Development of a Test Method for Adhesive Tapes Certification and Application

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ABSTRACT

Sufficient airtightness of the building envelope is important both to ensure the overall energy efficiency of a building and to prevent moisture-related damage to the structure. Air leakages typically occur in the context of joints and perforations in vapour barriers installed inside walls and roofs. It is essential to give proper attention to details to achieve sufficient airtightness of building envelopes and joint's durability. The aim of research presented in this paper is to contribute to the development of test methods with sufficient accuracy, reproducibility, and repeatability to be used in the development and certification of tape products and systems.

Keywords:

Building envelope

Airtightness

Experimental test method

Durability of joints

Adhesive tapes

HIGHLIGHTS

- Development of an experimental method that provides a reliable assessment of airtightness in adhesive tape joints.
- Evaluation of the effectiveness of the method in the context of the established product certification procedure.
- Assessment of the applicability of the method regarding certification and product development.
- Evaluation of the effectiveness of the method performance in relation to other established methods.

1. Introduction

The Energy performance of buildings directive (EPBD) was initiated by the European Union (EU) to provide a legislative framework for promoting energy efficiency in buildings. Among its stated goals is to "achieve a highly energy efficient and decarbonized building stock by 2050" [1]. The latest proposal for a revision of the EPBD from 2021 establishes a vision for achieving a zero-emission building stock by 2050. In Norway, technical requirements regarding energy efficiency are defined in the Regulations on technical requirements for construction works i.e., TEK, with its newest edition TEK17 taking effect in 2017 [2]. TEK is guided by EPBD in posing stricter requirements to the overall energy efficiency of buildings and emphasizing building airtightness in Norway. The purpose of posing requirements for building airtightness is to prevent leakages of cold outdoor air into the building, as well as humid indoor air from leaking into the internal structures of the building envelope. Sufficient airtightness is thus important both to ensure the overall energy efficiency of the building, and to prevent moisture-related damage to the structure, like mold and rot. Air and vapour barriers are installed in the walls and roofs of buildings to prevent air from penetrating through the structure. Air leakages typically occur in the context of joints and penetrations in these barriers. It is thus essential to give proper attention to these details, both at the design stage and during construction, to achieve sufficient airtightness. In recent years, adhesive tapes have become a trendy way of air-sealing joints and penetrations in the building envelope. Early on, these tapes had a reputation for having poor adhesive properties and durability. More recently, along with further product development, adhesive tapes have been recognized for their ability to provide adequate airtightness [3]. The use of tape also allows for innovative solutions, along with simple and quick application, making it a highly convenient option for air-sealing details. However, as adhesive tapes constitute a relatively new way of air-sealing building, there are concerns and uncertainty regarding the long-term durability of the products and solutions. Current evaluation methods used in certification of products and systems are primarily based on assessing the mechanical and adhesive properties of products rather than addressing the airtightness directly. The usefulness and validity of these established evaluation methods may seem to depend on the existence of a direct correlation between the airtightness and adhesion of the tape joints. However, research results have suggested otherwise, as while adhesive properties in many cases remain unchanged or even improved over time, the airtightness is in most cases reduced [4]. The uncertainty has led research communities to recognize the need for new test methods. The Norwegian institute of applied research (SINTEF) initiated the research project TightEN in 2019 to increase experience and knowledge regarding the airtightness and long-term durability of sealing systems utilizing adhesive tapes [5]. Research and results presented in this paper focus on evaluating the usefulness of a medium-scale test method for assessing the airtightness of joints sealed with adhesive tapes. The aim is to contribute to the development of test methods with sufficient accuracy, reproducibility, and repeatability to be used in the development and certification of tape products and systems in the future.

With further improvement, the proposed experimental method in development is considered applicable as a means of evaluating the durability of adhesive tapes as part of product development or certification. In the context of separate tape evaluation, the method could potentially constitute a supplementary test to currently established evaluation methods. Durability of tensile strength, peel and shear resistance is regarded as important to ensure the joint can withstand mechanical strains over time. However, a direct assessment of the actual airtightness is deemed beneficial to ensure the products fulfill their purpose of air-sealing building envelopes in the long term.

An improved version can achieve satisfactory precision in determining specimen leakage rates by incorporating improvements aimed at minimizing system leakage rates. In terms of durability evaluation criteria, it is considered more suitable to establish absolute threshold values for permeability before and after ageing, in contrast to current guidelines for peel and shear resistance evaluation, in which durability is evaluated based on relative change in material properties after artificial ageing.

2. Theory

Air enters and leaves buildings through ventilation or infiltration. In modern buildings, ventilation is often provided through balanced ventilation with heat recovery which makes the airflow predictable and controllable. Modern ventilation systems also make it possible for heat batteries to reclaim energy from the exhaust air to limit heat losses. Infiltration is driven by differences in air pressure, Δp, between the inside and the outside of the building envelope. This results in airflow, $\dot{V}$, moving from areas with high air pressure to areas where it is comparatively lower. Pressure differences are typically caused by wind pressure and pressurization from mechanical ventilation. Temperature differences will simultaneously contribute to pressurization through the stack effect, as warm air rises through building and creates a higher pressure in its upper levels compared to its base [6]. A building envelope will never be entirely airtight, as it is virtually impossible to eliminate leakages and infiltration completely.

2.1. Norwegian regulations

Norwegian construction projects must meet the Regulations on technical requirements for construction works, TEK17. This building code determines requirements regarding a building's overall energy efficiency, including its airtightness through upper limit values concerning the air change rate, *n50*. The air change rate is herein defined as the volumetric airflow, $\dot{V}_{50}$, leaking through the building envelope divided by the internal volume of the building, V, when an air pressure difference of 50 Pa occurs between the inside and outside environment [2]:

$$n50 = \frac{\dot{V}_{50}}{V} \quad (1)$$

All Norwegian building projects, including total renovation, must be built according to the minimum requirements in TEK17. Buildings can be built with an even higher level of energy efficiency than required by TEK17. This can be achieved by designing the building according to the Passive House Standards NS3700 or NS3701, for residential and non-residential buildings respectively [7-8]. Table 1 shows the different airtightness requirements that are relevant to the construction of new buildings and total renovation of existing buildings in Norway. From January 1, 2013, the air leakage rates of new buildings are required to be verified by an independent controller [9]. Verification can be carried out by performing the blower-door test described in the NS-EN ISO 9972:2015 standard [10].

Table 1
Norwegian air change rate requirements.

Requirement	n50	Applies to:
TEK17 Minimum requirement	≤ 1,5 1/h	All buildings
TEK17 Energy-savings measure	≤ 0,6 1/h	Residential building
NS3700 Passive house requirement	≤ 0,6 1/h	Residential buildings
NS3701 Passive house requirement	≤ 0,6 1/h	Non-residential buildings

2.2. Airtightness in practice

Joints between the separate sheets of a barrier membrane itself are critical, along with penetrations in the building envelope which may be intentional, as for plumbing and electrical works, or accidental, resulting from ruptures occurring during construction or in the operational phase. Manufacturers offer adhesive pipe sleeves for sealing intentional penetrations in air and vapour barriers [11].

Fig. 1 highlights some of the details of a building envelope in which air leakages typically occur. The figure outlines in red, an imaginary, continuous airtight layer. Sealing critical points is essential to achieve the continuity of the barriers, thus ensuring the overall airtightness of the building. There are several options for sealing joints and connections, such as clamping, sealants and using adhesive tapes.

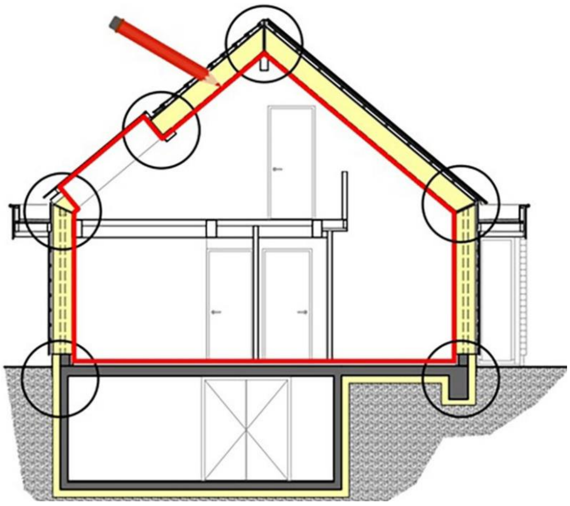

Fig. 1. Critical details concerning air leakages in a building envelope [12].

Fig. 2. Adhesive tape is used to join sheets of vapour barrier membrane, and to connect the membrane to the timber frame [13].

Adhesive tapes can be used as the primary way of sealing and as reinforcement of clamped joints, helping provide continuity in the barrier layers. Fig. 2 illustrates the practical application of adhesive tape on a vapour barrier membrane in the walls and ceiling of a timber frame house. Adhesive tapes can be used to join boards and sheets of membrane together, and to connect these to other building components, such as floors and ceilings [14]. Rigid boards can be joined by a simple connection, while joining two sheets of membrane requires the sheets to overlap [15]. This principle is illustrated in Fig.3. which shows a vertical cross section of an exterior wall, where rigid gypsum boards constitute the air barrier, and a PE membrane makes up the vapour barrier.

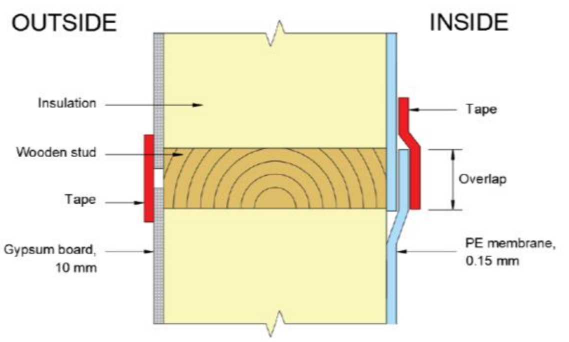

Fig. 3. Cross section of an exterior wall showing a simple tape connection of boards.

For the use of tape to be successful, it is important that the products' performance and durability is accurately assessed and documented. The airtightness of a joint or opening sealed by tape is affected by several different parameters, such as type of substrate, and its resilience to moisture, changes in temperature or relative humidity, exposure to UV radiation, chemical compounds, and dust. These conditions may affect the function of deterioration by causing dimensional change, material fatigue or oxidation. Factors can also combine in ways leading to synergistic effects, accelerating the deterioration of the tape's airtightness even further [16]. It is therefore important that tapes are tested in realistic and relevant conditions, to examine how the products react to different climate conditions, including frost, moisture, heat, and exposure to sun. Research also suggests that installation conditions can have a major impact on the airtightness of tape joints [17].

2.3. Experimental test methods

Fufa et al. describe a lack of reliable test procedures for tapes used in building applications and express the need for new methods to evaluate the durability of product performance [18]. Efforts to develop new test procedures for adhesive tapes have resulted in a range of methods, using different layouts, scales, and substrate materials. Some studies combine airtightness evaluation with the measuring of mechanical tape properties such as peel and shear resistance. The developed experimental methods take different approaches to evaluate tape durability. Most apparent is the difference in how the standardized methods mainly rely on quantifying adhesive properties, while the experimental methods assess airtightness. The methods differ in several ways but also share common features. Table 2 provides an overview comparing some of their aspects.

Table 2
Experimental methods for durability assessment of adhesive tapes.

Method	Antonsson	Møller and Rasmussen	Van Linden and Van den Bossche	Ylmén et al.
Dimension	3 x 3 m	0.5 x 0.5 m	1.2 x 1.2 m	2.2 x 2.2 x 2.4 m
Airtightness	Yes	Yes	Yes	Yes
Peel resistance	No	Yes	No	Yes
Shear resistance	No	Yes	No	Yes
Substrates	Air/vapour barrier	Vapour barrier	Concrete/OSB/fiberboard	Air/vapour barrier
Ageing procedure	Heat, RH	Heat, RH	Dynamic pressurization	Heat, RH
Load	60°C, 50%	70°C, 90%	1000 Pa	80°C, 50%
Duration	6 weeks	84 + 84 days	200 pulses	12 months

The methods developed by Antonsson [17] and Ylmén et al. [16] simulate building components with realistic dimensions, making the tests and ageing processes highly representative. However, full scale testing can be cost and time consuming. Issues with reproducibility have also led to questions whether the full-scale methods are assessing the quality of implementation rather than product properties according to Leprince et al. [19]. Studies conducted by Antonsson and Ylmén et al. only involved testing one single specimen of each configuration, making it difficult to conclude on the reproducibility of the two methods. Møller and Rasmussen [4] and Van Linden and Van den Bossche [20] were able to test more samples, making it easier to evaluate the reproducibility of their methods. Reduction of scale may, on the other hand, cause the results to be less representative. Nevertheless, both Ylmén et al. and Møller and Rasmussen concluded that there is no clear correlation between airtightness and mechanical properties, such as peel and shear resistance. Despite their differing test scales, both studies found that peel and shear resistance tend to improve after accelerated ageing while the airtightness deteriorates. Still, some of the observations may appear counter-intuitive when compared with other research: while Van Linden and Van den Bossche found that the airtightness of taped joints depended on the substrate, Sletnes and Frank [21] found that peel and shear resistance varied more between different tapes than between different substrates.

Out of the evaluation methods mentioned, Van Linden and Van den Bossche are the only ones addressing airtightness using concrete as a substrate. All the mentioned methods except the one of Van Linden and Van den Bossche include adhesive tape joints linking two or more varied materials, for instance wood and PE membrane or wood and concrete. Varied materials undergo different dimensional changes in response to varying temperature and moisture content, which might lead to skewed deformation and tension in the tape. This can in turn affect adhesive properties or airtightness [16]. Studying this phenomenon in isolation would be relevant to better understand how the airtightness of tape joints evolves in the long-term.

3. Material and methods

An experimental method has been under development to evaluate the air permeability and durability of joints sealed with adhesive tapes. The method in development is presented in Section 3.1. The procedure used to collect and analyze data is inspired by NS-EN 12114:2000 [22]. The reproducibility, repeatability and accuracy of the method is assessed through a measurement program described in Section 3.2.

The program involves measuring the air permeability of specimens from 6 different material samples. Each test sample consists of a given combination of one adhesive tape and a substrate. Test samples and specimens are described in Section 3.2.2. Specimens are tested before and after artificial ageing to assess whether the test setup is suitable for evaluating the durability of adhesive tapes. The ageing procedures are described in Section 3.4. Parallelly to the air permeability evaluation, the same material samples are tested for peel resistance in accordance with the national standard NS-EN 12316-2:2013 (Standard Norge, 2013c) [23]. The peel resistance measurements are conducted on non-aged and artificially aged test specimens, exposed to the same ageing procedure as the corresponding air permeability specimens. The purpose of performing standardized peel resistance measurements of the material samples is to examine how the durability evaluation from the method in development compares to a test method, i.e., NS-EN 12316-2:2013 [23]. Results from the two methods are compared to observe whether there is a correlation between the air permeability and adhesive properties of the materials.

3.1. Air permeability test method

Experiments are conducted using a test rig in the laboratories of SINTEF Community. A schematic drawing of the setup is shown in Fig. 1. The setup includes a box-shaped test stand made of welded-together steel plates into which a test specimen is installed, creating an enclosed volume.

The test stand is pressurized while measuring the supplied airflow rate using one of three flow meters. Flow meters are enumerated 1, 2, 3, and can measure flow rates within the ranges 0 - 0.4, 0 - 10 and 0 - 100 *l/min,* respectively.

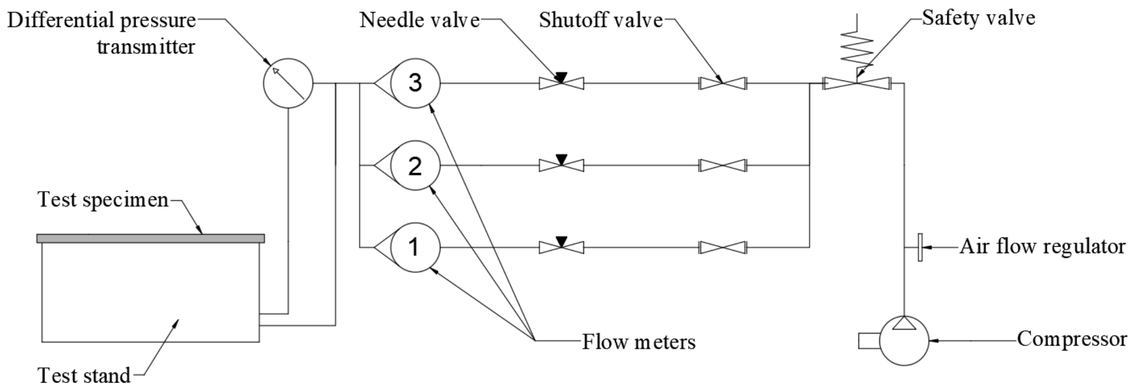

Fig. 4. Schematic drawing of the test setup.

3.1.1. Test stand

The test stand consists of a box welded together from three steel plates, 2mm thick, leaving one side open for mounting test samples. The box is outfitted with 50 mm flanges pointing outwards from said opening. The flanges act as support for the test samples and allow for the fastening of clamps. The test stand is designed with dimensions allowing test samples to fit inside the heat chamber used for artificial ageing at SINTEF Community. A stylized cross section of the assembled test stand with a test sample installed in it is shown in Fig. 4.

3.1.2. Data collection

Data collection is conducted in accordance with the test procedure described in NS-EN 12114:2000 [22]. The measuring begins with pressurizing the test stand with compressed air through the pressurization rig, creating a positive pressure on its inside. The airflow is regulated manually, until the pressure difference rests at one of several predetermined levels. Pressure steps are determined according to Annex A of NS-EN 12114:2000 [22]. 100 Pa is used as the highest pressure difference Δp_{max}, while 10 Pa is used as the lowest pressure Δp_{min}. The number of pressure steps N is chosen to be 7. The pressure Δp_i is determined by Equation 2, giving intervals between steps on a logarithmic scale:

$$\Delta p_i = 10^{i\frac{(\log(\Delta p_{max})-\log(\Delta p_{min}))}{N}+\log(\Delta p_{min})} \quad (2)$$

This formula gives the following 7 pressure steps: 10, 15, 22, 32, 46, 68, 100 Pa. Three pulses of pressurization equal to 110 Pa (10% greater than Δp_{max}, according to NS-EN 12114:2000) [22] are applied for three seconds, before proceeding to the pressure steps. To obtain the leakage rate at a given pressure step, the system must be in a steady state, where the pressure difference remains static at the given air flow rate. A steady state implies that the supplied airflow to the test stand is equal to the total leakage $\dot{V}_{tot}$ through the sample and test stand as shown in Equation 3.

$$\dot{V}_{tot} = \dot{V}_{sample} + \dot{V}_{system} \quad (3)$$

The leakage through the sample can further be divided into joint and substrate leakage as shown in Equation 4.

$$\dot{V}_{tot} = \dot{V}_{joint} + \dot{V}_{substrate} + \dot{V}_{system} \quad (4)$$

If the substrate is considered airtight, the substrate leakage is neglected.
Fig. 5 illustrates the diverse types of leakages.

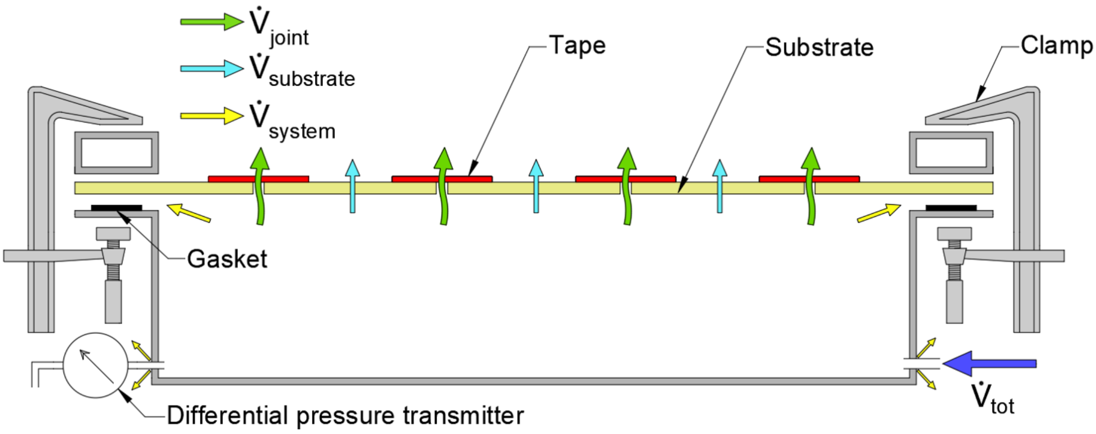

Fig. 5. Stylized cross section of the test stand showing air supply and leakage types.

3.1.3. Data processing

The recorded air leakage rate $\dot{V}_{tot}$ includes extraneous leakages going through the substrate and the test stand itself that need to be subtracted to obtain the air leakages going through the tape joints. Leakage through the test sample, $\dot{V}_{sample}$, is calculated by subtracting the system leakage from the total leakage rate:

$$\dot{V}_{sample} = \dot{V}_{total} - \dot{V}_{system} \quad (5)$$

Further subtracting the substrate leakage results in the leakage through the joints:

$$\dot{V}_{joint} = \dot{V}_{sample} - \dot{V}_{substrate} \quad (6)$$

The substrate leakage of a given sample is evaluated by implementing the previously described measurement procedure on an intact piece of the associated substrate, free from cuts and tape joints. The intact substrate is tested before and after artificial ageing, parallel to the sample with tape joints. PE foil is considered practically airtight, hence $\dot{V}_{substrate}$ is neglected when evaluating the joint leakage of samples where these materials constitute the substrate.

A regression model described in NS-EN 12114:2000 [22] is used to find the correlation between the pressure difference and leakage rate for each test sample. The aim is to express the relation between the pressure and leakage rate as a power law as seen in Equation 7:

$$\dot{V}(\Delta p) \rightarrow \dot{V} = C(\Delta p)^n \quad (7)$$

The data sets containing the reference measurements $\dot{V}_{system}$, substrate leakage $\dot{V}_{substrate}$ and the total leakage rate $\dot{V}_{total}$ are treated separately, resulting in three different regressions. Table 3 outlines the process resulting in the three regressions for any given specimen.

Each of the leakage types are evaluated through two separate measurement series $\dot{V}_{tot,i}$, $\dot{V}_{sys,i}$ and $\dot{V}_{sub,i}$ per specimen. The substrate leakage is measured on a separate specimen, consisting of an intact piece of the substrate.

Table 3
Overview of data collection and processing for a specimen.

Leakage type	**Measuring** →	**Correcting** →	**Average** →	**Regression**
Total	$2 \cdot \dot{V}_{tot,i}$	$2 \cdot \dot{V}_{0,tot,i}$	$\bar{\dot{V}}_{tot}$	$C_{tot}(\Delta p)^{n_{tot}}$
System	$2 \cdot \dot{V}_{sys,i}$	$2 \cdot \dot{V}_{0,sys,i}$	$\bar{\dot{V}}_{sys}$	$C_{sys}(\Delta p)^{n_{sys}}$
Substrate	$2 \cdot \dot{V}_{sub,i}$	$2 \cdot \dot{V}_{0,sub,i}$	$\bar{\dot{V}}_{sub}$	$C_{sub}(\Delta p)^{n_{sub}}$

3.2. Measurement program

The measurement program is planned out with the intention of assessing the accuracy, reproducibility, and repeatability of the test method, and it includes following actions: 1) the test stand leakage evaluation, 2) the choice of material samples and evaluation, 3) identical parallel specimens' testing, 4) the repeatability evaluation, and 5) the comparison to peel resistance.

1) The test stand leakage evaluation is performed by installing a sheet of PE foil over the test stand's opening, before pressurizing the test stand until a steady pressure difference of 100 Pa is achieved. The airflow rate going into the test stand is simultaneously recorded under the assumption that the PE foil is airtight. The recorded flow rate is consequently assumed to be equal to the system leakage.

This test procedure is repeated, varying the number of clamps to assess how this affects the system leakage rate. The test starts out using 8 clamps (see Fig. 6) before the test is repeated using 12 clamps.

2) The material test samples used in these experiments consist of combinations of three commercially available tape products and two different substrates, as shown in Table 4. The tapes chosen for the samples include a universal tape (T1) for use in both air and vapour barriers, an air barrier tape (T2) and a duct tape (T3). Both T1 and T2 have received Technical Approval from SINTEF for their respective areas of use. The duct tape, T3, is developed for sealing applications in HVAC systems (heating, ventilating, air conditioning) and has not received any Technical Approval from SINTEF for use in either air or vapour barrier systems.

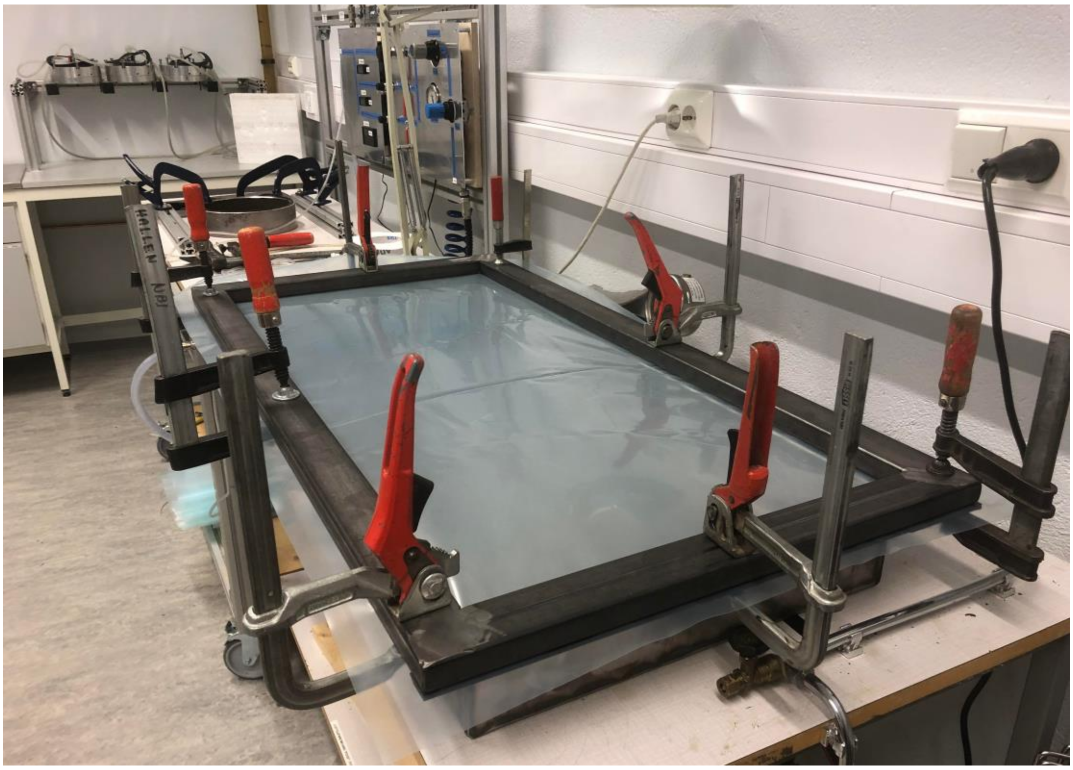

Fig. 6. Test stand leakage evaluation setup using 8 clamps

Different substrates are chosen to observe how the air permeability of the tapes varies depending on the surface it is adhered to. Some substrates, such as PE foil are practically airtight, making it easier to measure an isolated joint leakage. For substrates that are more air permeable, it is necessary to measure and subtract the leakages going through the substrate itself before obtaining the joint leakage.

Both air barrier material and PE membrane constitute standard substrates in the context of SINTEF Technical Approval and are among the end-use substrates with which adhesive tapes are typically used. Because of this, they were considered the most relevant substrates, along with wood and concrete.

Table 4
Material samples.

Tape	*Description*	*Substrate*	*Description*
T1	Universal tape, for air and vapour barrier application, acrylic adhesive with flexible backing	***PEF***	Polyéthylène foil vapour barrier, 0.20 mm
T2	Air barrier tape, modified acrylic adhesive with rigid backing	***ROM***	Polyurethane roofing membrane covered with polypropylene felt
T3	Duct tape, rubber adhesive and PE. coated fiber backing		

3.3. Peel resistance test

Peel resistance is measured in accordance with the Norwegian national standard NS-EN 12316-2:2013 [23]. The measurements are performed in the laboratories of SINTEF Byggforsk, in line with their accredited test procedure.

3.4. Ageing procedures

The artificial ageing procedure varies depending on the substrate material: in a manner inspired by guidelines for *vapour barriers* where PEF constitutes the substrate and, in a manner, like the guidelines for *air barriers* where ROM constitutes the substrate, according to the Technical Approval of SINTEF [24].

3.4.1. Heat chamber

The material samples which include PEF as substrate are artificially aged in a ventilated heat chamber at 70°C for 6 weeks.

3.4.2. Climate simulator

Accelerated ageing of the ROM samples is performed using the method NT BUILD 495 over the course of 6 weeks, where samples are exposed to UV light, heat, water, and frost to simulate climatic strains [25], see Fig. 7 and 8.

NT BUILD 495 is included in the standard procedure for artificial ageing of air barrier tapes and systems during Technical Approval, in which peel and shear resistance samples are exposed to the climate simulator for 2 weeks, followed by 12 weeks of heat ageing [24].

Fig. 7. Air permeability specimens in the climate carousel.

Fig. 8. Peel resistance specimens in the upper half.

4. Results

The following sections present results from the measurement program used to evaluate the suitability of the test method in development.

4.1. Test stand leakage

The test stand leakage evaluation was performed on two different dates: 24.03.2023 (3-24-23) and 12.04.2023 (4-12-23). On both occasions, the test procedure was performed through two separate measurement series. The first two measurement series were performed prior to testing the material samples, and thus constituted the earliest utilization of the test stand. The subsequent measurement series was performed 3 weeks later. During these 3 weeks, the test stand had already been used to measure air permeability rates of non-aged material samples through 15 separate measurement series. Fig. 9 illustrates results from the test stand leakage evaluation, showing the leakage rate at a 50 Pa pressure difference, $\dot{V}_{50}$, estimated from linear regression. The illustration shows the estimated leakage rates when using 8 and 12 clamps, respectively. Estimated leakage rates vary substantially between each of series, ranging from 0.00503 to 0.04500 m³/h. The number of clamps used to seal the specimens seem to affect the airtightness of the test stand, but this effect is insignificant compared to the variations observed between the individual measurement series. In the tests conducted on 12.04.2023, the measured leakage rates were significantly higher, having increased on average by a factor of 6.6 compared to the prior measurements. For comparison, increasing the number of clamps from 8 to 12 only led to a 7% reduction in the leakage rate on average. The lowest leakage rate measured at 100 Pa in any of the measurement series was 0.00912 m³/h, which is 1500 times larger than the lowest recorded system leakage of the pressurization rig, 0.000006 m³/h, at 100 Pa, when not accounting for the test stand. Because of this, it is assumed that the system leakage rate can be traced back to the test stand and its connections, rather than the pressurization rig. Leak detection tests using soapy water were performed on both occasions. None of the tests revealed any air leakages around the tube connections, welding joints or rubber gasket.

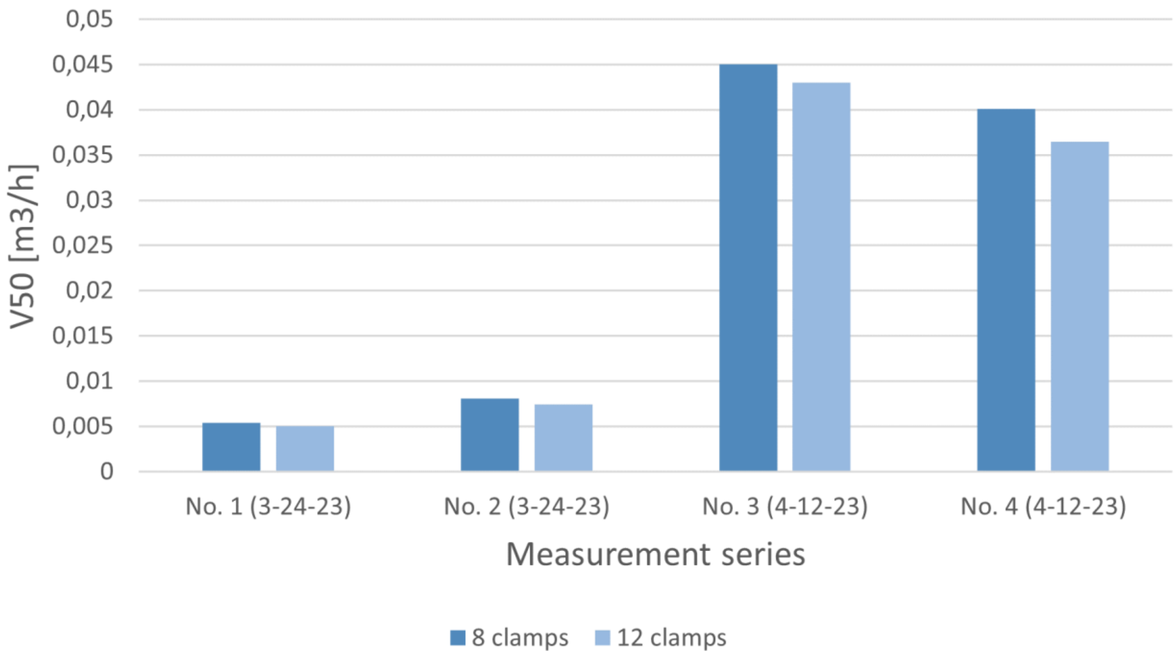

Fig. 9. System leakage rates $\dot{V}_{50}$, resulting from test stand leakage evaluation.

4.2. Air permeability tests

Air permeability evaluation of material samples was performed in accordance with the previously described measurement program, using 12 clamps for sealing the specimens during tests.

4.2.1. Material samples durability

Specimens were tested according to the same procedure before and after artificial ageing to determine the durability of joint permeability. All artificially aged specimens were conditioned in the laboratory at (23 ± 2) °C and 48% RH for more than 48 hours prior to performing the tests. Fig. 10 shows the results from the durability evaluation expressed as average air permeability at 50 Pa, before and after ageing. The calculated average values do not consider specimens which deviated significantly from the other parallel specimens, including T1-PEF-A, T1-PEF-D and T2-PEF-C. These neglected specimens are nevertheless addressed later, as part of the reproducibility evaluation in Section 4.2.2. All parallel specimens of sample T3-PEF and T3-ROM failed after artificial ageing, as illustrated by the hatched bars in Fig. 10. For illustrative purposes, the height of these bars is not representative of the actual permeability of the failed specimens. Failed specimens are addressed in Section 4.2.5. The dashed line in the chart corresponds to the passive house threshold of 0.048 $m^3/m \cdot h$, as described by Van Linden and Van den Bossche [20].

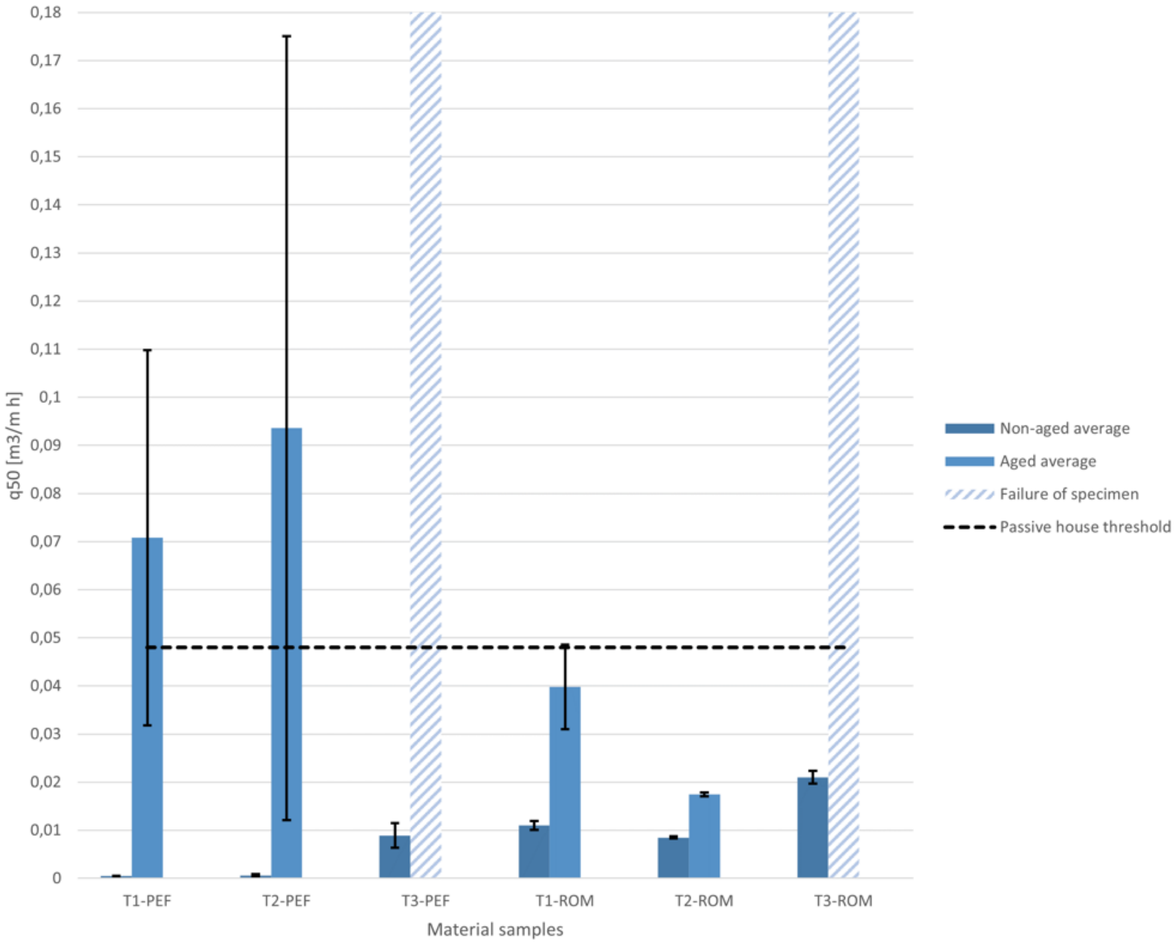

Fig. 10. Average air permeability of material samples before and after artificial ageing.

A horizontal line corresponds to the aforementioned passive house threshold. The height of bars representing failed specimens does not correspond to the actual permeability. Table 5 shows relative changes in air permeability after artificial ageing for four settings of two of the selected to be tested tapes (T1 and T2) in combination with the two different substrates (PEF and ROM), see more in Table 4.

Table 5
Relative change in air permeability after artificial ageing.

Material samples	Relative change
T1-PEF	+15 200 %
T2-PEF	+14 800 %
T1-ROM	+260 %
T2-ROM	+105 %

All the material samples become more air permeable after artificial ageing.

However, the increase is more significant among the PEF samples. While the PEF samples are comparatively less permeable before ageing, they eventually surpass the permeability rates of the ROM samples when tested after the ageing process. All material samples are within the passive house threshold prior to ageing, but only T1-ROM and T2-ROM remain airtight enough to stay below this threshold in artificially aged condition. Table 4 shows the relative change in air permeability among the material samples, not including the failed T3-PEF and T3-ROM.

4.2.1. Reproducibility

Fig.11 shows the estimated mean joint permeability q_{50} of test specimens prior to ageing at 50 Pa. Specimens tested through several measurements series as part of the repeatability evaluation are represented by the average permeability rate from the three measurement series. T3-PEF-A is excluded from the chart for visual purposes, as its air permeability was considerably higher than the other specimens, with q_{50} estimated to 0.1098 m³/m·h. Apart from T3-PEF-A, all specimens have joint permeability rates lower than the passive house threshold of 0.048 m³/m·h described by Van Linden and Van den Bossche [20]. Air permeability varies substantially among the PEF samples and between individual parallel specimens, most clearly in the case of sample T1-PEF, where the air permeability of the specimens ranges from 0.00041 to 0.01971 m³/m·h. The ROM samples are on average less air permeable, but the measurement results remain more consistent between parallel specimens.

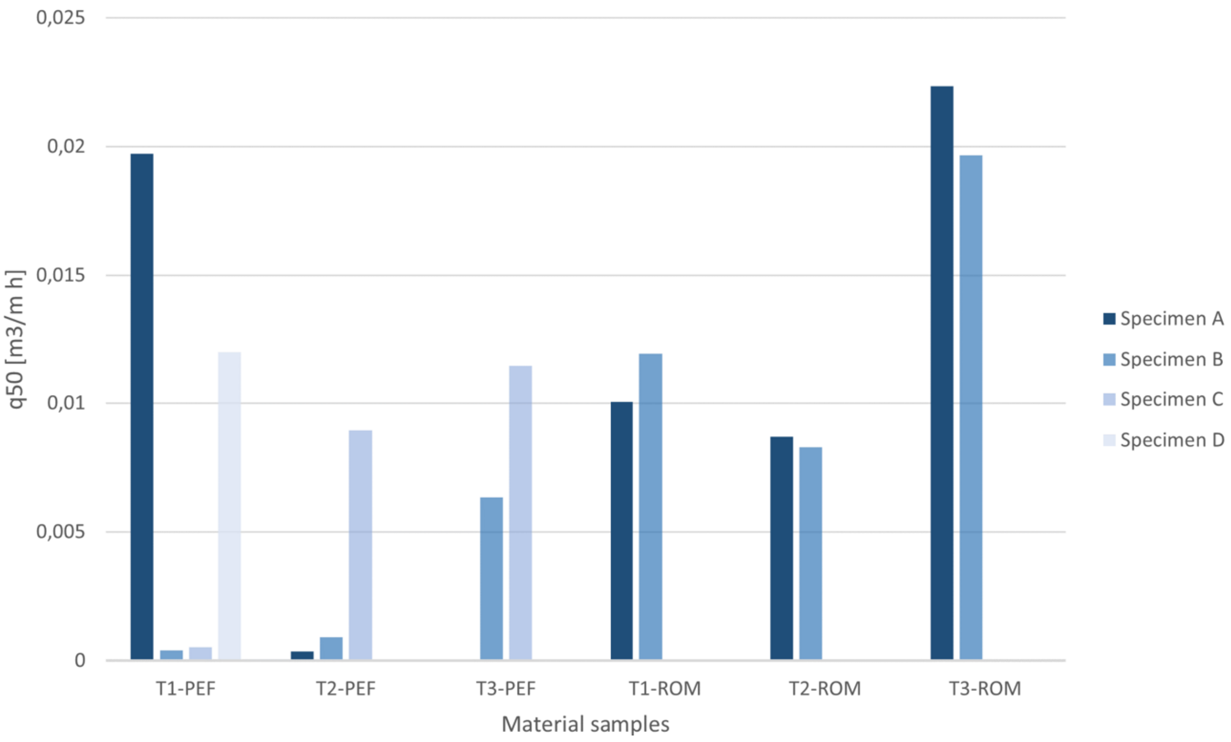

Fig. 11. Joint permeability rate of non-aged specimens.

Fig. 12 shows the estimated air permeability rates of specimens after 6 weeks of artificial ageing at 50 Pa. T3-PEF and T3-ROM are not included, as they failed during the ageing process. Specimens

T1-PEF-D, T2-PEF-C were not exposed to artificial ageing due to time constraints. In the chart, a dashed horizontal line marks the passive house threshold, while a solid line indicates the upper limit for what is considered "good airtightness" at 0.238 m³/m·h according to Van Linden and Van den Bossche [20].

Apart from T1-PEF-A and the failed T3-PEF and T3-ROM specimens, other specimens retain "good" airtightness after ageing. Like the non-aged measurements, the permeability rates of the PEF samples vary significantly between parallel specimens, while ROM samples provide more consistent results. When comparing individual parallel specimens, those which were permeable initially likewise became increasingly more permeable after ageing.

In specimens with air permeability q_{50} < 0.005 m³/m·h, the measured system leakage and total leakage rates were in most cases easily distinguishable, for instance when evaluating T1-PEF-A1 in non-aged condition. In some of the less permeable specimens, the difference between system leakage and total leakage was not as apparent. Several specimens were also estimated to be significantly less permeable than the test stand itself, i.e., $\dot{V}_{joint} \ll \dot{V}_{sys}$.

The minor differences between system and total leakage were measurable when using Flow Meter 1. However, the measurements are thought to have become more uncertain when using Flow Meters 2 and 3, as these readings had lower resolutions and were prone to fluctuations.

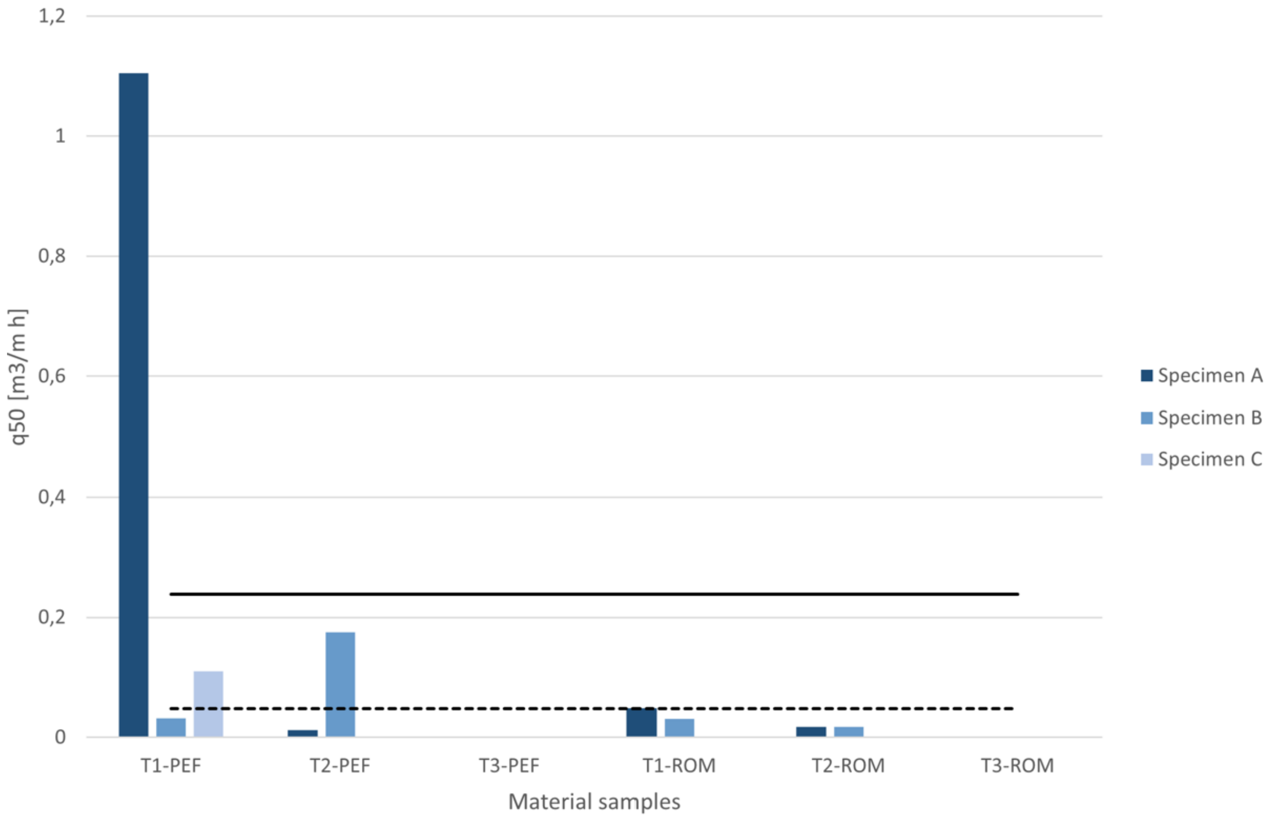

Fig. 12. Joint permeability rate of aged specimens.

4.2.2. Repeatability

The repeatability evaluation featured air permeability measurements of three specimens, each tested through three separate measurement series in non-aged condition. Fig. 13 shows the estimated mean joint permeability q_{50} obtained through regression of each measurement series. The air permeability of T1-PEF-D varied substantially between each measurement series, with a standard deviation of 0.00529 m³/m·h, making up 44% of the specimen mean. The standard deviations of T1-PEF-A and T2-PEF-C are 0.00192 and 0.00087 m³/m·h respectively, which constitutes approximately 10 % of the mean value for both specimens. The average standard deviation is 0.00269 m³/m·h when accounting for all three specimens.

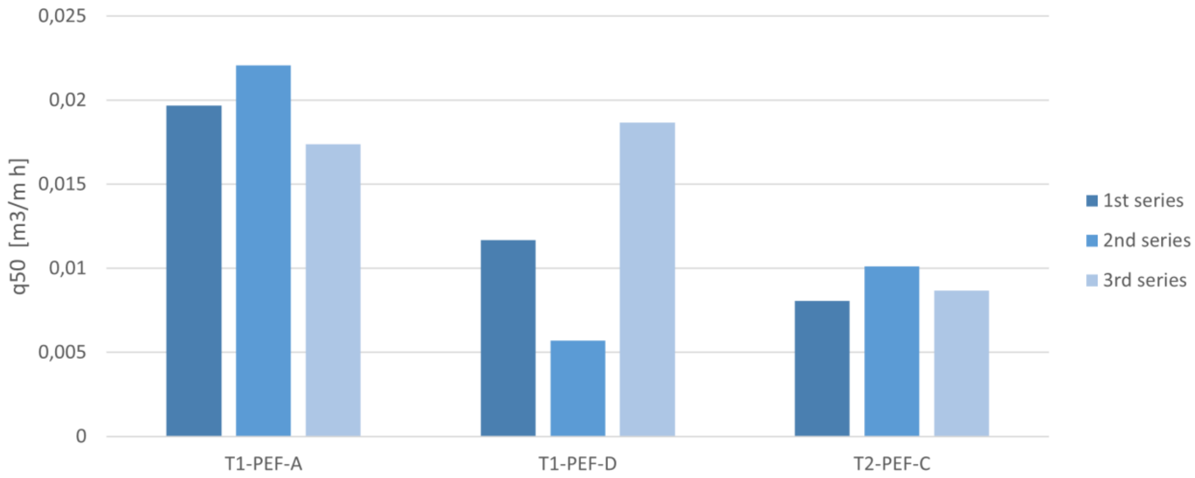

Fig. 13. Repeatability evaluation results showing joint permeability rates at 50 Pa.

4.2.3. Visual inspection of specimens

Specimens were visually inspected before and after performing the ageing procedures. to observe and map imperfections in specimens which may have impacted air permeability measurement results as shown for the test set up T3-ROM-A in Fig. 14. In this case, both specimens of the T3-ROM sample were taken out of the climate simulator after 12 days after a visual inspection. The tape was separated from the substrate in several local points along the joints. The failure appears to have occurred within the adhesive, as the adhesive was still attached partly to the substrate and partly to the backing material. The specimens were tested to determine the leakage rates, but in both cases, an airflow rate of 6 m3/h was not sufficient to elevate the pressure difference ΔP beyond 3 Pa. Because of this, both T3-ROM specimens were deemed as failed tests after artificial ageing.

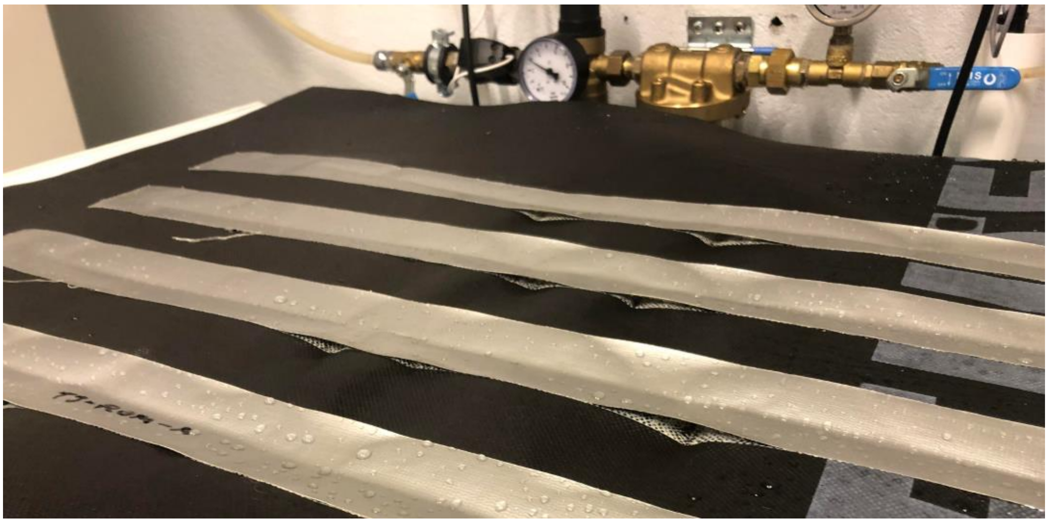

Fig. 14. Failure of tape joints in T3-ROM-A.

4.3. Peel resistance measurement

Peel resistance measurements were performed on non-aged specimens, and specimens exposed to artificial ageing for 6 weeks. Results from the tests are expressed as the average peel resistance across 5 parallel specimens from each material sample, calculated according to NS-EN 12316-2:2013 [23]. Results from the measurements are presented in Fig. 15 with error bars representing standard deviations.

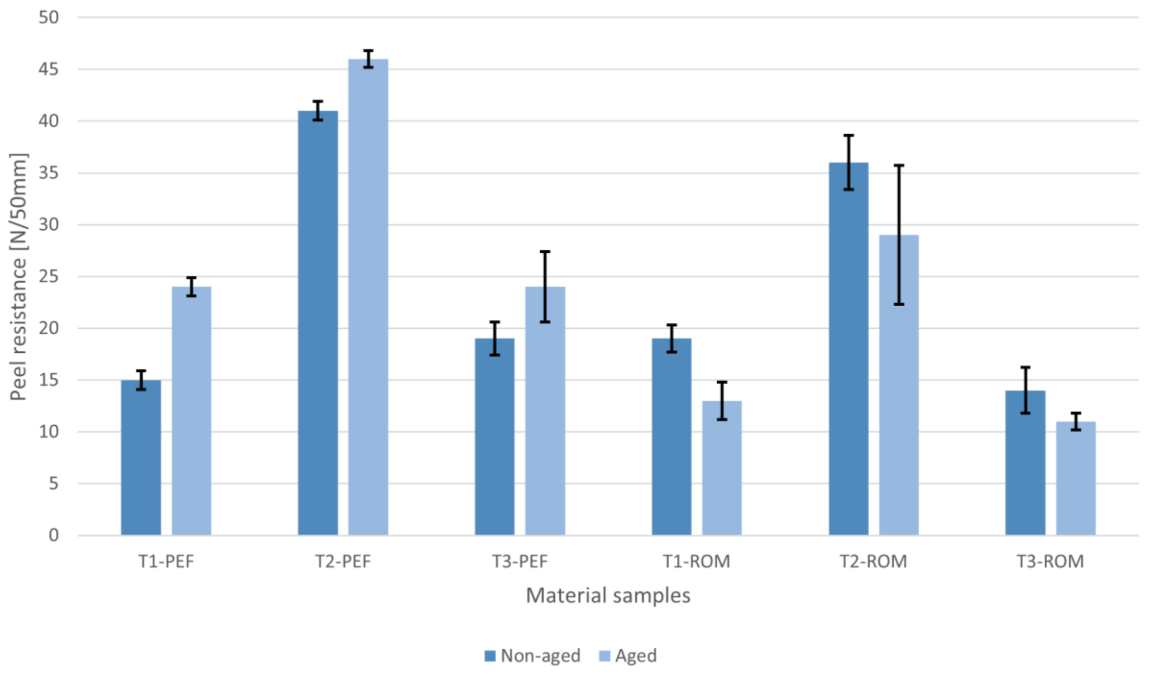

Fig. 15. Peel resistance measurement results.

Average peel resistance measured among the non-aged specimens ranged from 15 to 41 N/50 mm for the PEF samples, and 14 to 36 N/50 mm for the ROM samples. On both substrates, T2 displayed a peel resistance approximately two times higher than that of T1 and T3. Following the heat ageing procedures, the PEF samples exhibited a moderate increase in peel resistance, while all ROM samples experienced a decrease in peel resistance after undergoing ageing in the climate simulator, as shown in Table 6.

Table 6
Relative change in peel resistance after artificial ageing.

PEF samples	Relative change	ROM samples	Relative change
T1-PEF	+ 60%	T1-ROM	-32%
T2-PEF	+ 12%	T2-ROM	-19%
T3-PEF	+ 26%	T3-ROM	-21%

Table 7 shows the most prevalent failure mode of each material sample. All non-aged specimens failed due to adhesive failure, i.e., mode A. Among the artificially aged specimens, failure mode A was still predominant, although the T2-PEF specimens failed due to delamination of sheet, i.e., mode C.

Table 7
Peel failure types.

Material sample	Non-aged specimens	Aged specimens
T1-PEF	A	A
T2-PEF	A	C
T3-PEF	A	A
T1-ROM	A	A
T2-ROM	A	A
T3-ROM	A	A

5. Discussion

In terms of airtightness durability, the tape T3 exhibited the poorest performance among the tapes on both substrates as all its associated specimens failed during the artificial ageing procedure. Since T3 is a tape not developed or certified for permanent application in air or vapour barrier systems, the failure of the T3-PEF and T3-ROM specimens can be regarded as an indication that the method in development is able to detect unsuitable tapes. In contrast, the peel resistance results alone did not provide sufficient grounds to conclude that T3 is unsuitable.

As none of the material samples displayed a peel resistance reduction larger than 50% after ageing, all tapes have sufficient adhesion to the substrates to meet the durability requirements outlined in the SINTEF Technical Approval guidelines for air and vapour barrier tapes. It is, however, important to acknowledge that the aging procedures employed in this study deviated to some extent from those specified in the SINTEF guidelines. Furthermore, the guidelines require testing of peel resistance to more substrate materials.

The method in development can be considered a medium-scale test method as it constitutes a compromise, in terms of complexity, between the standardized peel, shear and tensile tests, and the full-scale methods presented in Section 2: Theory.

The permeability test method is considered less reliable in quantifying properties inherent to various product combinations compared to the peel resistance test, NS-EN 12316-2 [23], as the permeability estimates appear to depend heavily on the implementation quality of individual specimens. Nevertheless, by measuring air permeability directly, the method in development does not rely on a supposed correlation between airtightness, and mechanical or adhesive properties. As the main purpose of an adhesive tape in this context is to provide airtightness, the concept of measuring air permeability directly is considered a potentially more valid approach to product evaluation.

The method in development is less complex compared to the full-scale methods utilized by Antonsson and Ylmén et al., as it only assesses individual barriers without considering components such as windows, timber framing or pipe penetrations. The reduction of scale and complexity is regarded as beneficial for time and cost efficiency in performing tests, and potentially also regarding reproducibility. Still, this scale reduction and simplification of specimens may cause relevant ageing mechanisms and factors to be disregarded, rendering the test less representative of realistic conditions.

The ageing procedure performed on the PEF peel resistance specimens deviates from the SINTEF Technical Approval guidelines for vapour barrier tapes, as it did not include exposure to UV radiation for 48 hours prior to heat ageing. In addition, the duration of the heat ageing procedure was only half of the 12 weeks used during durability evaluation in Technical Approval. As for the ROM samples, current guidelines for Technical Approval of air barrier tapes demand only 2 weeks in NT BUILD 495 as opposed to 6. According to the guidelines, air barrier tapes must undergo additional heat ageing for 24 weeks.

The measurement program exclusively involved specimens with joints composed of simple tape joints used to cover cuts in membranes, thus not accounting for overlapping joints. Overlapping joints are believed to potentially exhibit different responses, compared to simple joints, to both climatic strains during artificial ageing and to mechanical strains induced by pressurization during the measurement procedure.

Moreover, as specimens were exclusively subjected to positive differential pressure, the impact of negative pressure differences on permeability rates remains unexplored.

6. Conclusions

Sufficient airtightness in buildings is essential to meet increasingly stringent energy efficiency requirements, and to prevent damages and issues arising from moisture transfer. In order to achieve this, it is crucial to seal joints, connections, and penetrations in the building envelope, using solutions and products with satisfactory performance in the long-term. For this purpose, a test method was developed as part of this thesis, to assess the durability of adhesive tapes based on air permeability.

Basing on results from the measurement program, the test method appears capable of measuring permeability rates with sufficient accuracy to distinguish different material combinations from each other, provided test specimens are prepared in a uniform manner. However, permeability rate estimates depended heavily on the implementation quality of individual specimens, making it difficult to determine what share of the leakages could be attributed to inherent product properties as opposed to the quality of workmanship. This impacted reproducibility negatively, in particular across material samples involving flexible substrates.

The degradation of airtightness observed after ageing in the permeability test was not consistent with the durability evaluation based on peel resistance measured according to NS-EN 12311-2 [26]. While all material samples experienced significant increase in air permeability after ageing, the parallel peel resistance measurements provided a significantly more optimistic durability assessment. Nevertheless, the results obtained from the method in development appear to correlate with those obtained from other experimental approaches that assess air permeability.

With further improvement, the method presented in this paper is considered applicable as a mean of evaluating the durability of adhesive tapes as part of product development or certification. In the context of separate tape evaluation, the method could potentially constitute a supplementary test to currently established evaluation methods, NS-EN 12311-2 [26], NS-EN 12316-2 [23] and NS-EN 12317-2 [27].

The test stand is considered highly configurable, as it allows for the specimen layout to be altered, for instance by utilizing solid boards as substrates and including additional components, such as adhesive pipe collars. This versatility makes it possible to perform permeability tests on the same standard substrates used in Technical Approval of air and vapour barrier tapes. Furthermore, specimens can be inverted, enabling exposure to both positive and negative pressure differences.

While the test method in its current form might not be capable of accurately determining the air permeability and durability of joints, it is believed that an improved version can achieve satisfactory precision in determining specimen leakage rates by incorporating improvements aimed at minimizing system leakage rates. The permeability of a specimen as a whole, expressed as leakage per unit area, can then be used for comparison against predefined threshold values. In terms of durability evaluation criteria, it is considered more suitable to establish absolute threshold values for permeability before and after ageing, in contrast to current guidelines for peel and shear resistance evaluation, in which durability is evaluated based on relative change in material properties after artificial ageing.

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