage detection and a visual inspection of visible assemblies of the air barrier with specific care on mastics, also seems to be a reasonable recommendation. However, a thorough leakage detection was done in (Moujalled et al., 2021) and no correlation was found between the evolution of the number of leakages and the evolution of the house airtightness.

Moreover, the following recommendations would help reduce the test result variability due to the testing procedure:

- The same standardized procedure should be followed for each test (for example ISO 9972), including for the calibration of measurement devices.
- A qualified tester shall perform tests; if possible the same tester shall perform the first and the second test.
- The measurement and data analysis methodology should be documented in detail so that repeated measurements can be performed as closely as prior tests, including a precise description of the building preparation (with e.g. locked and unlocked external doors).
- Measurements shall be performed in low wind conditions.
- The airtightness level shall be compared at 50 Pa rather than 4 or 10 Pa.
- The average of pressurisation and depressurisation shall be used for comparison.
- Even if the impact is unclear, for wooden houses, tests shall be performed in the same season.

Additionally, changes in C and n determined through multi-point measurements contribute to the results analysis.

4. Experiments in a controlled environment

Experimental studies compared to on-site studies have the advantage to ease the identification of the specific impact of single factors such as implementation conditions, product use, type of construction, etc. They also allow to perform artificial ageing which is useful for long-term durability tests. There is however a big challenge to achieve a proper accelerated simulation of real natural ageing with various load types.

In this section the different load types for airtightness durability studies are detailed first, followed by a literature review on these ageing tests. A discussion on accelerated ageing in laboratory is presented in Annex 2.

4.1. Loads on the air barrier and equivalent artificial ageing

4.1.1. Pressure loads – mechanical ageing

Pressure due to wind can be estimated using formula (1):

$$p_{wind} = \tfrac{1}{2}.\ \rho.\ Cp.v^2 \qquad (1)$$

With:

- *Cp*: pressure coefficient (-) (up to 0.5 according to EN 16798-7:2017 (CEN/TC156, 2017))
- *v*: wind speed at building level (m/s); it can be calculated from meteorological wind speed data according to ISO 15927-1 (ISO/TC163, 2003)
- *ρ*: air density (kg/m^3)

When the maximum pressure on the air barrier is known, BRE digest 346 part 7 proposes pressure loads to simulate 50 years of mechanical ageing, as illustrated in Figure 3. This is useful to test the durability of the air barrier since it includes both positive/negative pressure cycles (more than 6,400) to simulate fatigue from average wind loads and a test at the maximum pressure load that can be encountered in a 50-year time to test resistance to extreme loads.

Very few studies have been performed to quantify loads on the air barrier. Ackermann (Ackermann, 2012) estimates that 60 to 75% of pressure loads reach the air barrier. The author followed the BRE Digest fatigue test protocol to evaluate the adhesive durability under the mechanical loads due to average and extreme winds. He designed a new appliance with adhesives loaded by weights in a jerk (see Figure 3). Nine adhesive tapes and seven glues were tested, among which three tapes and one glue failed the test. It seems that it is important to test both the pressure cycles and the maximum load since one adhesive passed the first but failed the second test.

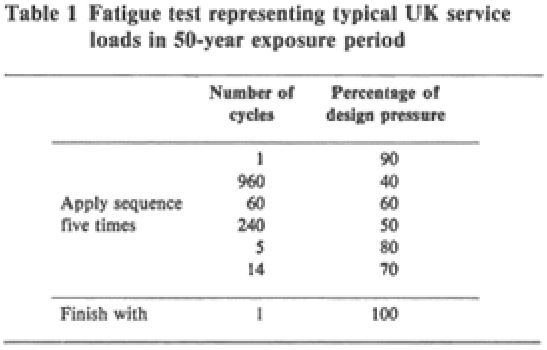

Table 1 Fatigue test representing typical UK service loads in 50-year exposure period

	Number of cycles	Percentage of design pressure
Apply sequence five times	1	90
	960	40
	60	60
	240	50
	5	80
	14	70
Finish with	1	100

Figure 3: BRE Digest protocol for a mechanical ageing test (left) and the corresponding experimental set up of Ackermann (right)

More recently, Fufa et al. (Fufa et al., 2018) also tested the impact of wind loads on the air barrier using two protocols given in Annex B of the standard EN 12211:2000 (for the wind resistance of windows and doors):

- A maximum dynamic pressure of 40 km/h (equivalent to a strong breeze) progressively applied in positive pressure (from the inside) and then in the opposite direction to reach a negative pressure of - 40 km/h.
- A maximum dynamic pressure of 113 km/h (equivalent to a violent storm) progressively applied in positive pressure (from the inside)

They used digital image correlation to measure displacements of wind-barriers' membrane joined by adhesive tapes under wind loads. The results show a limited permanent deformation after the first protocol but a significant one after the second protocol with a deformation and sliding of the tape. They stressed the need for further research on this topic, to increase knowledge on the degradation process and the bounding mechanical properties between tape and substrate. One can also note that only strong pressures were tested, without fatigue simulation with numerous pressure cycles.

4.1.2. Thermal and humidity loads – physical ageing

Many adhesives are composed of polymers. It is known that high temperature and relative humidity are effective in the artificial ageing of polymers (Møller and Hansen, 2017).

The estimation of these thermal and humidity loads is however more difficult than the pressure load and depends on the air barrier position. Table 2 presents whether constraints should be applied on the internal or external air conditions depending on the type and position of the air barrier to test its durability. One can note that internal and external conditions differ from one country to another.

Table 2: Air barrier position and constraints

Type of air barrier	Air barrier position	Constraints
Membrane, adhesives and accessories	External side of the insulation	It depends on its actual position. It may be exposed to high temperature when used in roofing
	Within the insulation thickness (in France the rule of maximum 1/3 of insulation inside air barrier applies)	
	Internal side of the insulation	Internal conditions
Plasters	On masonry with insulation inside	External conditions
	Internal side of the insulation	Internal conditions
Plasterboards, mastic and accessories	Internal side of the insulation	Internal condition

About humidity loads, Lamoulie et al. have studied the resistance of bio-based materials to mould according to climatic conditions (Lamoulie et al., 2015). This is actually a durability test under humidity loads with test conditions that could be applied to air barrier systems as well. According to this study, the usual hygrothermal conditions of the usual roof and wall configurations in France can be classified according to 2 use classes:

1. a dry use class usually lower than 85% RH with laboratory test conditions of 85% RH and 26°C,
2. a wet use class with a usual relative humidity that can be greater than 85% for more than 48 hours with laboratory test conditions of 95% RH and 26°C.

One can note that for assemblies containing a large amount of timber, it is the cycling of humidity that has the greatest effect on growth and shrinkage of the materials. This is however a slow process as it is constrained by the transport of moisture from the core of the timber, mostly through diffusion once out of the capillary transport regime. To simulate this, humidity cycles would need to have a long period.

In order to perform artificial ageing due to temperature variations, the 'time-temperature superposition principle' can be used. For a polymer, the principle is that a translation factor can be found between time and temperature. Therefore, chemical ageing can be performed rapidly by maintaining a polymer at high temperature (below its glass transition temperature), which allows long-term durability test in a short time (Sudarsanan et al., 2020) (Billon, 2021) (Zeggai et al., 2018). This translation factor is often computed using the WLF model[1] or Arrhenius law (Dorléans et al., 2021). However, this factor depends on actual solicitations and materials. It remains unclear for us how it can be applied to an assembly.

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[1] Williams-Landel-Ferry equation

Therefore, some references, such as ASTM D3611-89 and SATAS give strongly inconsistent information regarding the equivalence between artificial and natural ageing as reported by Ackermann (Ackermann, 2012) and illustrated in Table 3. Møller and Hansen have also stated that if it is not possible to make a general correlation between artificial and natural ageing, artificial ageing is the best option for a relative evaluation of the durability (Møller and Hansen, 2017). The glass transition temperature of the products should not be exceeded (Litvak et al., 2019) which is why the maximal safe temperature for accelerated ageing of polymers is considered to be around 60°C to 70°C (Jelle, 2012), but higher temperatures can occur for short periods of time reaching for example up to 90°C under dark coloured roof tiles (Fufa et al., 2018).

Table 3: Correlation between artificial and natural aging compared by Ackermann (Ackermann, 2012)

Artificial aging at 65 °C / 80 % r.F. in days	Natural aging following ASTM D3611-89 in years	Natural aging following SATAS in years
21	10,5	3
40	20	5,7
80	40	11,4
120	60	17,1

4.1.3. Outdoor weathering loads (Irradiation and wetting)

In rather cold climates, the airtightness system is usually on the interior side, sheltered from solar radiation and heavy rains. However, some sealing products such as building joints can also be used on the exterior side of the wall. In rather hot climates the airtightness system is usually placed on the exterior side; durability tests should include in this case ultraviolet (and possibly infrared) irradiation as well as wetting tests.

Fufa et al. (Fufa et al., 2018) underlined that even tapes intended for indoor vapor-barrier application can be affected by solar radiation or wetting during the transportation, storage or construction period. They consider that these products should also be tested under radiation, water spray and freezing conditions.

Finally, as discussed in Annex 2, it is important to perform simultaneous load tests when they interact. A heat load can for example reduce the pressure load resistance (Litvak et al., 2019).

4.2. Review of ageing tests for airtightness durability assessment

4.2.1. Artificial ageing for indoor air barrier components/systems

In addition to the already mentioned studies in paragraph 4.1.1 focusing on wind loads, other accelerated ageing tests were performed with also (or only) temperature and humidity loads. Table 4 summarizes all these existing studies on the artificial ageing of the air barrier or part of it. Only the main results are briefly given but more details about the protocols, results and recommendations for each study are presented in Annex 3.

In addition, there is no standard for airtightness durability tests of wall assemblies in laboratory; a summary of existing standards and regulations around this subject is given in Annex 4. Most of them were cited and/or used in the studies listed in Table 4.

These studies show a wide variety of measurement conditions regarding the type and the size of the tested samples, the applied physical constraints and the ageing criteria. Most studies were performed in the last decade, which shows an increasing concern about the durability issue of sealants.

Table 4: Summary of the artificial ageing studies

Country	Assembly			Size		Constraints				Ageing criteria			Test duration	Ageing Equivalent	Main results	Ref.
	Product alone	2 products	Complete wall	Reduced size	Full size wall	Extreme loads	Cycles	Heat treatment	Details	Visual	Material properties	Airtightness				
Belgium		X		X		X			Water pressurisation			X	45-70 min	?	For the sealing of building penetrations: EPDM gaskets most durable; rigid tapes are the worst	(Bracke et al., 2014)
Belgium			X		X	X	X		Pressure cycles (up to 1000Pa) 20/90% RH (3 cycles of 1 day) -10/70°C (50 cycles of 140 mn)			X	Visual	?	Impact of each load different depending on the kind of air barrier: a general protocol should include them all	(Michaux et al., 2014)
Belgium		X		X			X		15/70°C(6 cycles of 48h) Rain +frost (40 cycles of 6 h) UV+HR (56 cycles of 10 h)			X	8 weeks	?	Low increase in permeability	(Langmans et al., 2015)
Denmark		X		X				X	84 days at 70°C - 90%; then 84 days in a ventilated oven at 70 °C.		X	X	168 days	?	Peel and shear resistance rather improved while the airtightness deteriorated significantly	(Møller and Rasmussen, 2020)
French standard	X			X				X	50°C 70% HR		X		168h	?	•	CSTB, cahier 3710
France			X	X		X	X	X	60°C 50% RH (21h); cycles of pressure load (2h); weathering test (4 points of 24h for 4 seasons); 3 8h pressure cycles (up to 150 Pa); break test (250 Pa, T increasing)	X		X		?	Airtightness only deteriorated by the wind exposure (and break test), and not very significantly: importance of simultaneous loads	(Litvak et al., 2019)
German standard	X			X				X	65°C; 80% RH		X		120 days	?	•	DIN 4108-11:2018
Lithuania	X	X		X			X	X	A: 40°C – 85% B: 48h cycles of multilevel temperature & humidity	X	X		A: 7 days B:40 days	?	Surface type impacts more the tack of adhesive than artificial ageing	(Jucienė and Dobilaitė, 2021)
Norway			X		X		X	X	A: Cycles 1 h of 4 climate exposure conditions (UV & IR, water spray, freezing and ambient conditions) B: 70°C	X	X		A: 2 weeks B: 24 weeks	?	Peel resistance more affected than shear strength; both resistances considerably more dependent on the tape than on the substrate.	(Fufa et al., 2018)
Norway		X		X			X		3 drying and wetting cycles			X	?	?	Strong increase in air permeability after each	(Gullbrekken et al., 2019)

									at 70°C						cycle, (lower when tape applied)	
Sweden			X		X			X	80°C, HR 50%	X		X	1 yr.	50 yr.	No correlation between the durability of the product alone and the assembly airtightness	(Ylmén et al., 2014)
Sweden			X		X		X	X	-150/ 150 Pa (1 cycle) 60°C/ 50%HR			X	7 days	?	One system with significantly reduced airtightness; the other one only slightly reduced	(Antonsson, 2015) (Antonsson and Emanuelsson, 2018)
US (ductwork sealants)		X			X			X	93°C, 84 Pa	X		X	2 yr.	30 yr.	Fabric backed tape with natural rubber adhesives fails more rapidly than all other duct sealants Visual degradation may not be correlated with airtightness decrease	(Sherman and Walker, 2004)

4.2.2. Ageing of outdoor sealing products

As previously mentioned, building airtightness usually relies mostly on an indoor (sheltered) system including an air or vapor barrier sealed with tapes. Theoretically, a perfectly airtight layer on the interior allows poor sealing on the exterior of the wall. However in practice the airtightness systems always include unintended air leakages with consequences on the infiltration airflow rate that will depend on the air permeability level of the other layers of the wall, including the exterior (Hurel et al., 2016).

As a result, even if it is mostly the internal side of the wall that is critical for the building airtightness durability issue, it is also interesting to evaluate the performance of external sealants under artificial ageing. This subject has also very limited literature publications.

Nicastro and Feero (Nicastro and Feero, 2015) tried to simulate typical annual cycles of building joints (about -25% compressed in the summer as the substrates heat up, and +25% extended in colder winter weather) on 184 specimens, combining weathering and movement loads. On average 29% of the specimens failed during the first cycle (from 7% to 55% depending on the sealant type), which shows that airtightness can deteriorate significantly in less than a year.

Ding et al. (Ding and Liu, 2006) have carried out accelerated weathering tests with 80°C heat exposure and 300W UVA radiation on both silicone and polyurethane sealants. They concluded that 5000 h of weathering was necessary to induce changes in sealant properties and that heat ageing had a more prominent effect on the mechanical properties of the sealants but short-wave UV also deteriorates the sealants by breaking chemical bonds.

Field and laboratory measurements (changes in modulus, stiffness, and stress relaxation) were performed by White et al. (White et al., 2009) to assess the impact of independent and combined environmental factors on the durability of building joints. It was observed that “cyclic fatigue, high temperature, or moisture, on sealant mechanical properties acting alone did not degrade the sealant. However, the combination (e.g., cyclic fatigue deformation with temperature and/or moisture) was detrimental, resulting in extensive embrittlement and leading to premature failure. Sealants exposed to field conditions exhibited the same behaviour, indicating that the accelerated test methodology provided an accurate estimation of the durability of sealants exposed outdoors. Similar conclusions about the impact of simultaneous climatic loads on structural sealant glazing systems were outlined by Wallau and Recknagel (Wallau and Recknagel, 2020).

Moreover, in addition to building joints, external weather conditions can also deteriorate building materials such as carbonation of concrete. Several authors have proved the correlation between carbonation rate and air permeability (Etchuya et al., 2020) (Neves et al., 2015), showing that it can also be a problem for the global long-term building airtightness durability.

4.3. Key points for laboratory airtightness durability assessment

Results of laboratory ageing studies differ from one another. One of the reasons may be that the protocol is not standardised. Nevertheless, the following general conclusions can be drawn (Langmans et al., 2015; Michaux et al., 2014; Ylmén et al., 2014):

- **Airtightness durability depends on many factors and further research is needed to better define each impact**:
    - product selection (Antonsson, 2015);
    - compatibility problems between products (Ylmén et al., 2014);
    - implementation conditions including both workmanship (see paragraph 5.15.1) and environmental conditions: temperature, humidity and dust conditions (see paragraph 5.2);
    - type of loads
- **Importance of testing the durability of wall assemblies rather than products alone.** Mechanical resistance tests (peel, shear, …) of specific products are often used to evaluate the ageing impact on adhesive tapes (Fufa et al., 2018; Jucienė and Dobilaitė, 2021). They seem however not to be relevant to evaluate the airtightness durability of wall assemblies (Ylmén et al., 2014), especially with implementation conditions for standardised mechanical resistance tests that could be too far from on-site conditions (Møller and Rasmussen, 2020).
- **All load types should be included in the protocol**. The impact of various constraints (extreme temperature, humidity or pressure) is different depending on the air barrier type, with plasters sensitive to humidity and temperature (cracks appeared when the plaster was too thin) and membranes sensitive to pressure variation (due to staples) (Michaux et al., 2014).
- **Necessity to test simultaneous loads**. This would be more representative of reality (see Annex 2), and is necessary since for example the required temperature to induce significant wall airtightness deteriorations is lower when a pressure load is applied simultaneously (Litvak et al., 2019)
- **A general standardised procedure to test the airtightness durability of wall assemblies through artificial ageing is missing** (Ylmén et al., 2014). The only existing standard on the durability of airtightness components in buildings focuses on adhesive tapes with the ageing impact evaluated through peeling tests (DIN 4108-11) (Stefan Hückstädt, 2019)
- **The ageing strategy has to be consistent with real solicitation of products**. The strategy may differ for an exterior, interior or embedded air barrier (Fufa et al., 2018).

The findings of laboratory tests are difficult to relate to the findings of field studies as field studies do not provide:

- enough information on construction products and implementation of the air barrier;
- information to quantify the impact of each parameter (measurement uncertainty, occupant behaviour, ageing, etc.) on airtightness change.

4.4. Recommendations for future laboratory studies

Some of the studies presented in paragraph 4.2.14.2.1, provide recommendations on how to improve the test protocol and can be useful for anyone willing to perform further experimental studies in laboratory on this airtightness durability issue:

- **Wait at least 24 hours after the tightening of the wall before the first tests.** This should prevent the release of tension in the joint during the ageing that could interfere with the durability evaluation (Møller and Rasmussen, 2020)
- **Use inert materials as sample holders,** to avoid wood expansion affecting the air permeability. If not possible, at least an initial measurement should be performed under saturated humidity conditions (Litvak et al., 2019)
- **Limit the duration of outdoor climate exposure tests for tapes intended for indoor application.** For durability tests simulating the potential maximum outdoor climate exposure during the construction period, the laboratory exposure time can be decreased from 2 weeks to 3 days for vapor barrier tapes (indoor application). In practice, they should indeed not be exposed to solar radiation and moisture during the construction but exposure is still possible during the transportation, storage and/or installation (Fufa et al., 2018)
- **Intensify the wind exposure test.** Increase the duration to at least 1000h, with higher pressures representing more stressing conditions compared to urban areas (Litvak et al., 2019)

- **Perform more airtightness durability tests on various surfaces (like wood)** to confirm the significant airtightness deterioration (Møller and Rasmussen, 2020)
- For standardized mechanical resistance tests **limit the number of substrates to one hard substrate** (as they all give similar results) **and the intended flexible membrane** (vapor barrier or wind barrier) (Fufa et al., 2018)
- To perform not only mechanical tests but also **evaluate the chemical properties**, with the use e.g. of Fourier- transform infrared spectroscopy (FTIR) or scanning electron microscope (SEM). (Fufa et al., 2018)

5. Implementation conditions impact

Both on-site and laboratory studies have underlined the importance of workmanship and ambient implementation conditions on the durability performance of building products/systems. To further investigate the impact of this construction phase, a special focus on this issue is presented in this chapter.

5.1. Workmanship

Many studies around the world have pointed out the significant impact of human factor in the building’s airtightness performance, both during the construction phase and the pressurization test.

Prignon and Van Moeseke (Prignon and Van Moeseke, 2017) gave a brief literature review regarding the impact of the design target, the supervision & workmanship, and feedback & guidance, with a general agreement that these aspects influence the airtightness performance.

In particular, the following parameters can impact the initial airtightness test results and the airtightness durability:

- **Workmanship quality and reproducibility**

In Netherlands Colijn et al. (Colijn et al., 2017) showed the influence of workmanship quality on the airtightness of dwellings. They noted differences in performance among building crews for 44 similar detached houses. The application of minor technical solutions and educational sessions allowed to reduce the specific air leakage rate of 14 houses by 27%.

In the Czech Republic the analysis of 558 tests on newly built houses between 2006 and 2019 showed large differences in the airtightness performance for identical types of houses built with the same technology and by the same construction company (Böhm et al., 2021). The authors concluded that the most important parameter influencing the resulting airtightness values was the control of the implementation of individual building details during the construction of a building.

Some studies at a smaller scale focus on the impact of workmanship on the airtightness performance of specific construction details. For example, in Norway Relander et al. studied the influence of widely used lightweight aggregate concrete element chimneys on the airtightness level of houses (Relander et al., 2010). They pointed out that the airtightness provided by the surface treatment was very sensitive to workmanship and that a thorough workmanship could make this influence negligible.

- **Airtightness tests reproducibility and repeatability**

Bracke et al. (Bracke et al., 2016) investigated the reproducibility and the repeatability of the pressurization test in extremely airtight houses. As a matter of fact, in addition to the workmanship quality during the construction phase, the human factor also impacts the airtightness test results even if the same protocol is followed. Concerning the reproducibility, with special attention to airtightness, they could obtain a variance coefficient of 12% on 15 quasi-identical houses, which is much lower than the 28% of a previous similar study of 29 houses with no special attention to airtightness (Laverge et al., 2014). They noted however that even with special efforts, the improved reproducibility of the workmanship is still far below that of the airtightness test itself. To investigate the repeatability issue on the pressurization test, 2 houses were tested up to 10 times a day, for 6 and 7 different days. On average, the measurements showed a standard deviation of 2.7% and 1.1% and a maximum variation within the same day of 7.7% and 3.5% respectively, which is in agreement with other literature results. Additional tests were performed to evaluate the impact of small preparation details such as locking doors (without neglecting standard EN 13829) and it was concluded that apparently small decisions can be determinative for passing the test for passive houses. This underlines the necessity of having the same operator testing all houses when studying other aspects such as the airtightness durability.

- **Last minute corrections**

Concerning the airtightness test phase, last-minute corrections can also impact the airtightness durability. Wingfield et al. pointed out that secondary sealing may have benefits in the short-term to pass the airtightness test but is prone to degradation over a relatively short time and is therefore not a robust long-term solution (J. Wingfield et al., 2008). The study was performed on 5 houses only, but drying, shrinkage and cracking were observed on-site, with silicone sealants having a limited movement tolerance for the typical deformation and cracking and several adhesive failures probably due to dusty surfaces prior to application. The authors also discuss the workmanship during the construction phase and stress that it is often the “context in which trades have to work, the lack of specific training, the buildability of designs, the lack of detailed design and the lack of a general quality control process that underlie many workmanship problems”.

- **Compatibility of products with implementation conditions**

Finally, laboratory studies such as (Fufa et al., 2018) have also underlined the importance of the surface condition for the adhesion performance with the necessity of a good adequation between the intended and actual tape use, and a special treatment of the substrate when required. Van Linden and Van Des Bossche tested 18 sealing materials and also stressed the importance following the manufacturers recommendations, attesting that faulty workmanship has a significantly greater impact on the material performance than artificial ageing (Van Linden and Van Den Bossche, 2020). Concerning building joints submitted to external environment, Nečasová et al. also noted the necessity to verify the compatibility of materials and to follow the recommendations since “in most tested cases, diversion from the above-given steps resulted in failure of the sealed joint” (Nečasová et al., 2017).

5.2. Temperature, humidity and dust conditions

Experimental studies on the impact of implementation conditions on the airtightness performance are limited.

One interesting study on this topic was carried out by Antonsson and Emanuelsson (Antonsson and Emanuelsson, 2018). They studied the durability of three airtightness systems with air permeability measurements before and after the artificial ageing for three implementation conditions:

- Ideal conditions: normal indoor laboratory climate
- Cold and humid environment: about 5°C and 90-95% RH on both sides of the wall
- Dusty conditions: artificial dust (made of crushed concrete sieved to a grain size of max. 0.063 mm, gypsum and wood sawdust) sprayed against the plastic foil

The three walls are about 3m high and 3m long, wooden frame with a window, ventilation and electrical pipes. They are similar but with sealing products from various manufacturers (not identified). The artificial ageing was done through heat treatment with 7 days under a temperature of 60°C for system 1 and 3 and 70°C for system 2 and a RH of 50%. The authors estimate that it is the equivalent of respectively 25 and 50 years of natural ageing.

The results presented in Figure 4 are strongly depending on the tested airtightness system:

- For the products of manufacturer 1, the airtightness level of the wall before the ageing is similar for the three implementation conditions and decrease significantly after ageing under cold, humid and dusty conditions; this is not the case for the ideal implementation conditions. This means that the temperature, relative humidity and dust can have an effect on the airtightness durability without impacting the initial permeability level.
- For the products of manufacturer 2 which are initially the most airtight, the implementation conditions do not significantly affect the durability of the airtightness, but the initial air permeability level is significantly higher for the implementation under cold and humid conditions
- For the products of manufacturer 3, the implementation conditions significantly impact both the initial airtightness level, and the one after ageing.
- For the three sets of products, the cold and humid environment during the implementation has a bigger impact on the airtightness than dusty conditions

In conclusion, depending on the set of products used for the sealing of the wall, the implementation conditions can more or less impact the initial airtightness level and its durability.

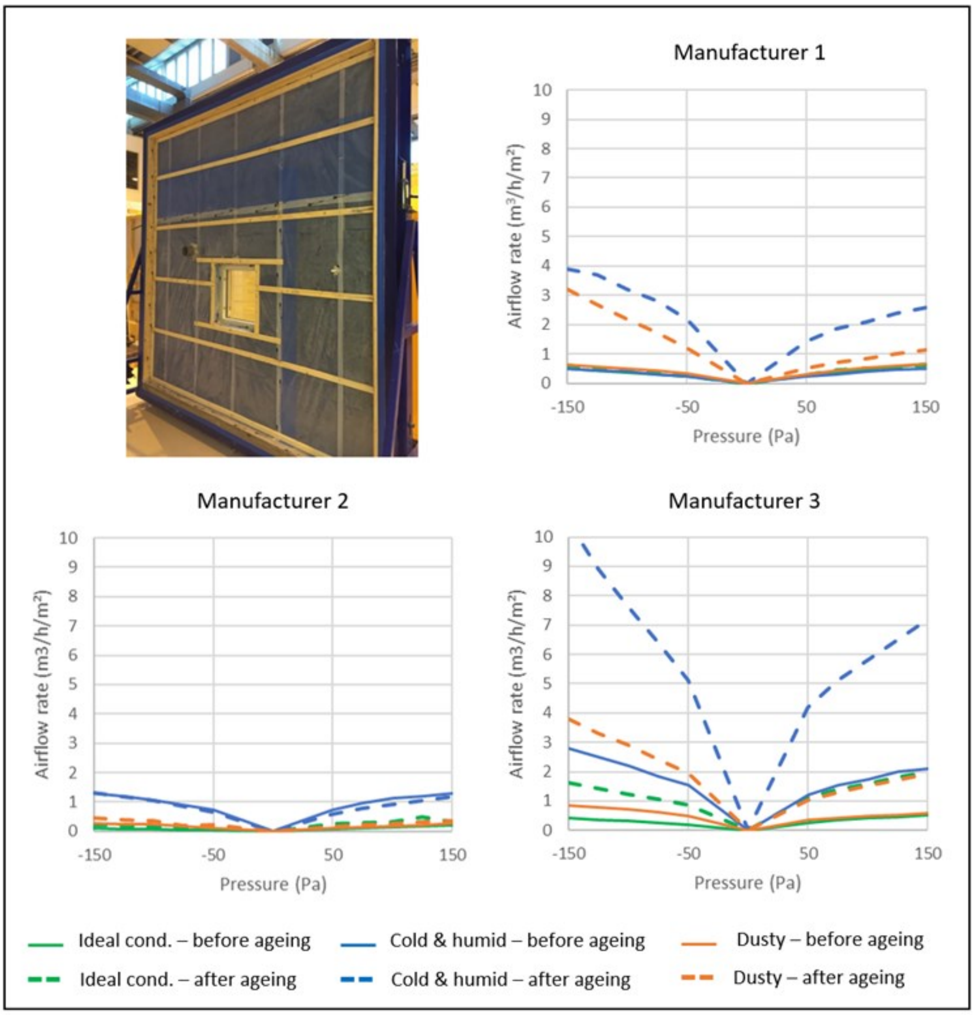

Figure 4: Results of the airtightness tests on 3 different sets of products from various manufacturers depending on the implementation conditions - data from (Antonsson and Emanuelsson, 2018)

As regards sealing implementation under dusty conditions, in their above mentioned study Wingfield et al. (J. Wingfield et al., 2008) also observed onsite that dust prior to application was often the reason behind the adhesive failure of the sealant. Fufa et al. (Fufa et al., 2018) also underlined the necessity of having a surface dry, free from dust and grease for a good adhesion. They noted as well that “adhesive tapes become hard and glassy with decreasing temperatures and higher temperatures make the adhesive stickier and reduce the adhesive’s strength. Thus, tapes should not be stored and/or applied to too cold or too warm temperatures. Special adhesive tapes designed for extreme temperatures can be used for very high or low temperature applications”. As part of their protocol they mentioned that the tested tapes were preconditioned at a temperature of 23°C and a relative humidity of 50% for 48 hours before being applied to the tested substrate.

Concerning the initial moisture content (MC) in wood products, Kukk et al. tested in laboratory 12 cross-laminated timber (CLT) insulated panels with two different initial MC: 13% and 26% (Kukk et al., 2021). They concluded that a low MC (about 13%) allows to consider the 5-layer CLT panels as an airtight layer, but on the other hand, a high initial MC significantly weakens the airtightness of the exterior wall. The higher the initial MC, the greater the shrinkage of the CLT lamination and the greater the cracks between laminations, inducing greater air leakages. These results are in accordance with Skogstad et al. who found that a dry-out of 15%-10% from the initial MC could increase the air leakage rate of the CLT panels by up to 10 times (Skogstad et al., 2011). As a result, special attention should be given during the construction phase to avoid increasing the MC of wood products, e.g. by applying a liquid coating on mass timber panels.

6. Conclusions

The analysis of 14 field studies from 8 countries shows that building airtightness is not robust and tends to deteriorate during the first years after completion before stabilizing. Nevertheless, there is a wide variability in results. The main key factors explaining the airtightness deterioration over time are the building's natural movement, external interventions, specific building materials and construction types, poor workmanship and unsuitable implementation conditions.

For future studies, special attention is needed on uncertainties in airtightness testing, due to variations in the testing protocol, wind and thermal draft, measurement uncertainty, regression model, etc. The main recommendations to avoid that the results are biased include:

- A qualified tester shall perform the tests, ideally the same tester for all tests, and the measurement (including building preparation) and data analysis methodology should be documented in detail.
- Measurements shall be performed with calibrated devices, in low wind conditions, in the same season for wooden houses.
- Airtightness shall be compared with average values of pressurisation and depressurisation results and at 50 Pa rather than 4 or 10 Pa, but multi-point measurements can be made to determine changes in C and n.

Moreover, to investigate the reasons of airtightness changes over time, it is suggested to repeat measurements year after year (and even every few months for the first 2-3 years) on large sample sizes. Detailed information should also be collected about the potential drilling made in the air barrier between measurements and on construction details such as the products used for the air-barrier, when the air-barrier was applied, and whether the air-barrier has been heated prior to the first test.

Regarding laboratory ageing tests, the analysis of 13 studies from 8 countries outlined the following points:

- A general standardised procedure to test the airtightness durability of wall assemblies through artificial ageing is missing.
- It seems difficult to define an accelerated ageing protocol that would be equivalent to a certain number of years of natural ageing.
- The airtightness durability depends on many factors (such as the product selection, compatibility problems, implementation conditions and type of loads) and further research is needed to better define each impact.
- It is important to test the durability of wall assemblies rather than products alone.
- All load types should be included in the protocol.
- It is necessary to test simultaneous loads.
- A general standardised procedure to test the airtightness durability of wall assemblies through artificial ageing is missing.

Recommendations from literature for future laboratory studies are listed, including waiting at least 24 hours after the tightening of wall before the first test and use inert materials as sample holders.

Eventually the literature review stresses the importance of implementation conditions on the airtightness durability, including workmanship and temperature, humidity and dust conditions. This issue should be studied both on-site through measurement campaigns during the construction phase and in laboratory.

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Annex 1: Details of the field measurement studies

In the US, Chan et al. (Chan et al., 2015) noticed that air leakage increased by 15% on average in the new built homes while no increase in the air leakage was observed in the weatherized homes. It was noted that for the weatherized homes, the joints between building components that were sealed, do not change their leakage characteristics with time. In new build homes, the moist wood materials may have shrunk over the first several years, potentially causing leaks in the building envelope.

In Belgium, Bracke et al have tested the durability of 15 nearly identical houses built by the same craftsmen with the same products (air barrier done by plaster on the masonry) (Bracke et al., 2016). However, ageing results vary from -3% to +120%; therefore, in this case, the main impact is probably not due to the ageing of products but to other factors such as the difference in building preparation and measurement uncertainty. Even more recently, Verbeke and Audenaert measured an averaged increase of 38% in air permeability but with some dwellings that became more airtight (Verbeke and Audenaert, 2020). The initial values were however low (median n50 of 0.48), so the variations were often rather limited in absolute terms. A slight tendency for increased permeability with increased time interval was noted but with no relevant regression found. Infrared thermography and fog dispenser were used to identify additional leaks, which were mostly found at windows or doors (improper air sealing or slight deformations) and cables or ductwork installed after completion of the dwelling. It was also pointed out that the two tests were not performed by the same people, which could induce biased errors with commercial entities who could have been tempted to be less strict on the guidelines for the initial test.

In the Swedish study (Hansén and Ylmén, 2012), conclusions were difficult to draw as the air leakage increased for half of the tested houses (up to 6 times) and decreased for the other half. This was correlated neither with changes made in the construction nor with the year of construction.

In Canada, Proskiw (Proskiw, 1998) concluded that performance of polyethene air barriers was unchanged over 8 to 11 years. Although three houses became leakier, the leakage detection showed that leakages were not occurring at locations associated with the polyethene portion of the air barrier. Conversely, houses built with the drywall approach degraded slightly over the 11-year monitoring period but there is no evidence that it was due to this approach.

In France (ADEME, 2016), a case study of 30 tested houses showed that the permeability of houses made of concrete blocks (air barrier made by plaster boards) deteriorates more compared to houses made of wood (air barrier made by a membrane). However, results were heterogeneous from one house to another. In this study, an important work was performed to compare leakage locations before and after a few years. It was observed that leakages were mainly located at:

- penetrations of the air barrier;
- electrical appliances;
- new non-airtight appliances (hood, recessed lighting, etc.).

Another on-site study from the project Durabilit'air 1 (Moujalled et al., 2021) focused both on mid-term (with 30 dwellings tested once per year the first 3 years) and long-term (31 dwellings tested after 3 – 10 years) changes in building airtightness. These two campaigns gave a similar mean increase of permeability with 18% for the mid-term (on the first year, a stabilisation is observed afterwards) and 20% for the long term. From these results it seems that the first year of the building's service is the most critical for the airtightness deterioration. A smoking device was used to detect leakages, but if the number of leakages increased with time, no correlation was found with the increase of air leakage rates. The author pointed out 3 factors that could explain the airtightness deterioration:

- number of storeys: 2-storey houses seem to deteriorate more than 1-storey ones which is maybe due to more substantial foundation settlement, and to the first-floor support beams penetrating the inner skin of the building envelope thereby providing additional leakage pathways.
- roof type: the airtightness of houses with exposed wood frame roofs seems to deteriorate more than other roofs. The joints between the wooden beams and the plasterboards may be the source of significant leaks, particularly in the case of wood shrinkage.
- building material type and air-barrier: it seems that the airtightness of wood-frame houses with airtightness obtained by an air-vapour barrier tends to stabilise or even improve over the years. A possible explanation given by the authors is that for these specific cases and climate there might have been a wood expansion

with humidity.

In Germany, airtightness measurements from the Fraunhofer Institute for Building Physics showed an average increase in air permeability of 24% (from 0.37 h-1 to 0.46 h-1), but with 26 houses out of 31 (83%) still meeting the passive requirement of 0.6 ACH (Erhorn-Kluttig et al., 2009). Feist et al from the Passive House Institute performed advanced leakage detection on the air barrier (made with plaster boards) (Feist et al., 2016). They concluded that only windows and doors gaskets (on the openings) deteriorated, so they were changed for the new test. In this study, the acrylic mastics, set on a backer rod, did not deteriorate at all. As part of another study from the same institute, 17 buildings with various types of constructions and airtight layers were re-measured 1 to 10 years after the initial airtightness test (Peper et al., 2017). Unlike most of the other on-site studies, it was concluded that the airtightness is durable, with changes almost always within measuring accuracy.

In the UK, Philips et al showed on a 23 dwelling sample study that the air permeability of two-thirds of the dwellings tested had increased while the air permeability of the remaining third had decreased (Philips et al., 2011). They observed that:

- Houses generally became leakier than the flats.
- Timber frame dwellings showed the largest change in airtightness compared to plastered masonry.
- Six of the eight results that achieved a performance improvement were heated with electric panels rather than a gas and radiator (may be due to the reduced number of service penetrations).

In another UK study where 5 houses were tested before and few weeks after heating, the air permeability of one of them increased by 30% because of the shrinkage of mastics that appeared when the house was heated for the first time (Jez Wingfield et al., 2008).

Conversely to the airtightness deterioration measurement, another British study focused on the impact of refurbishment on the airtightness improvement (Johnston and Lowe, 2006). The air permeability of the 12 tested dwellings built in the early 1970s was reduced by 55%. They noted that the use of a type of plasterboard-lining (masonry with glue dabs holding the plasterboard) as an internal finish can result in very high leakage rates when it deteriorates and advised to separate the air barrier function from the plasterboard lining to provide a more reliable and probably more durable solution.

In the Czech Republic, a study from Novák (Novák, 2018) focused on the airtightness evolution for 4 similar passive houses with limited uncertainties: all the tests were performed by the same people, with the same equipment, following the same protocol, mostly under the same climatic conditions. The buildings A and B were tested at the commissioning, 3 years after and then each 2 years or even each year while the buildings C and D were tested only twice, at the commissioning and 11 years later. It was found that the air permeability increased significantly in all buildings, mainly during the first years; e.g. building B increased from 0.5 to 0.65 ACH during the first 3 years and from 0.65 to 0.7 ACH during the next 7 years. Information collected on external interventions allowed to explain the highest increases (+137% and +103%) on building C & D compared to buildings A & B (+35%) and to underline the importance of the air barrier system that needs to be designed and executed carefully but also protected during the building’s life (from users and external interventions).

Annex 2: Discussion on accelerated ageing

The reproducibility issue

A good reproducibility is required for a protocol to be used in the context of certification.

Most of the projects have not tested the reproducibility of their protocols. A major limitation of testing a whole scale 1:1 system is the reproducibility of the protocol as:

- The quality of implementation may have an important impact on product results.
- It is too expensive to test several times the same system and use the average as the result.

Therefore, the bigger the assembly (large with many products) the more difficult it is to guarantee the reproducibility of the test.

The simultaneous load issue

In most studies, the impact of wind load and heat load are tested one after the other; it seems appropriate for estimating the impact of each load separately. However, for thermoplastic products that may undergo temperature over their glass transition temperatures (such as adhesive located under the roof), it seems interesting to characterize the behaviour of products/systems subjected to the following cycle:

- simultaneous heating over glass transition temperature and wind load;
- cooling under glass transition temperature with wind load.

This will allow to check if the plastic deformation under mechanical constraint has an impact or not on the performance of the system. If the heat treatment is done over the glass transition temperature without a wind load, the product could soften during the treatment but get back to its initial state when cooled (reversible phenomenon). However, if the sample is pressurised during the heat treatment and then cooled according to the cycle proposed above, the product could remain distorted when cooled which may have an impact on its airtightness.

This was done by (Litvak et al., 2019) with a “break test” where the tested wall was pressurised at 250 Pa and the temperature was increased until significant airtightness deterioration. For one wall, staples were detached at 60°C while the airtightness was not affected at this temperature without the pressure load (see Annex 2).

Practical limitations of an approach to these simultaneous loads include:

- the maximum pressure the air barrier may undergo simultaneously with the maximum temperature is unknown;
- it complicates the test apparatus and procedure.

Ageing issue

Most studies only include a heat treatment which is not an ageing protocol (they do not pretend to be equivalent to a certain number of years).

Defining a chemical ageing protocol may be an objective to simulate realistic service lifetimes, for example, by using the Arrhenius law based on the fact that chemical reactions are accelerated at high temperatures.

However, we are unsure if Arrhenius laws are applicable and yield the same equivalent ageing for all materials (thermosetting plastics, elastomer and thermoplastics). For thermoplastics, it is important not to pass the glass transition temperature to avoid irreversible changes that would not occur in 'real-life'.

Moreover, chemical ageing is not suitable to account for physical ageing (induced by humidity variations) and mechanical ageing (induced by pressure variations) and it is unclear whether chemical, mechanical or physical ageing predominates when it comes to airtightness products.

To consider mechanical ageing equivalent to 50 years, probably wind cycles should also be implemented.

Overall, it seems impossible to develop a protocol that could guarantee to be equivalent to a 50-year ageing for every product. Even if a protocol could reproduce "real" constraints (in terms of intensity and number), according to the location and the kind of building, the equivalent age would be different. It is more relevant to develop a protocol with realistic constraints that aims at comparing the performance of products' assemblies.

Steps to develop a protocol

Error! Reference source not found. Table 5 summarizes the pros and cons of various options for a protocol.

Table 5: Pros and cons of various options to define a protocol

		Pros	Cons
Type of assembly:	**Product alone**	Simple	No correlation between ageing of products and ageing of assemblies
	Simple assembly (with 2 products)	Product implemented	(1) Impact of implementation (2) Interaction between products
	Complete wall	Product implemented	(1) Interaction between products (2) Impact of implementation => Reproducibility? (3) Cost of experimental setup
Assembly size:	**Full-size wall**	More representative	Cost of experimental setup
	Reduced size	Lower cost (use of an existing stove, etc.)	(1) Longest samples do not react as shortest (proved for adhesives by (Antonsson, 2015)) (2) May be difficult to measure very low flow rates
Type of constraints:	**Extreme load**	Guarantee resistance at normal constraints	Not representative of actual constraints, products not made to resist
	Accelerated cycles	Representative	(1) Apart from pressure load, difficult to define cycles (2) Takes long
	Heat and humidity treatment (chemical ageing)	Stoves already exist	Equivalent ageing difficult to determine
Procedure for applying constraints	**Simultaneously**	More representative	(1) Difficult to estimate the impact of each (2) Complexify the apparatus
	One after the other	Impact of each	Impact of reversible phenomena not seen
Criteria for Ageing evaluation:	**Visual**	Simple, easy to communicate	(1) Subjective (2) No correlation with airtightness
	Properties of material	Standards exit	No straight correlation with airtightness

Obviously, there is still a lack of knowledge to develop a test protocol and facility to characterise the performance of an air barrier system over time, but there are important steps to underline in such investigations:

1. Design the testing facility considering that:
    (a) reduced scales may not be representative,
    (b) tests have to be repeatable and reproducible.
2. Define implementation conditions (temperature, relative humidity, dusty area, etc.).
3. Specify the loads on clear bases and considering:
    (a) worst conditions the air barrier undergoes in the field (maximum and minimum temperature, relative humidity and pressure);
    (b) preliminary tests to evaluate which impact between steady worst condition or cycling prevails.
4. Consider preconditioning samples focusing on the comparison of products, not on actual ageing. Ageing laws for chemical ageing can be considered bearing in mind that these are applicable to specific product families and reversible effects. The influence of wind cycle loads on mechanical ageing still needs to be investigated.
5. Implement small-scale preliminary tests to evaluate the feasibility and results. One should keep in mind that product characteristics (e.g. tape) can vary a lot depending on the sample size (e.g. performance of tape can be good on a 50-cm but bad on a 3-m facility).

Annex 3: Details of the laboratory measurement studies

Sherman and Walker tested the durability of ductwork sealants (by maintaining the assembly at 93° and 84 Pa during 2 years) (Sherman and Walker, 2004). They found that the "fabric backed tape with natural rubber adhesives fails more rapidly than all other duct sealants". They also noticed that visual degradation may not be correlated with airtightness decrease.

Langmans et al. tested the durability of taped joints in an exterior air barrier. The joints were exposed to temperature cycles, humidity, ice, UV and the study concluded that the increase in permeability was low (Langmans et al., 2015).

Michaux et al., tested more than 50 buildings walls under pressure, humidity and temperature variations (Michaux et al., 2014). The impact of each solicitation was different depending on the kind of air barrier: plasters were sensitive to humidity and temperature (cracks appeared when the plaster was too thin) while membranes were sensitive to pressure variation (due to staples). Therefore, if one wants to define a protocol that would apply to all kind of air barriers, all type of constraints shall be included in the protocol.

RISE (former SP, Technical Research Institute of Sweden) (Ylmén et al., 2014) tested both products properties alone and products assemblies implemented in a cell. They observed no correlation between the durability of the product alone (in terms of pealing, etc.) and the durability of the assembly airtightness. According to the research team involved, this was due to:

- compatibility problems between film and tapes,
- the difference in the results for smaller and full-scale specimens,
- air channel appearing during the heat treatment.

Therefore, they concluded that it was required to develop durability tests of the complete airtightness systems on full-scale set-up.

According to the results of this 1st research project, researchers from RISE decided to test products implemented at full-scale wall constructed on a steel frame of 3m*3m (Antonsson, 2015). They applied heat treatment (60°C, 1 week) and pressure load (-150/+150 Pa) on the sample with a climatic chamber and a pressurisation device docked on the wall (not simultaneously). Two systems were tested with this protocol and significant deviations were observed in the results. With the first system, a significant change in air leakage was observed after the heat treatment, while with the second system very little change was observed.

Juciene and Dobilaite published a study on the impact of climatic effects and various surfaces on the tack of adhesive tapes (Jucienė and Dobilaitė, 2021). A total of 16 adhesive tapes were tested on 6 surfaces with the impact of artificial ageing evaluated through the measurement of both the thickness change (according to EN 1942) and the tack (with a rolling ball test). A humidity ageing consisting of 7 days under 85% RH and 40°C was performed on three tapes, with no significant impact on the adhesive thickness but with wrinkles on the protective film of one of them that could question airtightness durability. Another artificial ageing was performed on all tapes. It was chosen to be representative of Eastern European climate and consisted of 48h cycles of multilevel temperature (ranging from -10°C to 50°C) and humidity (ranging from 15% to about 100%), repeated 20 times. The results showed that artificial ageing did not affect the thickness of any adhesive tape, and in most cases it did not affect the tack either. On the other hand, it was pointed out that the surface has a significant effect on the tack of the adhesive with best results on plywood, OSB and cement bonded particle boards, and worst results on plaster.

Moller and Rasmussen tested the joints durability of nine different air and vapor barriers with their compatible sealants (Møller and Rasmussen, 2020). Both the joints between 2 membranes and between a membrane and aerated concrete were tested through three measurements before and after artificial ageing (84 days at 70°C and 90% RH followed by 84 days in a ventilated oven at 70 °C):

- Peel resistance according to EN 12316-2: 2013 (ideal implementation conditions)
- Shear resistance according to EN 12317-2:2010 (ideal implementation conditions)
- Airtightness (non-standardized method detailed in (Møller and Hansen, 2017), designed to simulate realistic conditions)

This study gave interesting results as the peel and shear resistance surprisingly rather improved after the artificial ageing, while the airtightness deteriorated significantly with airflows about 2 to 3 times higher as shown in Figure 5. The authors were questioning whether the standardized mechanical resistance tests were relevant, since implementation conditions were possibly too far from on-site conditions. On the other hand, the airtightness test method gave results in accordance with the practitioners' observations which seem to be reproductive. The authors recommended to perform more tests on other surfaces like wood and to wait at least 24h after the tightening before the first tests to avoid a release of tension in the joint during the ageing that could interfere with the durability evaluation.

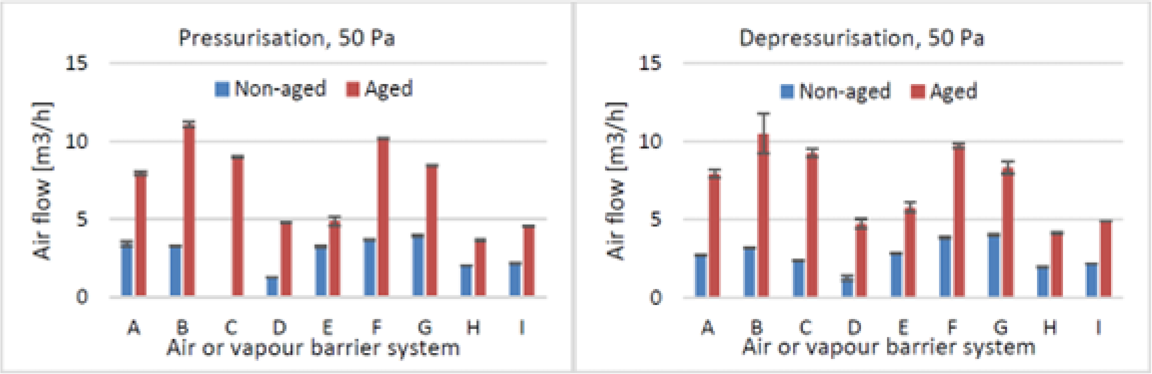

Figure 5: Air permeability measurements on 9 airtightness systems before and after artificial ageing (Møller and Rasmussen, 2020)

Gullbrekken et al. (Gullbrekken et al., 2019) studied the airtightness durability of clamped joints under drying and wetting cycles, a traditional sealing technique used in Norway. Three samples of reduced scale (to limit wetting time) wood studs with a vapor barrier were tested under three cycles of moisture content oscillating between about 7% and 14% (values found by a numerical simulation to be representative of real conditions). The results showed that despite a very low initial air permeability, the airtightness decreased significantly with the first drying due to the shrinkage of the wood. Wetting had, on the contrary, a slightly improvement effect on the airtightness due to the swelling of the wood, but overall, the air permeability increased significantly at each cycle due to these movements inducing an increased stress on the joint of the screw and wood. The author concluded that the use of adhesive tape is probably a more robust solution but noted that it is not possible to observe the failure of these products, or to replace them and that there is a need for standards or guidelines to help verify their durability over the expected service life of a building.

Fufa et al. (Fufa et al., 2018) also tested the durability of 4 adhesives for both indoor and outdoor applications on 7 types of substrates with two test series- A & B (either performed one after the other or Test series B alone):

A) 2 weeks with in turns 1h exposure of 4 climate conditions: UV and IR irradiations (black panel temperature of 63 °C), water spray (15 dm^3/(m^{2}h)), freezing (-20 °C) and ambient laboratory condition. The aim was to simulate the potential maximum outdoor climate exposure during the construction period
B) 24 weeks at 70°C (according to NS-EN 1296) to simulate the ageing during the building service life

The tapes performance was evaluated with both the peel and shear resistance test methods. Test series A significantly affected the peel and shear resistance of vapor barrier tape joints while test series B affected only the peel resistance. The peel resistance was also more significantly affected for wind barrier tapes. For further research on tapes durability the authors suggested:

- To limit exposure of phase A) to 3 days for vapor barrier tapes (indoor application) as they should not be exposed to solar radiation and moisture during the construction but exposure is still possible during the transportation, storage and/or installation.
- To limit the number of substrates to one hard substrate (as they all gave similar results) and the intended flexible membrane (vapor barrier or wind barrier)
- to perform not only mechanical tests but also evaluate the chemical properties, with the use for example of the Fourier transform infrared spectroscopy (FTIR) or a scanning electron microscope (SEM).

The results of this study are included in a paper presenting data from 10 years of adhesive tapes testing at SINTEF on more than 30 tapes and a variety of substrates (Sletnes and Frank, 2020). Conclusions confirm that peel resistance is a more affected by artificial ageing than shear strength and that both resistances are considerably more dependent on the tape than on the substrate. This was published as part of an ongoing TightVent project (2019-2023) aiming at developing robust test and evaluation methodology for adhesive durability.

In France, as part of the Durabilit'air 1 project, an experimental set-up for 1m² walls (see Figure 6) as well as a protocol were developed to test the airtightness durability under 4 cycles simulating various load types:

1) Thermal creep test: 60 °C and 50% RH for 21h
2) Weathering test with a cycle of 4 conditions representing the 4 seasons lasting 24h each: -10°C; 15°C and 60% RH; 30°C and 45% RH; 5°C (followed by a stabilization time of 12h before measurement)
3) Wind exposure: 3 cycles of 8 hours with pressure ranging from -150 Pa to 150 Pa
4) Break test: temperature increasing until significant increase of air flowrate at 250 Pa

This protocol was tested on 3 types of assembled products for the joints between windows and walls:

- expensive weather seal foam: turned out too porous to be tested;
- sealant (mastic) with backing foam: first 2 cycles improved airtightness (probably due to the expansion of the wood frame with moisture saturation), cycle 3 slightly decreased the airtightness, and a rupture during cycle 4 at 120°C with cracks formation observed
- adhesive and membrane system: no significant airtightness changes for the first 3 cycles; rupture after 40 min at 60°C with detached staples (probably due to the interaction between heating and pressure loads since cycle 1 had previously not affected the airtightness with heating load only)

The author gave the following main recommendations to improve the protocol for further research:

- use inert materials as sample holders to avoid wood expansion affecting the air permeability (or at least an initial measurement under saturated humidity conditions)
- increase the duration of cycle 3 to at least 1000h, with higher pressure to represent more stressing conditions than urban areas

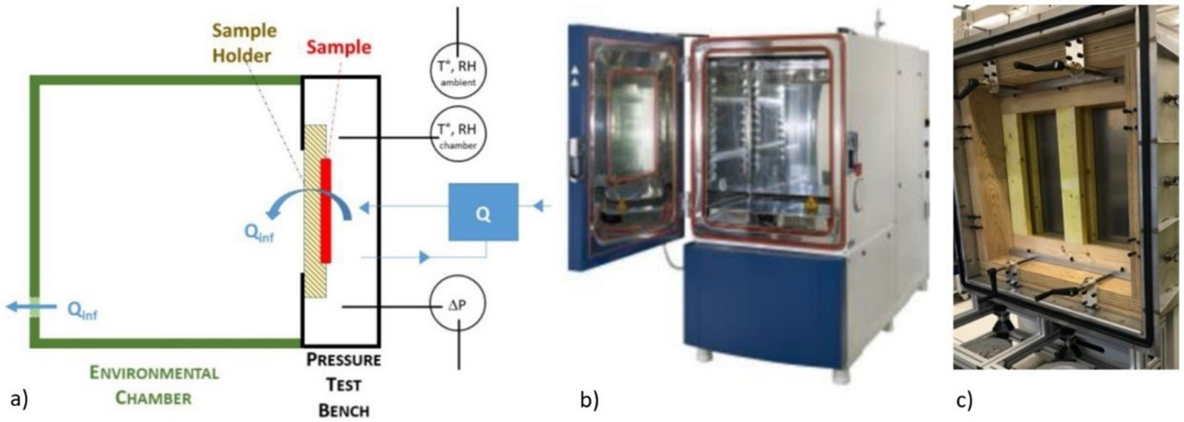

Figure 6: Schematic view (a) and pictures of the experimental set-up without (b) and with (c) the sample holder (Litvak et al., 2019)

Annex 4: Standards and regulations on the subject

Document reference		Subject	Cited as reference in:
Loads characterisation and general information to create a protocol			
ETAG004	Guideline for European technical approval of external thermal insulation composite systems with rendering (replaced by EAD 040083-00-0404)	General information Loads characterisation	cf. langmans_2015
ETA GD003	Assessment of working life of products	General information	
EC Guidance paper F	Durability and the construction product directive (revision December 2004)	General information	
BRE Digest 346	The assessment of wind loads – Part 7: Wind speeds for serviceability and fatigue assessment	Loads characterisation	Ackerman_2012
Ageing protocols			
ASTM D 3611-89	Standard Practise for Accelerated Aging of Pressure sensitive tape	Ageing protocol	Weissmueller_2013 Ackermann_2012 Møller_2017
EN 1296 (2001)	Flexible sheets for waterproofing. Bitumen, plastic and rubber sheets for roofing. Method of artificial ageing by long term exposure to elevated temperature	Ageing protocol	Fufa_2018
NT BUILD 495	Building materials and components in the vertical position. Exposure to accelerated climatic strains	Ageing protocol	Fufa_2018
EN 12211 – Annex B	Windows and doors - Resistance to wind load - Test method	Ageing protocol (wind loads)	Fufa_2018
Durability test			
ASTM E2342-03	Standard Test Method for Durability Testing of Duct Sealants	Durability test	cf. Sherman_2004
DIN 4108-11	Thermal insulation and energy economy in buildings - Part 11: Minimum requirements to the durability of bond strength with adhesive tapes and adhesive masses for the establishment of airtight layers	Durability test	Weissmueller_2013 Fufa_2018 Møller_2020
Material characterisation			
EN 12865 (2001)	Hygrothermal performance of building components and building elements - Determination of the resistance of external wall systems to driving rain under pulsating air pressure, CEN, Brussels, Belgium.	Water permeability test	Bracke_2014
ASTM E2357-11	Standard Test Method for Determining Air Leakage of Air Barrier Assemblies.	Air permeability test	Bracke_2014
EN 12114 (2000).	Thermal Performance of Buildings Air Permeability of Building Components and Building Elements Laboratory Test Method	Air permeability test	Bracke_2014

EN 1027 (2016)	Windows and doors - Water tightness - Test method	Water permeability test	Bracke_2014
German MO-01/1	Wall connection of windows	Air permeability test	
ISO 11600 (2002)	Building construction — Jointing products — Classification and requirements for sealants	Products characterisation test	
EN 12316-2 (2013)	Flexible sheets for waterproofing - Determination of peel resistance of joints - Part 2: Plastic and rubber sheets for roof waterproofing	Products characterisation test: peel resistance	Møller_2020
EN 12317-2 (2010)	Flexible sheets for waterproofing - Determination of shear resistance of joints - Part 2: Plastic and rubber sheets for roof waterproofing	Products characterisation test: shear resistance	Møller_2020
EN 12311-2 (2013)	Flexible sheets for waterproofing - Determination of tensile properties - Part 2: Plastic and rubber sheets for roof waterproofing	Products characterisation test: tensile properties	
EN 1850- 2 (2001)	Flexible Sheets for Waterproofing - Determination of Visible Defects Part 2: Plastic and Rubber Sheets for Roof Waterproofing	Products characterisation test: visible defects	
UL 181 B	Standard for Closure Systems for Use With Flexible Air Ducts and Air Connectors	Products characterisation test (peeling, etc.)	cf. Sherman_2003

ANNEX 5

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