Bachelor's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

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Radon barriers: A state-of-the-art review and future opportunities

Radonsperrer: Fra dagens state-of-the-art løsninger til fremtidens muligheter

Bachelor's thesis in Civil and Enviromental Engineering
Supervisor: Bjørn Petter Jelle
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Report is OPEN

Problem definition, describing the project and performance goals

In this project we want to test, show and conclude if alternative radon protection measures can be used instead of traditional radon barriers. This has been done by using airtightness and radon diffusion resistance. We have compared materials by making a table with all the essential properties for radon protection capabilities.

Keywords:

Radon, Radon barrier, Radon diffusion, Air tightness, Air permeance, Concrete, Review.

Norwegian Abstract

Forskjellige løsninger for radonsperrer har blitt sammenlignet og studert. Kommersielle radonsperrer og andre materialer har blitt satt opp mot hverandre for å vise hvilke av de som kan være velfungerende barrierer. De viktige egenskapene for å bestemme akkurat dette er radondiffusjonmotstand, lufttetthet. I tillegg har andre essensielle egenskaper også blitt inkludert. Den samlede informasjonen for kommersielle radonsperrer kan bli brukt for å gi en oversikt av fordeler og ulemper for hver state-of-the-art sperre, som kan brukes til å visualisere hvert materialets potensial. Betong kan muligens fungere som radonbeskyttelse hvis den er støpt riktig eller lagt riktig, men flere utfordringer som kommer med betong har også blitt diskutert som sprekker og aldring. Andre potensielle radonsperrer som PVC duk, bitumen og flere andre materialer har også blitt gjennomgått og noen ser ut til å ha en tilfredsstillende verdi for radondiffusjonmotstand. På en annen side så er det uklart hvor anvendelig disse materialene er. Videre så har varigheten til kommersielle radonsperrer, i tillegg til deres brukbarhet, bli evaluert. Utover så forklarer og introduserer denne oppgaven noen kommersielle sperrer og fremtidige teknologier og produkter som inkluderer selvhelbredende betong og membraner samt bioplast. Videre så kan denne oppgaven bli brukt til å vekke interesse for radonteknologiens utvikling og føre til fremskritt for radonbeskyttelse.

Preface

This bachelor thesis constitutes the finalization of the three-year bachelor program within the department of civil and environmental engineering. It is written under the faculty of engineering at the Norwegian University of Science and Technology (NTNU), during the spring term of 2023.

This thesis entails a review of the state-of-the-art radon barriers on the market and discusses the possibility of their replacement by other common materials. Furthermore, this thesis dives into less known current- as well as prospective materials on the market with self-healing or more sustainable capabilities, for future development. NTNU instigated this thesis through Bjørn Petter Jelle and SINTEF research on radon. We would like to extend a special thanks to our teaching supervisor Bjørn Petter Jelle, in acknowledgement for his willingness to help and invaluable guidance. Without him, this thesis would not have been realized.

The research to write this thesis has been instructive and we hope that our work will be of similar instructiveness for readers. This study is intended for submission for a scientific journal.

Maria Mørch

Maria Elisabeth Mørch
Trondheim, Norway
May 2023

Erik Molin

Erik Alexander Molin
Trondheim, Norway
May 2023

Future perspectives

We would have liked to do an experiment, instead of using values from earlier articles. This would have facilitated more reliable values presented in Table 2 and especially in Table 3. We would also have liked to include more data in the tables and have more time to do research to find the airtightness of all the products, if these values have even ever been measured. Furthermore, we would have liked to study why some commercial radon barriers have higher radon diffusion resistances even though the materials are thinner, how the additives work, what mixing and ingredients directly affect the radon tightness. It would be interesting to research if a combination of the different strengths of the materials could give a better solution, then what we have today. For example, if it would be possible to combine concrete with cardboard? The combinations would be endless and it might be possible to find a match that could work theoretically and practically to further improve radon protection in the future.

There should be further research regarding radon in general as well as radon barriers. We hope that the future possibilities mentioned in this thesis are inspiring for the building industry. Moreover, we wish that the future possibilities are further studied and explored, so that they can be implemented and realized to such a degree that they can become commercial. This will likely lead to less waste of materials, less renovation labor and thus leading to preserving energy, money and contributing to a more sustainable future.

Thesis Contents

Radon barriers: A state-of-the-art review and future opportunities

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Abstract

To compare different solutions for radon barriers, potential materials have been studied. Firstly, commercial radon barriers and secondly other materials that might have potential as radon barriers. Multiple properties have been analyzed such as radon diffusion resistance, air tightness and others. The collected information for commercial barriers can be used to give an overview of the strengths and weaknesses of each state-of-the-art barrier, and may help visualize their potential. Concrete has potential to work as radon protection if installed properly, therefore, multiple uses, types and challenges with using concrete as radon barriers, have been discussed such as cracking and aging. Other potential radon barriers such as PVC sheets and bitumen and more have also been reviewed and some seem to have a satisfactory radon diffusion resistances value. However, their applicability is still unclear. Moreover, the durability of commercial state-of-the-art barriers as well as installations of these products have been evaluated. This study also further explains and introduces some state-of-the-art and future technologies and products that include self-healing concrete, self-healing membranes and bio-plastics. Moreover, this study may be used to spark the interest into these technologies for further development and advancements in the field of radon protection.

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Keywords:

Radon, Radon barrier, Radon diffusion, Air tightness, Air permeance, Concrete, Review.

1. Introduction

Radon barriers are often a thin polymer material placed in the building foundation, to protect the building from accumulating a high indoor radon gas concentration. Exposure to radon gas increases the risk of lung cancer, hence it is of great importance that this barrier remains intact. However, research on these barriers' life expectancy is not available today. Hence a sustainable material would be helpful, especially when the building industry is leading in this direction. Moreover, a sustainable material would probably not require a replacement or further measures of radon protection, and therefore benefit users both economically and time-wise. Nevertheless, both state-of-the-art radon barriers and other common building materials have limitations and advantages. This study examines state-of- the-art barriers on the market today and other potential materials, along with a discussion of issues of these barriers, and future solutions and possibilities.

By using Jelles (2012) mathematical model it was found that the most important characteristics for radon protection are radon diffusion resistance and air permeance. A high radon diffusion resistance and a low air permeance value through a barrier is necessary to protect buildings from a high radon concentration. There are different methods to calculate these two values. For radon diffusion resistance, Jiránek and Kačmaříková (2019) calculated this value by two ways depending on the value of fraction of two variables, which determined if the material should have a linear or exponential radon distribution. Another method was introduced by Keller and Hoffmann (2000), where they instead focused on "radon tightness", and wrote that a material should be radon tight if the thickness is three times the radon diffusion length. Both methods are included in this study, where the method by Jiránek and Kačmaříková is used in the tables. Two air permeance methods are mentioned, but only one has been used, which is NBI 167/02 (SINTEF, 2016).

The objective of this study is to review commercial radon barriers and also other common building materials, to research different methods of measuring air tightness and radon diffusion resistance, and to explore various future perspectives and opportunities for radon barriers. In order to comply with these purposes, this study will first present different methods of calculating radon diffusion resistance and air tightness. Secondly it will give a review of data collected for state-of- the- art review barriers and other materials. Lastly, future materials and possible solutions. Many of the commercial barriers in this study have a technical approval by SINTEF. However other commercial barriers without approval and other common building materials are included in order to compare their radon protection potential.

2. Theoretical basis

2.1 Radon

Radon (^{222}Rn) is an element which comes as the decay product of radium (^{226}Ra), which again is the decay product of uranium (^{238}U). Uranium is all over the world and as uranium rich soil is common, workers and residents have to deal with its decay products and the health impacts of these radioactive elements.

Radon is a noble gas that appears as an invisible, odorless gas that seeps through the ground. Radon is known mainly as gas because of its low boiling point. Uranium and radium have boiling points at 4131 °C and 1737 °C respectively, while radon has its boiling point at a substantially lower temperature -61,7 °C. Thus, this difference causes uranium and radium to stay in the ground while radon seeps up from the soil and into the air as gas (Nuclear-power, 2023; HBCP, 2023).

Radon gas concentration in indoor environments has increased as the standards for housing and buildings have become more airtight. This change prevents radon gas from escaping the room it is encapsulated by. Changing one aspect of a house such as insulation, airtightness or ventilation will lead to a series of unexpected changes for that house. One such unexpected change was the rise of indoor radon levels. Typically, the buildup of this concentration stems from leakage through the basement ground and floor. Microcracks in concrete and other layers of the foundation of the house combined with air tightness towards upper floors and the outside of the construction frame will lead to a high indoor concentration of radon within that respective story.

The danger of radon comes from the effects it has on the people inside an enclosed construction. Exposure to a high concentration of radon for a significant amount of time will increase the risk of developing lung cancer. Only smoking leads to a higher percentage of lung cancer cases (United States Environmental Protection Agency, 2023). Therefore, according to World Health Organization (WHO) and the Norwegian DSA, it is recommended to keep the radon concentration under 100 Bq/m^3 in environments with permanent residence (DSA, 2023.; World Health Organization, 2023). In addition, according to TEK17, which is the regulatory framework for building quality in Norway, a house is not allowed to have a concentration over 200 Bq/m^3 for any room with permanent residence. A similar limit can also be found in other countries and regions as presented in Table 1 (DIBK, 2017).

Table 1: Regulatory framework for different countries and regions.

Definition	Country/Region	Explanation	Unit	Value	Regulatory framework
Levels of radon gas in buildings	Norway	Recommended maximum limit before taking action	Bq/m^3	100	Regulatory framework (TEK17) with guidance (DIBK, 2017)
Levels of radon gas in buildings	Norway	Absolute maximum limit value, actions necessary	Bq/m^3	200	Regulatory framework (TEK17) with guidance (DIBK, 2017)
Levels of radon gas in new buildings	Sweden	Absolute maximum limit value, actions necessary. (Applies to construction of new houses)	Bq/m^3	200	Regulations from the Swedish National Board of Housing, Building and Planning (2011) and the Swedish Radiation and Safety regulatory act 2018:506 (Sveriges riksdag, 2018; Boverket, 2018)
Levels of radon gas proposed by the European Union (BSS)	EU	Absolute maximum limit value, actions necessary	Bq/m^3	300	EU´s Basic Safety Standard (EU's basic safety standard, 2018) (Council of the European Union, 2013)
Levels of radon gas in buildings (EPA)	USA	Recommended maximum limit before taking action	Bq/m^3 (Originally given in pCi/L 2-4)	74-148	United States environmental protection agency (United states environmental protection agency, 2022)
Levels of radon gas in buildings (EPA)	USA	Absolute maximum limit value, actions necessary	Bq/m^3 (Originally given in pCi/L 4)	148	United States environmental protection agency (United states environmental protection agency, 2022)

2.2 Common measures against radon

There are typically three types of measures against high radon concentrations indoors. These are radon barriers, soil depressurization systems and ventilation systems. The first of these three will be the main focus of this thesis and therefore has its own subchapter 3.1, but the last two are also important radon measures so they will be explained briefly.

Difference in air pressure is the driving force for radon transmittance and therefore by neutralizing that difference, it is possible to mitigate most of the radon that goes into a building. The main place where the building envelope lets in a significant amount of radon is through the lowest floor in a building and so one would typically do the depressurization in the soil beneath the house. This can be done by placing air open pipes that will absorb the radon gas and then pump out the gas with an electrically powered fan. This system is very common in countries like the U.S. In Norway it is more common to use a radon well for soil depressurization, which is an inactive measure against radon. The radon well will be active in situations with high concentrations of radon, but most of the time it will not be active, while a typical American system would be an active radon mitigation system, that constantly runs a fan to pump all the radon out of the soil (Radonmannen, 2023.). The gas then gets transported safely outside the building envelope in pipes so the radon will not be able to get back into the house (United States Environmental Protection Agency, 2016). The problem with this solution is the fact that the pipes that go through the house take up a large amount of space and complicates the structural construction. In addition, the more complicated systems will demand resources for maintenance and the visual aspect of these pipes may be displeasing.

Also, this prevention method uses electricity and can generate some amount of noise which residents can find annoying. Most of these systems therefore have a muffler which will make the whole process quieter (Department of health USA, 2023). It is possible that the U.S. uses soil depressurization as the standard for radon protection as it is a stronger measure than radon barriers as both Radonseal and DSA concludes (DSA, 2023; Radonseal, 2023). Radonseal also further mentions that a radon barrier is just a soil gas retardant. Therefore, it is possible that the U.S. does not see radon barriers as a strong enough measure.

Ventilation is the third way of preventing large radon concentrations in indoor air. This measure uses positive ventilation to pump fresh air into the building. With this constant stream of new air, the radon concentration indoors is being significantly diluted (Envirovent, 2023). However, with this measure it is typically necessary to also install a heater with the ventilator as the residents do not want cold air to get pumped into the house. This ventilation system is efficient in homes with radon levels up to 500 becquerel per cubic meter, so this measure is typically more limited to cases where the radon concentration naturally is too high (PropertEco, 2016).

2.3 Radon detection and mathematical formula for radon concentration indoors

Typically, the radon level of buildings is tested through radon detecting devices. These devices consist of two main categories. Digital radon detectors and measuring using trace film (Airthings, 2018). In addition to these physical measuring methods, there is a mathematical model developed by Jelle in 2012 that gives the indoor concentration of radon (Jelle, 2012):

$$C_a = C_e + P_w\,(C_e - C_a)\cdot \frac{Aw}{V}\cdot\frac{1}{n} + v\,(C_m - C_a)\cdot \frac{S}{V}\cdot\frac{1}{n} + P\cdot(C_g - C_a)\cdot \frac{A}{V}\cdot\frac{1}{n} + q\Delta p\,(C_g - C_a)\cdot \frac{A}{V}\cdot\frac{1}{n} \qquad (1)$$

where C_a = radon concentration in indoor air (Bq/m^3), C_e = Radon concentration in outdoor air (Bq/m^3)
P_w = Radon diffusion transmittance between indoor and outdoor air (m/s)
A_w = Building area towards outdoor air (m^2)
V = Building volume (m^3)
n = air changes per hour (h^{-1})
ν = radon building material exhalation coefficient (m/s),
C_m = Radon concentration in building materials (Bq/m^3)
S = Indoor surface area of building materials containing radon (m^2)
P = Radon diffusion resistance of ground/radon barrier (m/s)
C_g = Radon concentration in ground (Bq/m^3)
A = Area towards ground (m^2)
q = Air permeance of ground ($m^3/(m^2hPa)$)
Δp = Air pressure difference between outdoor ground and indoor ground (Pa)

From this model using the two last parts of the formula, $P\cdot(Cg - Ca)\cdot\frac{A}{V}\cdot\frac{1}{n} + q\Delta p(Cg - Ca)\frac{A}{V}\cdot\frac{1}{n}$ which represent the diffusion and air leakage from ground, it is possible to see which characteristics a material should have in order to possess radon protection capabilities.

For a given number of air exchanges n^{-1}, a constant area and volume, A and V, and given that radon concentration from ground C_g is hard to control, indoor radon level C_a is equal to itself and for a given air pressure difference Δp. One sees that the aspects of the formula linked to the soil/ground depend on the materials radon diffusion transmittance P (m/s) and the air permeance of the ground q ($m^3/(m^2hPa)$). These two metrics specifically have to do with a material used as a ground layer. Which means that for high radon tightness, the two most important metrics for a radon barrier are radon diffusion transmittance (m/s) / resistance (s/m) and its air tightness/air permeance ($m^3/(m^2hPa)$). These two values are therefore emphasized in both Table 2 and 3 to clearly show what commercial radon products and alternative materials have the most potential to be used as radon barriers.

2.4 Radon diffusion resistance

Radon diffusion transmittance is how much radon that goes through a layer for a given time. Typically, the unit for this is m/s. Different materials have varying transmittance values and therefore some materials make much better radon barriers. Radon diffusion transmittance and resistance are opposites and therefore by dividing 1 with the radon diffusion transmittance it becomes the radon diffusion resistance (s/m). The minimum radon diffusion resistance to get technical approval by SINTEF is $\geq 5 \cdot 10^7$ (s/m) (Guidelines for SINTEF Technical Approval, 2022). Typically for many of the articles used, this value (m/s) was given in the form of a radon diffusion coefficient D (m^2/s) and radon diffusion length l (m). The radon diffusion length is the characteristic distance traveled by the radon atoms during one half-life 3.8 days (Mayya, 2015). The diffusion length was available for most materials, but if it was not clearly stated in an article, the diffusion length could be calculated from formula 2:

$$l = (\frac{D}{\lambda})^{0.5} \qquad (2)$$

Where λ is the radon decay constant $2.0833 \cdot 10^{-6} s^{-1}$.

Going from the coefficient to the resistance is simply done by using the materials thickness d and dividing it by the radon diffusion coefficient D (m^2/s). Resulting in the radon diffusion resistance (s/m), which is easily transformable to transmittance (m/s). This formula of going from coefficient to transmittance/resistance was found as a model used by M. Jiránek in 2019, but the formula itself is older (Jiránek & Kačmaříková, 2019).

$$R_{RN} = \frac{d}{D} \qquad (3)$$

This turns out to be an older formula for calculating the radon diffusion resistance/transmittance. Jiránek also proposed a new model for radon resistance properties in this study. This other formula considers that a material's radon content might not be linear through the material, as proposed by formula 3. It was found that in certain materials, the radon distribution instead is exponential. The radon resistance should then instead be calculated by:

$$R_{RN} = \frac{\sinh(d/l)}{\lambda \cdot l} \quad (4)$$

The same article from Jiránek also presents us with a way of calculating if the radon distribution is linear or exponential. The way to check this is with formula 5:

$$\frac{d}{l} \geq 0.8 \quad (5)$$

If thickness divided by the diffusion length (m) equals 0.8 or higher, then formula 4 should be used to determine the radon diffusion resistance as the radon distribution is exponential. If d/l is lower than 0.8 then formula 3 should be used. These two formulas have been used several times in Table 3 to go from radon diffusion coefficients (m^2/s) to radon diffusion resistances (s/m) and transmittances (m/s). In Table 3 "AM" is used to indicate that an advanced method, which is formula 4, has been used. If a calculated radon resistance uses formula 3, it does not say AM. Further explanation of the theoretical knowledge behind these formulas can be found in another article by the same author Jiránek, "A new approach to the assessment of radon barrier properties of waterproofing materials" (Jiránek & Svoboda, 2017)

Additionally, there exists a principle to determine if a material is "radon tight". This principle is based on the article by G. Keller and B. Hoffmann (2000), "The Radon Diffusion Length as a Criterion for the Radon Tightness". Their principle states that if the thickness of a sample is 3 times the diffusion length it can be considered "radon tight" (Keller & Hoffmann, 2000). Based on this principle the materials included in this thesis can be categorized as "radon tight" or not based on the tests in chapter 9.

2.5 Airtightness

Airtightness, also called air permeance of air permeability, is a unit for the amount of air that can pass through a material. The more air that passes through, the higher the air permeance. It is important to differentiate between air permeance (the air that passes through the material) and air leakage, which is the air that passes through holes or gaps. The method used in this article for figuring out the airtightness for materials for Table 2 and 3 is NBI 167/02, which is used by SINTEF to test radon barriers airtightness (SINTEF, 2016). The box used in this test method is shown in Figure 1.

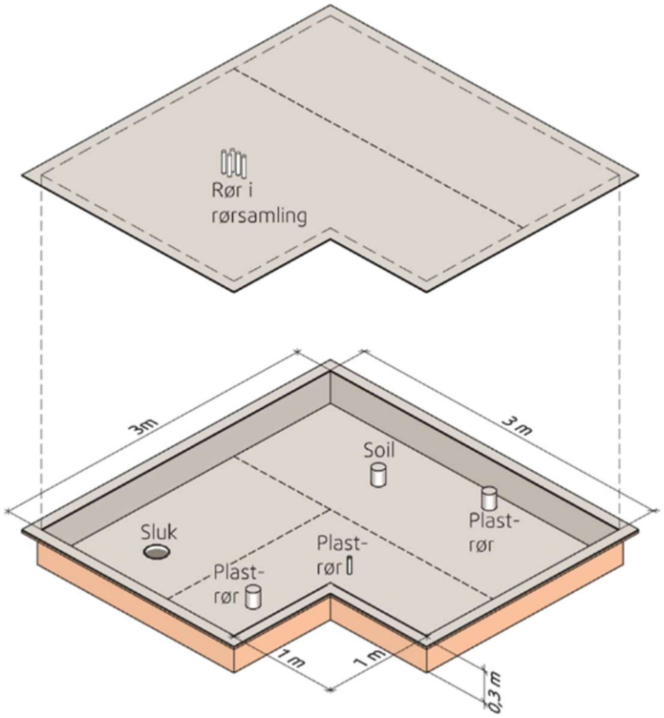


Figure 1: Test rig for measuring air tightness of radon barriers with joints (shown dotted line), corners and openings by NBI 167/02. Area: 19.6 m^2 *(SINTEF, 2016).*

However, the unit used for this in Norway is l/min, liter per minute, which is common in Scandinavia, but internationally $m^3/(m^2hPa)$ is more usual. Therefore, the tables include both the Norwegian and the international units for airtightness. Below is an independent calculation formula to go from l/min to $m^3/(m^2hPa)$, based on test method NBI 167/02:

$$\frac{l}{min}\cdot\frac{1}{m^2\cdot Pa}=\frac{m^3}{\frac{1000\,h}{60}}\cdot\frac{1}{m^2\cdot Pa} \qquad (6)$$

Method to calculate l/min to $m^3/(m^2hPa)$ with 30 Pa pressure difference:
q = 5.0 L/min x 1/ (A x 30 Pa) = 5.0 L/min x 1/ (19.6 m^2 x 30 Pa) = 5.0 x (m^3/ (1000 h/60)) x 1/588 m^2Pa
= $5.1\cdot10^{-4}$ $m^3/(m^2hPa)$

Method to calculate l/min to $m^3/(m^2hPa)$ with 50 Pa pressure difference:
q = 5.0 L/min x 1/ (A x 50 Pa) = 5.0 L/min x 1/ (19.6 m^2 x 50 Pa) = 5.0 x (m^3/ (1000 h/60)) x 1/980 m^2Pa
= $3.1\cdot10^{-4}$ $m^3/(m^2hPa)$

where A is the area of the box in NBI 167/02: 19.6 m^2, this is why this value has been used for area in the calculations above.

The requirement in Norway to get technical approval from SINTEF for sufficient air tightness is to have below 5.0 L/min (Guidelines for SINTEF Technical Approval, 2022). Similarly, $5.1 \cdot 10^{-4}$ m^3/(m^{2}hPa) in international units calculated with the method above.

Another test method is the ASTM E-2178 as shown in Figure 2, which is used in the US, where the maximum accepted air permeance through a material is 0,004 cfm/ft^2 or 0.02 L/(s•m^2) at 75 Pa. This value is additionally used by the Air Barrier Association of America (ABAA) in their evaluation of air barrier materials as well as also being the threshold in the international energy conservation code known as IECC (W.R meadows, 2023).

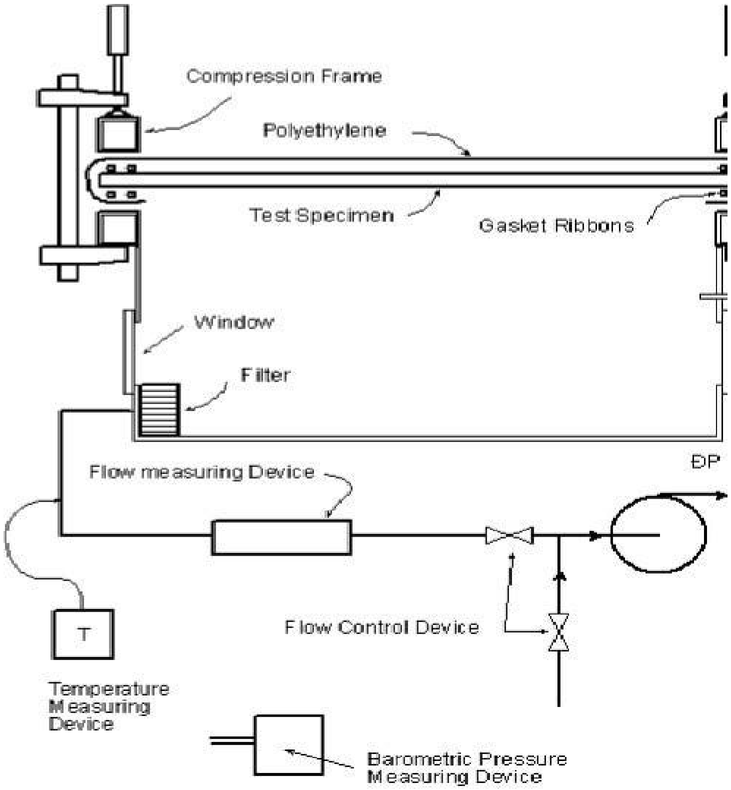


Figure 2: ASTM E2178-13: Standard Test Method for Air Permeance of Building Materials
(W.R meadows, 2023).

2.6 Radon concentration worldwide

Radon concentration worldwide varies substantially by region and country. Figure 3 shows radon levels for most countries. Sweden, Finland, and Mexico have some of the highest values. Only 35 percent of all countries worldwide have radon data available, whereas Africa only has mapped 6 percent. However, 76 percent of the population in the world has radon data available and 71 percent of the surface of the continents is mapped (Zielinski, 2014). The reason for high radon levels in Sweden and Norway is the bedrock, which contains mostly granitoids and sediments such as black shales that are enriched in uranium (Dose, 2022). As Norway has such a high natural amount of radon as can be seen with the orange coloring in Figure 3, it was necessary to have a measure against high indoor radon concentrations. The consensus within the Norwegian directorate for building quality was that radon barriers were sufficient enough to stop radon leaking into the building envelope in most cases. This as stated earlier, is not the case worldwide as can be seen with the radon mitigation systems used in the US that work differently. This thesis mainly focuses on radon barriers as this is the standard measure in Norway.

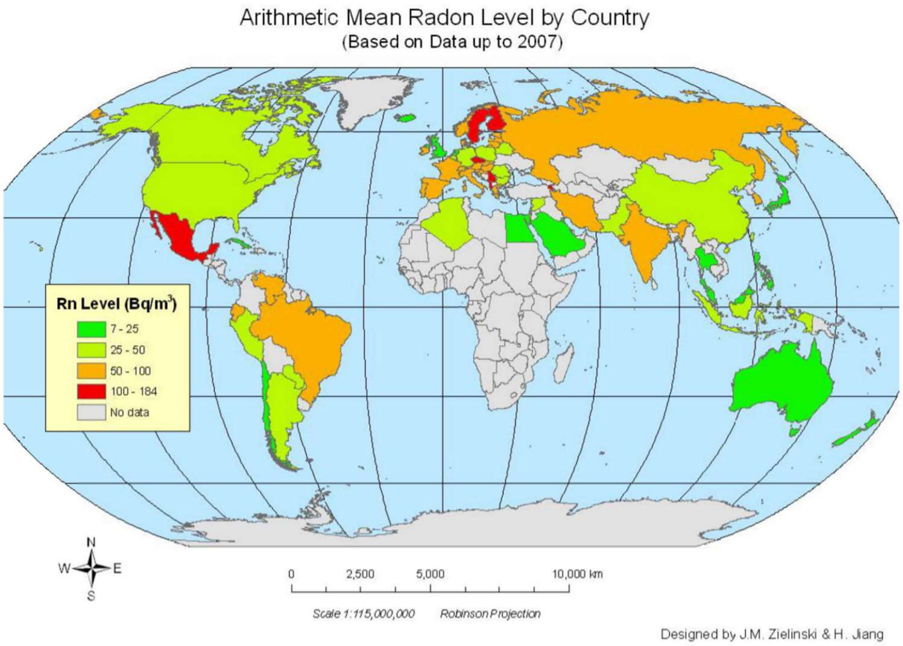


Figure 3: Radon level by country (Zielinski, 2014)

3. Radon barriers

3.1 Commercial radon barriers

Radon membranes/barriers is the most common measure of radon prevention in Norway. A commercial radon barrier is a sheet made of plastic that will keep most of the radon gas out of a building if properly installed. Therefore, execution of the radon barrier installation needs to be as flawless as possible because only a small puncture in the barrier will result in a high concentration of radon in indoor air (Jelle et al., 2011). This prevention method is more energy efficient than active soil depressurization methods as the barriers uses no energy to function. Once it is installed it should work as an independent active measure against radon, because it does not rely on anything else such as electricity so the residents will not know it is there.

The reason that plastic sheets are used as radon barriers is simple: plastic is long-lasting, strong, airtight, watertight, and cheap. Radon barriers also typically use the most common type of plastic polyethylene (PE). Most radon barriers that have been tested in Table 2, can be seen to be made from polyethylene or polyolefin and the polyolefin group again includes polyethylene and polypropylene (Britannica, 2022). So, the materials named polyolefin are one of these two types, but it is not stated in the technical approvals whether it is polyethylene or polypropylene. Polyethylene, is commonly used for packaging such as plastic bags, firms, bottles, etc. The price also makes this type of plastic mass-producible for use in radon barriers. Radon barriers are typically a form of PE that is tougher, thicker and made for being radon tight, airtight and watertight. PE can also be made in a stronger form such as HDPE. High-density polyethylene (HDPE) is a thermoplastic polymer made from petroleum. This specialized material can also be used for similar purposes. HDPE is known for its outstanding tensile strength and large strength-to-density ratio, in addition to a higher-impact resistance (AcmePlastics, 2023). All the polymeric materials have damp proofing capabilities and can thus be used as a damp proofing sheet. Therefore, it is also common to use radon barriers as a substitute for damp-proofing membranes in floors as well as in basement walls.

Some materials are characteristically better suited for radon protection uses and when it comes to commercially sold radon barriers these materials tend to be made of plastic, bitumen, asphalt, and such. These are materials that naturally have a high radon diffusion resistance, sufficient air tightness as well as often being cheap and efficient. However, alternative materials could also be acceptable as buildings can be approved in Norway without a radon barrier, if sufficient radon protection can be proven (DIBK, 2017). Concrete and other materials that can be used for flooring might have the potential to be used for a barrier instead of the polyethylene plastics that are used today.

3.2 Concrete

Concrete is the most common building material in the world as the material is cheap, strong, and reliable (Kilgore companies, 2021). However, as this article mainly focuses on radon, some more overlooked attributes in concrete such as airtightness and radon resistance will be able to give the answer to if concrete floors need separate measures for radon protection or if the concrete in itself is sufficient. Therefore, multiple types of concrete have been tested and presented in Table 3 to visualize radon- and airtightness. The types selected are common concrete both as cast-in-situ slabs and precast factory blocks, as well as heavyweight concrete, aerated concrete, and polymer concrete, see Figure 4.

Cast-in-situ common concrete typically has a porosity of around 9% to 10% (Cruz et al., 2015) and has a weight of typically 2500 kg per cubic meter (All about public works, 2008). These attributes constitute a material which in pristine condition might be able to protect from alpha radiation. However, many of the current concrete walls, slabs and floors in Norwegian basements are not radon tight (Rognerud, 2009). The lack of tightness stems from irregularities when the concrete was casted and from the fact that concrete will change over time. Concrete that was acceptable as radon protection 20 years ago might not be sufficient now, because of new laws and regulations, but also because of physical degradation. This is the case for cast-in-situ common concrete, but concrete is also bought precast in the shape of factorized blocks. Concrete blocks or concrete masonry units are produced both as full blocks and as hollow cores. There exist several variations of these two block types such as concrete stretcher blocks, concrete corner blocks, lintel blocks and so on. The advantage with these blocks is that they do not need to be cast on field as cast-in-situ concrete needs to. Thus, the installation of concrete is no longer weather dependent and can be installed at any time as they are also typically quicker and easier to use. In addition to this, wall thickness can be reduced with blocks as the material can hold more weight, as well as the fact that it provides better thermal insulation, in addition to several other benefits. However, this type of concrete is more expensive and is more likely to be subject to water seepage (Singh, 2023). Especially if there are cracks developing in the material.

Heavyweight concrete is not as widely used as common concrete and mainly serves as radiation shielding. The heaviness of this concrete comes from heavier aggregates such as barytes, magnetite or metals. The dry density must be over 2600 kg per cubic meter to be called heavyweight, but the density of this type of concrete can even exceed 9000 kg per cubic meter (Concrete Society, 2023). With these metrics in mind, heavier concrete seems to serve the role as a radiation protector better than common concrete. However, metrics presented Table 3 should be used to conclude if heavyweight protects better from radiation than common concrete. However, a consumer should know that typically a higher density concrete will be more expensive per cubic meter.

Aerated concrete is a lighter type of concrete consisting of 80% air and therefore the typical density of this material is 300 to 1800 kg per cubic meter (Almalkawi et al., 2018). This type of concrete is primarily made into desirable shapes in the factory and sold as blocks. So, it is not a cast-in-situ concrete. This type of concrete is also airtight, resistant to water, rot, mold, and insects (Portland Cement Association, 2023). Therefore, it could be a satisfactory material for radon protection if the radon diffusion resistance is high and air tightness is sufficient.

Polymer concrete (PPC) is another type of concrete that has been included in Table 3. Polymer concrete is a composite concrete with synthetic polymer within the binding material. This binding gives the concrete lower permeability, higher durability, higher tensile strength, and better resistance to weather (Mishra, 2021). The higher durability will logically help slow down the degradation process of the material so PCC will not, in most cases, lose its radon diffusion resistance as fast as common concrete. Same as aerated concrete, PCC is also watertight and will therefore never corrode. It is roughly at the same density as common concrete, 2370-2450 kg per cubic meter (Pyataev et al., 2019). Polymer concrete is commonly used for swimming pools, repairing manholes, drainage pipes and more.

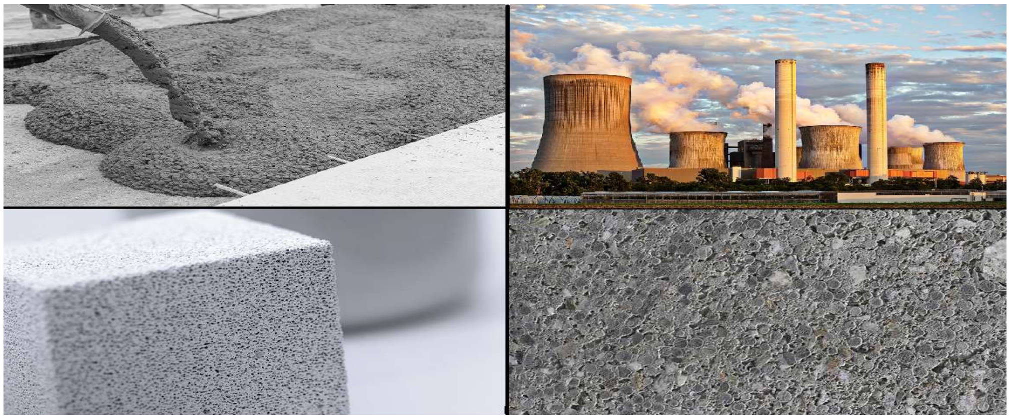


Figure 4: Different types of concrete and some uses. Top left common cast-in-situ concrete (National ready mixed concrete association, 2023), top right heavyweight concrete for nuclear stations (Monroy 2021), bottom left aerated concrete (Eckart, 2023) and bottom right polymer concrete (Capital Concrete cutting Inc., 2018).

3.3 Cracks in concrete

Concrete structures may be subjected to different cracking mechanisms during their lifetime, but concrete cracking is detrimental when it comes to durability, aesthetics, air- and water tightness and radon diffusion resistance. The main reasons for crack development in concrete are mechanical loading volume changes, environmental conditions, and chemical reactions (Klausen, 2017).

As mentioned before, cracks have a major impact on the gas tightness of concrete. Micro surface cracks and flexural cracks do not go through the whole material but will still increase the concrete's permeability. However, for such cracks, the gas still must be transported through solid concrete and the permeability is in this way still porosity- dependent. Through- cracking shown in Figure 5, is the leading crack mechanism when it comes to gas tightness, because under such conditions the permeability is no longer porosity-dependent but crack- dependent. The gas will then pass through the crack instead of using the diffusion process within the material. The flow rate through a concrete through-crack is proportional to the width cubed, and therefore the permeability increases considerably with increasing crack width (Klausen, 2017).

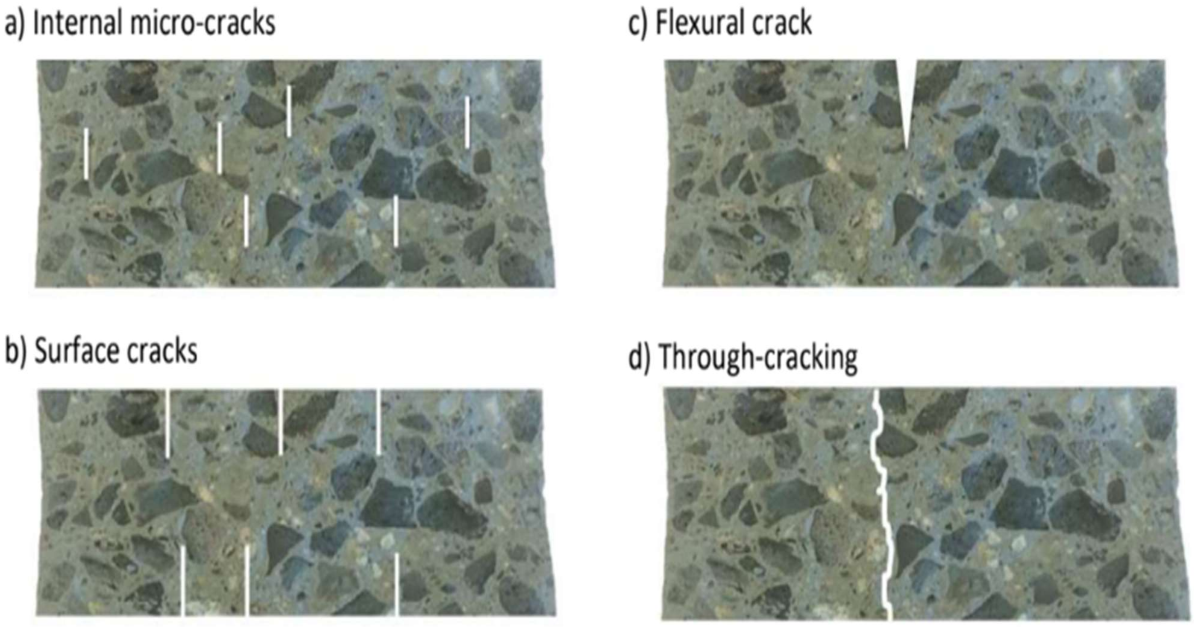


Figure 5: Different crack types in concrete (Klausen, 2017)

3.4 Other materials

The choice of materials that have been featured in this category is mainly because they had a known radon diffusion coefficient, found in earlier articles about radon.

Limestone: According to PubChem limestone is practically insoluble in water. However, it is soluble in acid rain (PubChem, 2023). The problem with limestone is its air and water porosity/permeability as this rock is not airtight or watertight (SimpleCoat, 2020).

Brick: Bricks are porous and are thus not airtight. Bricks are often used as the outer layer of a wall that protects from driving rain as bricks are water resistant, but not watertight. This is the reason that brick cannot protect the wall entirely from damp or excess moisture from seeping into the inner layers of the wall. The mortar between the bricks also contributes to high water permeability (Scott, 2023).

Gypsum: Gypsum can be used to achieve airtightness, this is proven with products like gypsum airtight drywalls (Building Science, 2009). Gypsum is water soluble; this means that it has to be mixed with additives or needs to have a separate coating made from other materials in order to not to be dissoluble in water.

Bitumen: Bitumen membranes (BM) are typically used for flat roofs as they are watertight (Sd=95m) (Riwega, 2021). Bitumen, also known as asphalt, is a sticky, black and highly viscous liquid, or semi-solid form of petroleum. Bituminous membranes are used as vapor barriers and vapor barriers are commonly watertight as well as airtight (Sika group, 2023).

EPDM: Ethylene propylene diene terpolymer (EPDM), is a high durability synthetic rubber used for roofing membranes. It is widely used in low slope buildings worldwide. Fossil fuels are made to manufacture this type of rubber as the main ingredients are ethylene and propylene (EPDM roofing association, 2023). EPDM is watertight and airtight.

Cardboard: Cardboard is a common term for hardened or heavy paper-based products. Additionally cardboard/paper can protect against the most basic forms of radiation. Radon gas, which radiates alpha particles, can easily be shielded with paper. The problem is that paper and cardboard is typically very porous and so it is not very airtight or watertight. However, there exist products like cardboard coating that make paper materials waterproof (GWP Group, 2018).

PVC Sheet: Polyvinyl chloride (PVC), is one of the most common plastic materials. PVC's original form is hard and strong. However, it can be mixed with elastomers, plasticizers or other additives, which gives the materials varying properties ranging from soft to rigid construction materials as well as change the air tightness and much more (Gop, 2023.; Fujian Sijia Industrial Material Co.,Ltd, 2023). PVC can be made to work as a waterproof material depending on its composition. As this is one of the most used materials for water pipes, it is proven under pristine conditions that PVC is a waterproof material (PVC Fittings Online, 2017).

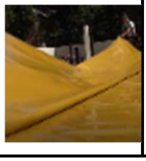
Aluminum foil: Aluminum foil is thin leaves made of aluminum that have a thickness of less than 0.2 mm (Aaluminum, 2023). They are easily bendable and therefore are often used for storing or keeping food warm as metals have a good ability to store heat. Aluminum foil also has a great ability to stop alpha particles and can therefore protect from radon radiation (Washington State Department of Health, 2003). However, aluminum foil is typically not airtight but there exist aluminum containers or tape products with this ability (AlFiPa, 2023).

4. Collection and comparison of radon barriers

Table 2 contains information about commercial radon barriers that are currently being sold in Norway. The main characteristics included in Table 2 are air tightness ($m^3/(m^2hPa)$), radon diffusion transmittance (m/s) and resistance (s/m). Information about the first 6 barriers originates from SINTEF Technical Approvals, while the last 3 have come from commercial websites. The website for some barriers did not include air tightness or tensile strength (N/50 mm). Therefore, these metrics could not be included for every product. For the radon coefficients in this table, the formula presented by Martin Jiránek, formula 3, has been used to go from radon resistances to radon coefficients. However, there were no diffusion lengths available and without the diffusion length, it is not possible to use formula 4 or 5. So these values could not be validated.

Table 2: Radon barriers products and properties.

				SP-Method 3873 / RISE-Method 3873		NBI-Method 167/01 and 167/02			EN ISO 12572:2001		EN 12311-2000(B)			
Producer	Product/ material	Visual representation	Radon diffusion coefficient (m²/s)	Radon diffusion transmittance (m/s)	Radon diffusion resistance (s/m)	Air permeance (ΔP=30 Pa) (l/min)	Air permeance (ΔP=30 Pa) (m³/(m²h Pa))	Material	Thickness (mm)	Mass per area (g/m²)	Tensile strength along (N/50 mm)	Tensile strength across (N/50 mm)	SINTEF technical approval (TG)	Source link
Isola	Radon barrier: Radonsperre 400 Plastic sheeting		$7.5\cdot10^{-12}$	$1.9\cdot10^{-8}$	$5.3\cdot10^{7}$	1.2	$1.2\cdot10^{-4}$	Polyethylene	0.4	400	≥ 400	≥ 400	Yes	(Isola, 2023)
Canes	Radon Barrier: Radonsperre Plastic sheeting		$6.0\cdot10^{-12}$	$\leq 2.0\cdot10^{-8}$	$\geq 5.0\cdot10^{7}$	0.7	$7.1\cdot10^{-5}$	Polyethylene	0.3	279	≥ 400	≥ 400	Yes	(Canes, 2023)
Glava	Radon Barrier: Radonsperre Plastic sheeting		$1.5\cdot10^{-13}$	$0.5\cdot10^{-9}$	$2.0\cdot10^{9}$	≤ 3.9	$4.0\cdot10^{-4}$	Polyethylene	0.3	285	≥ 400	≥ 380	Yes	(Glava, 2023)

Jackon	Radon Barrier: Radon Barrier A Plastic sheeting		$2.0 \cdot 10^{-11}$	$2.0 \cdot 10^{-8}$	$5.1 \cdot 10^{7}$	0.8	$8.2 \cdot 10^{-5}$	Polyolefin [1]	1.0	950	≥ 800	≥ 800	Yes	(XL bygg, 2023)
Jackon	Radon Barrier: Radon Barrier B Plastic sheeting		$7.8 \cdot 10^{-12}$	$2.0 \cdot 10^{-8}$	$5.1 \cdot 10^{7}$	0.8	$8.2 \cdot 10^{-5}$	Polyolefin [1]	0.4	386	≥ 300	≥ 300	Yes	(XL bygg, 2023)
Ultipro	Radon Barrier: Radonsperre Plastic sheeting		$2.2 \cdot 10^{-13}$	$0.3 \cdot 10^{-8}$	$130 \cdot 10^{7}$	≤ 5.0	$5.1 \cdot 10^{-4}$	Polyethylene/ polyamide	0.28	259.4	≥ 350	≥ 350	Yes	(Optimera, 2023)
Wallmann	Radon Barrier: Radonsperre no noise Mixed sheeting		$1.3 \cdot 10^{-13}$	$<6.8 \cdot 10^{-11}$	$1.5 \cdot 10^{10}$	16.06[2]	$1.6 \cdot 10^{-3}$	HDPE	2.0	200[3]	-	-	No	(Bauhaus, 2023)
Radoncorp	Radon Barrier: Radon Block Plastic sheeting		$5.4 \cdot 10^{-13}$	$1.1 \cdot 10^{-9}$	$9.5 \cdot 10^{8}$	-	-	Polyethylene / Ethylene vinyl alcohol	0.51	498	-	-	No	(Radon Environmental, 2023)

Juta	Radon Barrier: GP1 Mixed sheeting		$9.7\cdot10^{-18}$	$1.6\cdot10^{-14}$	$6.21\cdot10^{13}$ [4]	-	-	Polypropylene Aluminum	0.6	370	600	480	No	(Juta, 2023)

[1]: From SINTEF technical approval the material listed for the barriers are polyolefin, which is a group of plastics rather than a type of plastic. Polyolefin can either be polyethylene or polypropylene or some less commercial type of plastics (Britannica, 2022).

[2]: Tightness measured with radon tape.

[3]: Calculated from given thickness, from kg/m³ to g/m^2.

[4]: The radon diffusion resistance here is more than a 1000 times more effective than any other product listed. This will be explained more in 3.4.

For these general materials included in Table 3 it seems to be much harder to find the air tightness and radon resistance. There was not enough external research and experiments available for many of the materials included in this table. However, it is likely that very few have considered the radon protecting capabilities of some of these materials. Materials included were based on the availability of radon diffusion and radon coefficient (m^2/s). Radon diffusion coefficients are not the standard units for radon resistance in Norway, so the same formulas, formula 3 and 4, have been used to calculate the radon diffusion transmittance and resistance from the coefficient. The coefficients in Table 3 have come from “Measurement of optimal thickness of radon-resistant materials for insulation using diffusion coefficient” by (Kumar & Chauhan, 2020) and “The Radon Diffusion Length as a Criterion for the Radon Tightness” by (Keller & Hoffmann, 2000). The credibility is somewhat diluted, as testing methods might be outdated. Thus, the reader should be critical of some of the values given. These values include radon diffusion resistance/transmittance for heavyweight concrete, aerated concrete, polymer concrete, limestone brick and gypsum. However, these values somewhat resemble the values given by SINTEF and in the article by (Kumar & Chauhan 2020), which provides some credibility.

Table 3: Other materials and properties for radon protection.

						(Becker, 2010)	Note the large span of thicknesses					
Material	Description	Radon diffusion coefficient (m^2/s)	Radon diffusion transmittance (m/s)	Radon diffusion resistance (s/m)	Air permeance (ΔP=50 Pa) (l/min)	Air permeance (ΔP=50 Pa) ($m^3/(m^2hPa)$)	Thickness (mm)	Density (kg/m^3)	Diffusion length (m)	Comments	Sources for radon diffusion coefficient	Sources density
Common concrete	Normal cast-in-situ concrete	$(1.23\text{-}1.47)\cdot 10^{-7}$	$6.25\cdot 10^{-6}$	$1.6\cdot 10^{5}$	[1]	[1]	22	2400	$(24.2\text{-}27.1)\cdot 10^{-2}$	-	(Kumar & Chauhan, 2020)	(Civil lead, 2023)
Heavy concrete	Casted concrete made with high density mixture	$7.0\cdot 10^{-9}$	$4.897\cdot 10^{-8}$ (AM)	$2.042\cdot 10^{7}$ (AM)	[1]	[1]	100	4000	$60\cdot 10^{-3}$	Density for this radon resistance is unspecified. 4000 is a common value.	(Keller & Hoffmann, 2000)	(Poyatos, 2022)
Aerated concrete	Lightweight precast foam concrete	$1.3\cdot 10^{-6}$	$1.23\cdot 10^{-5}$	$7.6923\cdot 10^{4}$	653.3[2]	0.00-0.04[2]	100	570	$800\cdot 10^{-3}$	Uses 200 mm square blocks to measure air permeance.	(Keller & Hoffmann, 2000)	(Becker, 2010)
Polymer concrete (PPC)	Concrete where hydrate binders are replaced by polymer binders	$<10^{-12}$	$9.62\cdot 10^{-8}$ (AM)	$1.0394\cdot 10^{7}$ (AM)	[3]	[3]	40	2370-2450	$7\cdot 10^{-3}$	-	(Keller & Hoffmann, 2000)	(Pyataev et al., 2019)
Lime stone	Pure Limestone	$3.4\cdot 10^{-7}$	$2.267\cdot 10^{-8}$	$4.41176\cdot 10^{5}$	[4]	[4]	150	2700	$400\cdot 10^{-3}$	-	(Keller & Hoffmann, 2000)	(Aqua-Calc, 2023)
Brick	Fired clay Red brick	$3.5\cdot 10^{-7}$	$2.33\cdot 10^{-6}$	$4.28571\cdot 10^{5}$	686[5]	0.042[5]	150	1920	$400\cdot 10^{-3}$	-	(Keller & Hoffmann, 2000)	(Civil lead, 2023)

Gypsum	Pure gypsum / Powdered gypsum	$2.35\cdot10^{-6}$	$2.35\cdot10^{-5}$	$4.2553\cdot10^{4}$	392[6]	0.024[6]	100	1410-1760	$1100\cdot10^{-3}$	Density is given for gypsum powder only	(Keller & Hoffmann, 2000)	(Civil lead, 2023)
Bitumen membrane (BM)	Plastic sheeting	$2.2\cdot10^{-11}$ (AM)	$4.32\cdot10^{-9}$ (AM)	$2.313\cdot10^{8}$	[7]	[7]	4	1040	$3.25\cdot10^{-3}$	Density is given for bitumen only	(Jiránek, 2000)	(Civil lead, 2023)
Ethylene propylene diene monomer (EPDM)	Rubber sheeting	$2.5\cdot10^{-10}$	$4.08\cdot10^{-8}$	$2.4490\cdot10^{7}$	[8]	[8]	6	860	$1.1\cdot10^{-2}$	-	(Jiránek, 2000)	(MatWeb, 2023)
Cardboard	Hardened paper	$(1.75\text{-}1.82)\cdot10^{-9}$	$1.82\cdot10^{-8}$ (AM)	$5.49\cdot10^{7}$ (AM)	[9]	[9]	56	689	$2.9\cdot10^{-2}$	-	(Kumar & Chauhan, 2020)	(Aqua, 2023)
Polyvinyl chloride (PVC)	PVC sheet	$(4.7\text{-}8.7)\cdot10^{-12}$	$1.02\cdot10^{-8}$	$9.831\cdot10^{7}$	[10]	[10]	0.6	1380	$1.5\cdot10^{-3}$	-	(Kumar & Chauhan, 2020)	(GAP polymer, 2023)
Aluminum foil	Aluminum metal cut into thin leaves	$(7.2\text{-}7.7)\cdot10^{-12}$	$7.46\cdot10^{-7}$	$1.34\cdot10^{6}$	[11]	[11]	0.01	2710	$1.9\cdot10^{-3}$	-	(Kumar & Chauhan, 2020)	(Science Skills, 2023)

[1]: Common and heavy concrete can be airtight according to SINTEF. However, concrete tends to crack over time or with pressure in addition to several other factors that can change the airtightness of concrete as mentioned in 3.2. Therefore, it is hard to give an estimate as concrete can vary immensely in its airtightness capabilities.

[2]: Air permeance in liters per second has been calculated using 0.04 $m^3/(m^2hPa)$.

[3]: Polymer concrete is mostly similar to common and heavy concrete in that airtightness varies a lot. However, polymer concrete is frequently more watertight than common concrete (Patel, 2019). Typically, higher water tightness means more air tightness, which would imply that polymer concrete in general, is more airtight than common concrete.

[4]: Limestone is not airtight unless sealed (Pacific shore stones, 2017).

[5]: Value for brick wall impregnated with paraffin.

[6]: Value for gypsum sheathing board.

[7]: Bituminous membranes are used as vapor barriers and vapor barriers are typically watertight as well as airtight (Sika group, 2023).

[8]: EPDM is airtight, but no specific value available (Obex, 2023).

[9]: Cardboard is neither watertight nor airtight.

[10]: PVC pipes are watertight but extremely hard to get airtight (Fujian Sijia Industrial Material Co.,Ltd, 2023).

[11]: Aluminum foil is usually not airtight unless installed perfectly (AlFiPa, 20

5. Visualization of levels for radon barriers and other materials

All the graphs above are figures for visualizing the values given in Table 2 and 3. In Figure 6 all materials radon diffusion resistance from both Table 2 and 3 are included. If a logarithmic scale had not been used to compare the values, then all columns except JUTA gas barrier GP1 would be insignificant in comparison. This is because GP1 has a much higher radon diffusion resistance value than all the other materials.

In Figure 11 the radon barriers air permeances are depicted by a bar chart that shows the differences between the barriers for a pressure difference of 30 Pa. Figure 12 and 13 compares commercial radon barriers air permeance to mass per area and thickness. For air permeance of the other materials, brick, gypsum, and aerated concrete in Figure 14, 15, and 16, a pressure difference of 50 Pa was used. Because of the different pressure values in Figures 11-13 and 14-16, they could not be merged and thus they are shown as two figures instead of one. The orange line is the maximum value allowed for these barriers to get SINTEF's technical approval.

Figures 7, 8, 9 and 10 are radon diffusion resistance graphs. Figures 7 and 8 are bar charts where only materials from Table 2 are included. Figure 9 and 10 are only materials from Table 3. The orange line is the minimum value for radon diffusion resistance to get SINTEF technical approval. Figure 17 is a bar chart with two columns to display the difference between tensile strength across and along the material, while it is also compared to thickness for the material. Figure 18 compares diffusion length to density.

5.1 Comparison of radon diffusion resistance

Figure 6-10 have been made to visualize the materials radon diffusion resistance in charts. The orange line is SINTEFs minimum limit to get technical approval this minimum limit is $5 \cdot 10^7$ (s/m). Therefore, all the columns which match or exceed the height of the orange line are approved for radon diffusion resistance purposes according to SINTEF.

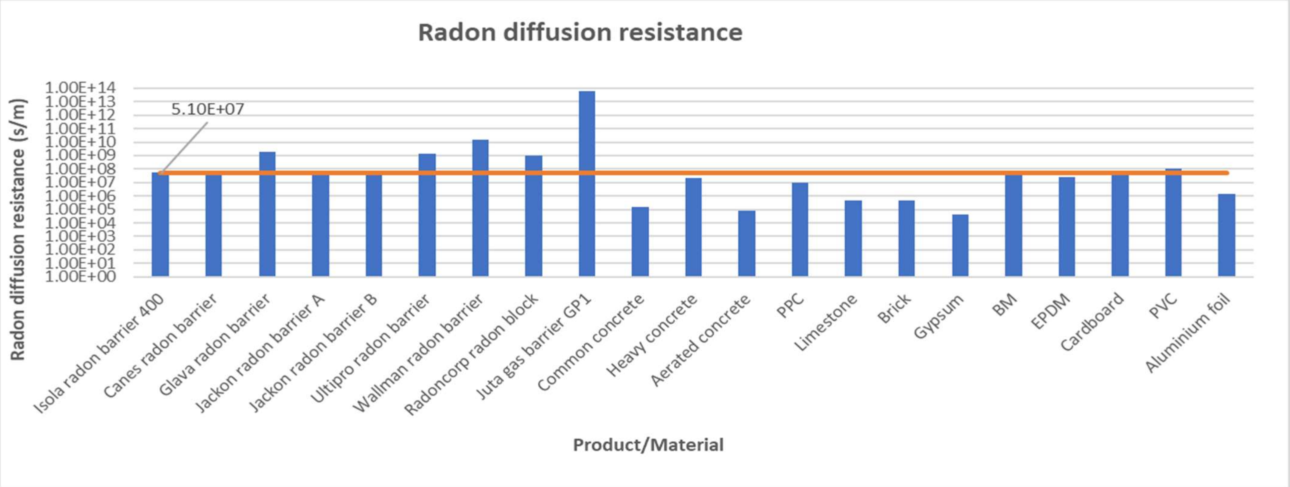


Figure 6: Radon diffusion resistance for all products from Table 2 and 3 with logarithmic scale for y-axis. Where the orange line is the minimum value for SINTEF technical approvals.

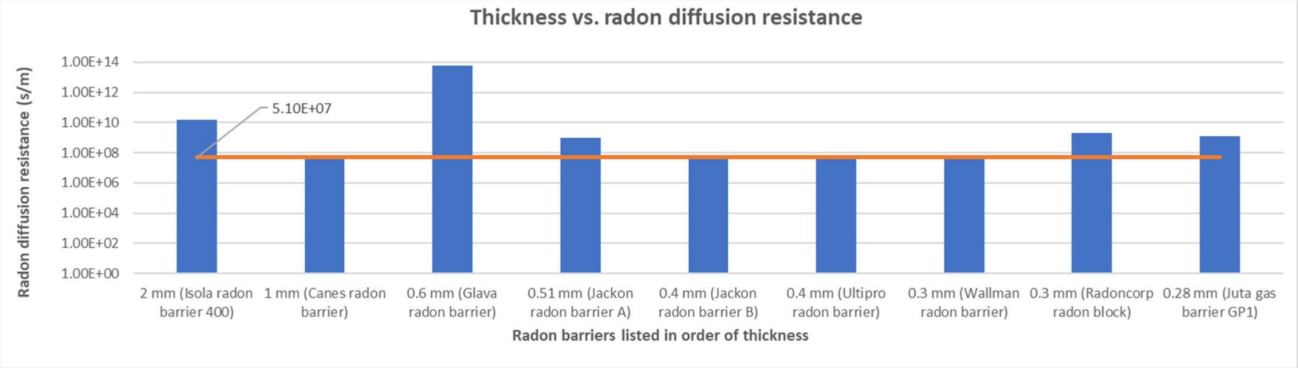


Figure 7: comparing thickness to radon diffusion resistance for commercial radon barriers. Where the orange line is the minimum value for SINTEF technical approvals.

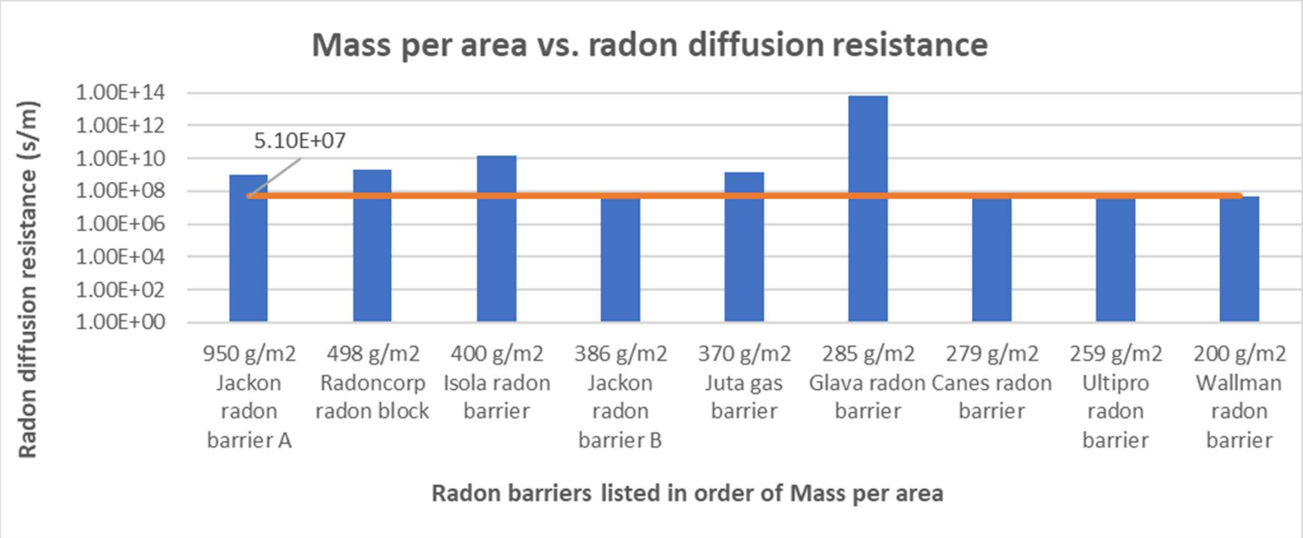


Figure 8: Comparing radon diffusion resistance to mass per area for radon barriers. Where the orange line is the minimum value for SINTEF technical approvals.

Abbreviations: CC- Common concrete, HC- Heavy concrete, AC- Aerated concrete, PPC- Polymer concrete, Ls- Limestone, B- Brick, G- Gypsum, BM- Bitumen membrane, EPDM- Ethylene propylene dien monomer, Cb- Cardboard, PVC- Polyvinyl chloride sheet and AF- Aluminum foil.

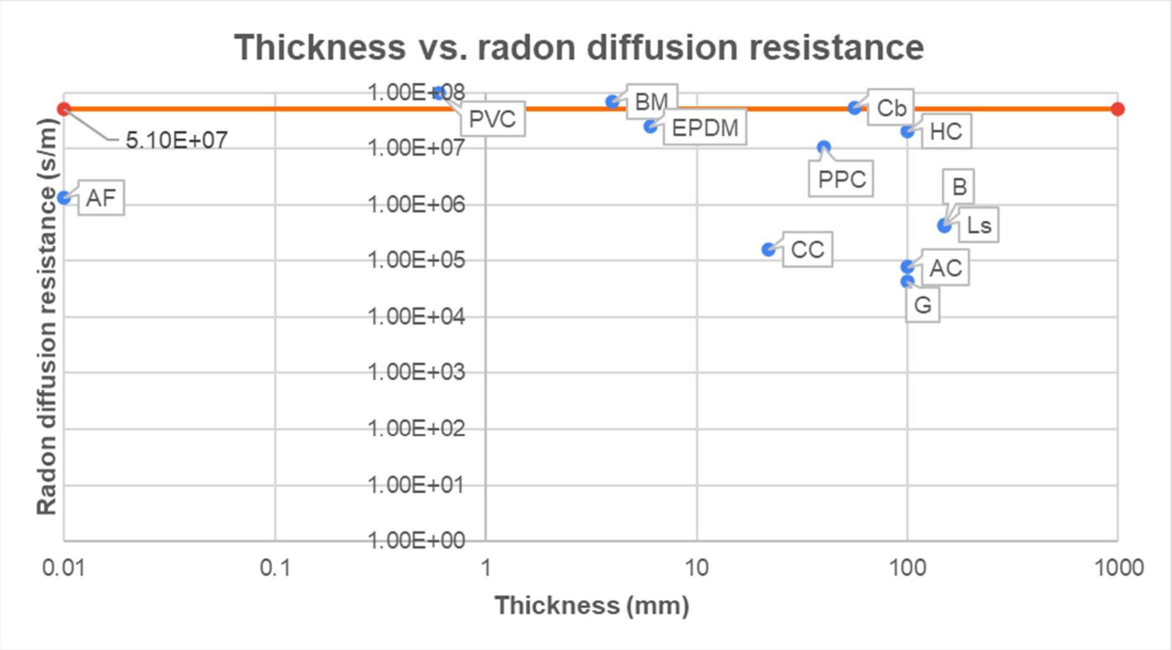


Figure 9: comparing other materials' thickness and radon diffusion resistance. Where the orange line is the minimum value for SINTEF technical approvals.

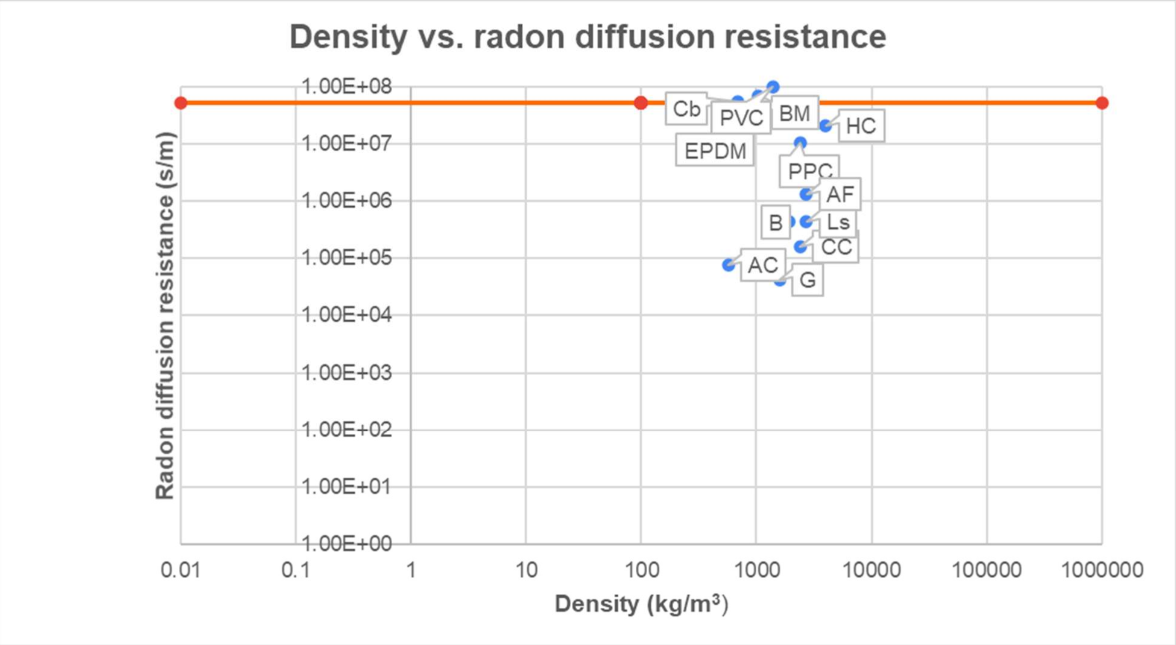


Figure 10: comparing other materials' density and radon diffusion resistance. Where the orange line is the minimum value for SINTEF technical approvals.

5.2 Comparison of air permeance

These next figures visualize air permeance for both commercial radon barriers and other materials. However, three commercial radon barriers had no air permeance value available and are therefore not included. Additionally, there are no graph with all the materials' air permeance due to the difference in pressure. The orange line is SINTEFs maximum value for air permeance though a material. For 30 Pa this value is $5.1 \cdot 10^{-4}$ $m^3/(m^2hPa)$ and for 50 Pa the value is $3.1 \cdot 10^{-4}$ $m^3/(m^2hPa)$. Therefore, all the columns which match or are lower than the height of the orange line are approved for airtightness purposes according to SINTEF.

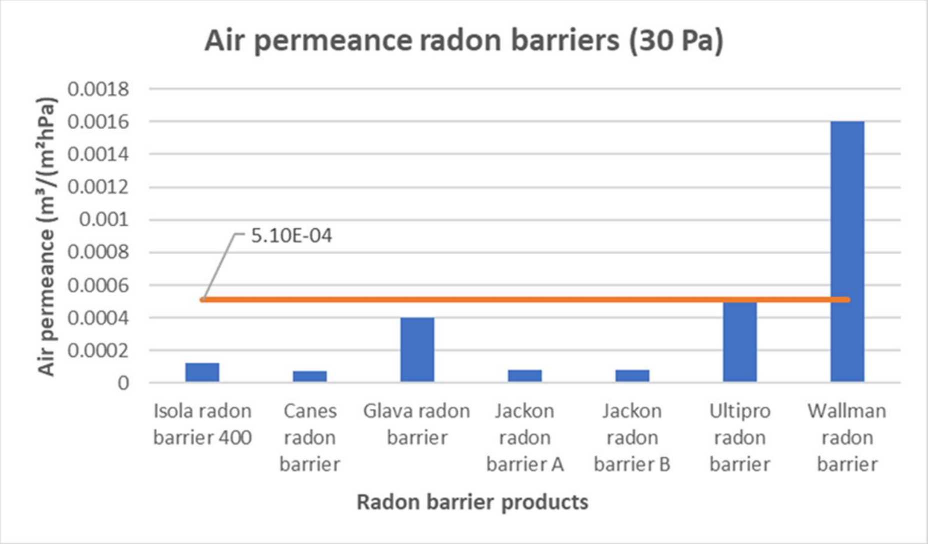


Figure 11: Commercial radon barriers air permeance. Where the orange line is the maximum value for SINTEF technical approvals.

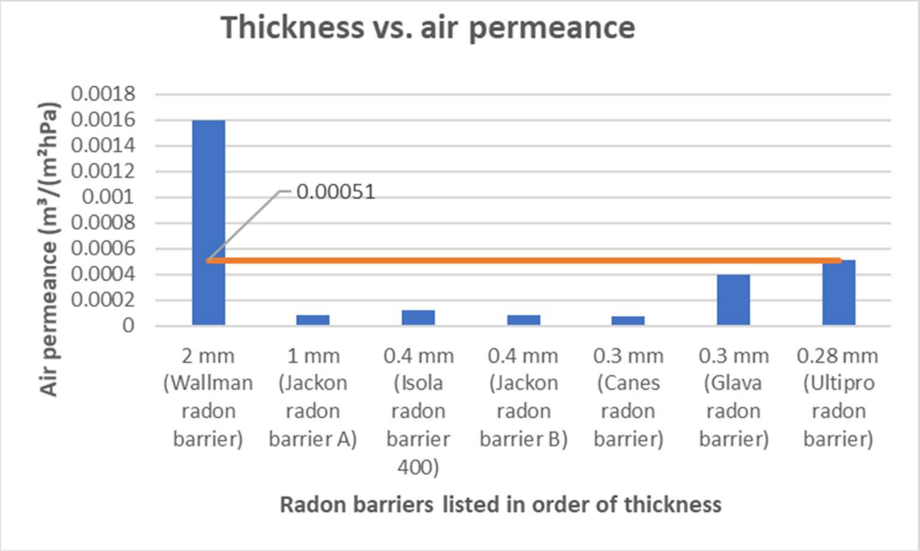


Figure 12: comparing thickness to air permeance for radon barriers. Where the orange line is the maximum value for SINTEF technical approvals.

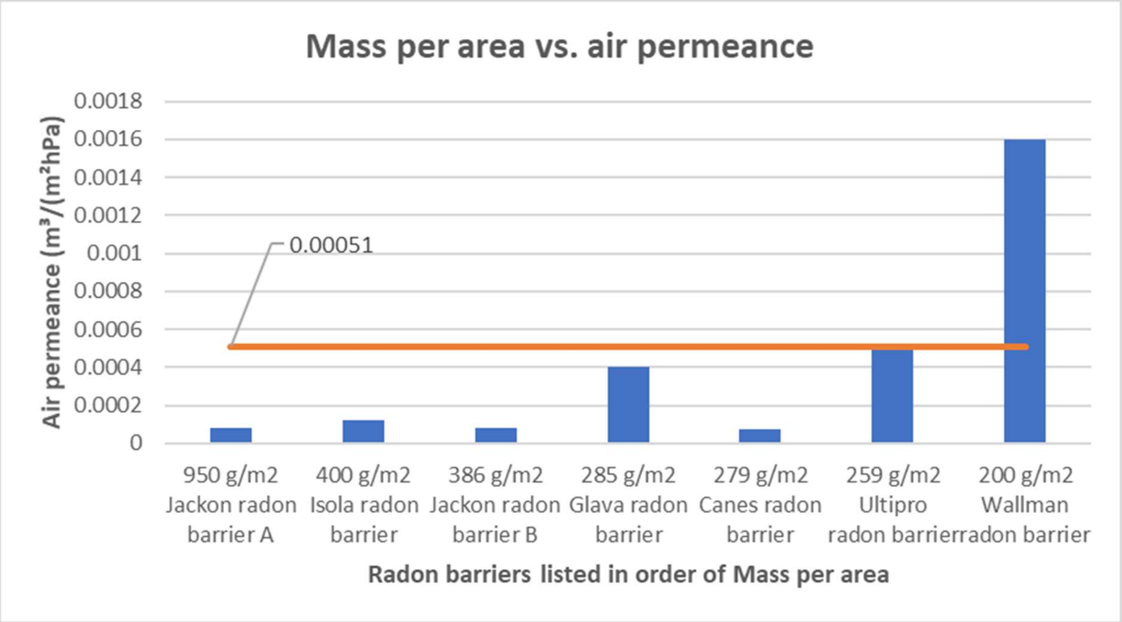


Figure 13: Comparing air tightness to mass per area for commercial radon barriers. Where the orange line is the maximum value for SINTEF technical approvals.

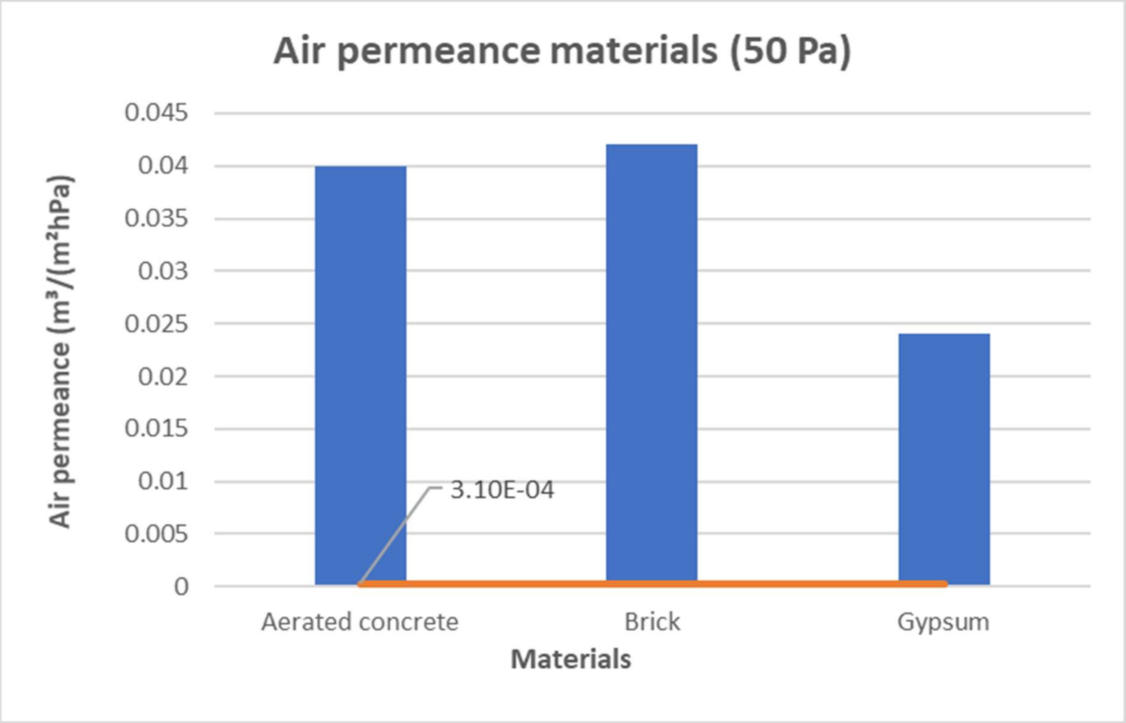


Figure 14: Other materials' air permeance. The orange line represents the maximum value for SINTEF technical approvals.

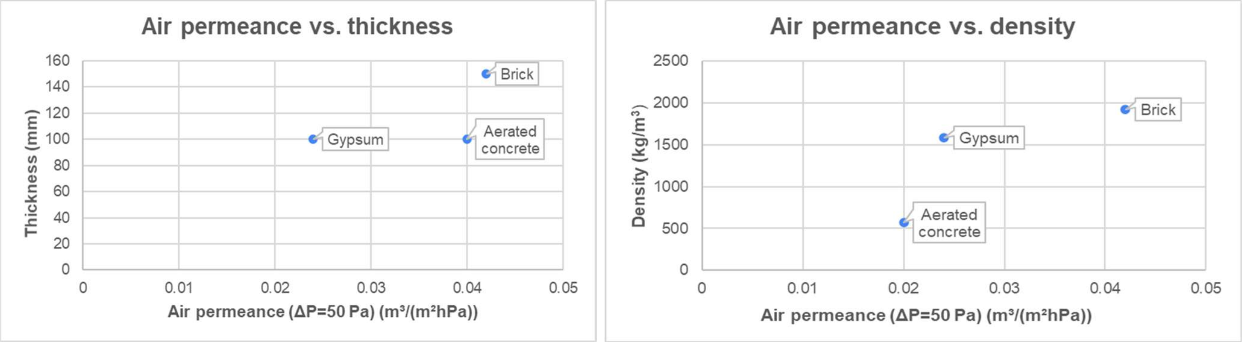


Figure 15 and 16: comparing air permeance to thickness and density for other materials used as radon barriers.

5.3 Tensile strength for commercial radon barriers

This figure compares thickness to tensile strength both along and across the material. The radon diffusion length is the characteristic distance traveled by the radon atoms during one half-life 3.8 days (Mayya, 2015). The thickest materials seem to have the best tensile strength. There also seems to be somewhat of a correlation between thickness and tensile strength.

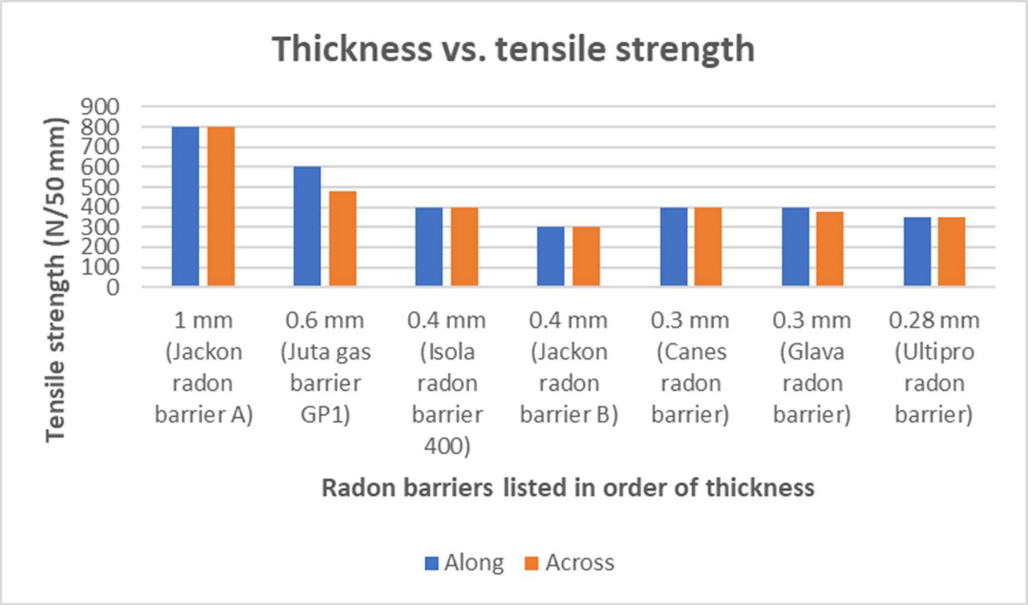


Figure 17: comparing tensile strength to thickness for commercial radon barriers.

5.4 Radon diffusion length for other materials

This figure compares radon diffusion length to density. This has been made to more clearly show the difference in density as heavyweight concrete can be seen to almost be ten times as dense as aerated concrete.

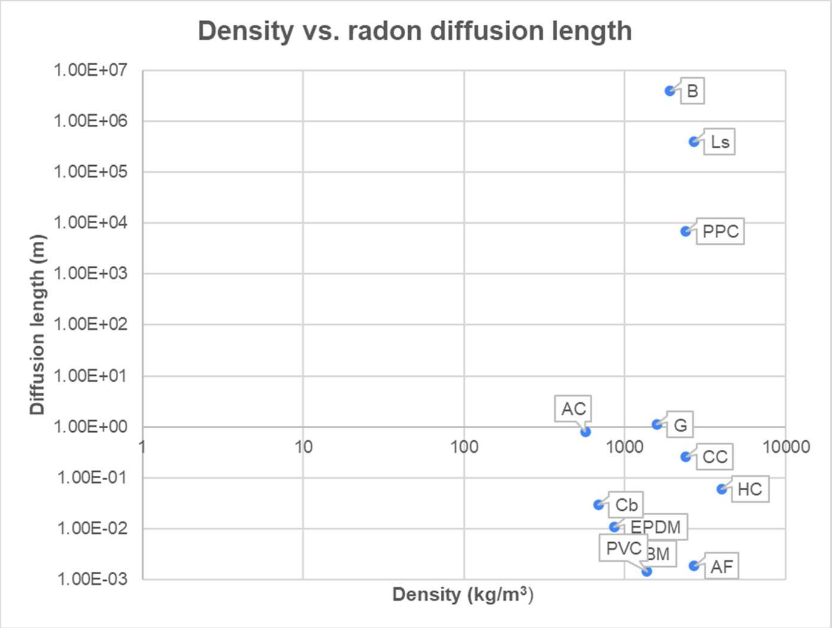


Figure 18: comparing other materials' diffusion length and density.

6. Discussion of miscellaneous radon barrier issues

As mentioned before, the tables presented are imperfect as they have some flaws and limitations, mentioned in chapter 4. All the values used in Table 3 have come from earlier research articles about the subject, instead of new tests done for this article. The reasoning behind not doing any tests for this thesis and using the results of earlier articles was simply that there was not sufficient time, as well as available equipment necessary.

The problem with using earlier articles is that technology moves rapidly, and what might be the way to test something today, might be considered imprecise or inaccurate 20 years into the future. The large gap in time between the two main articles used might give a difference in values that would not have been present if both articles were made at the same time. The articles use the same general principles and units, but it is hard to determine their compliance and if the numbers should even be compared. As well as these very specific limitations there might also have been some more general and common faults such as miscalculations and values for earlier articles being wrong, misspellings etc.

Using the data and comparing them directly, it is possible to make some general assumptions about the materials. Even as this is not the largest pool of products to compare, this pool of 9 commercial barriers seems to indicate some similarities. Most commercial plastic radon barriers seem to have a radon diffusion transmittance of around 10^{-8} to 10^{-11} (m/s). With most products being in the 10^{-8} range. Juta's barrier however seems to be a very clear outlier at $6.21 \cdot 10^{13}$ (m/s). This is because of the radon diffusion coefficient used for calculating the radon diffusion transmittance/resistance is given as $8.0 \cdot 10^{-15}$ (m^2/s). This value is significantly lower than any other value given for all the other commercial products. However, reading from the website of the barrier one can see that this is not a standard barrier for radon, this product is multilayered and made to be used where ground gas contamination is already present. This is therefore a barrier which has a significantly higher radon resistance than the other barriers. In other more common situations, a radon barrier with minimum of $5.0 \cdot 10^7$ (s/m) radon diffusion resistance seems sufficient. As this is the lowest value given for any of the commercial radon protection products.

When it comes to the air tightness/air permeance for the radon barriers one can see that they typically range from 10^{-4} to 10^{-5} ($m^3/(m^2hPa)$). There is also a small outlier in this metric as Wallmann radon barrier has an air permeance of $1.6 \cdot 10^{-3}$($m^3/(m^2hPa)$), this means a high air leakage, comparatively. This, however, is likely to come from the fact that the air permeance has been tested in another way than NBI 167/02, but the test method was not included on the website. The website for the product simply states that this is the air tightness for when this barrier is used with radon tape for a pressure difference of 30 Pa. As this is the case and as the taping might have been done with worse execution, it is likely that this barrier has a higher air permeance. As higher air permeance means more leakage, one would want the lowest possible air permanence. So, by this fact it seems Canes radon barrier is the best when it comes to air tightness at a value of $7.1 \cdot 10^{-5}$ ($m^3/(m^2hPa)$) with both Jackon barriers being close runner ups at $8.2 \cdot 10^{-5}$($m^3/(m^2hPa)$).

Additionally, it is interesting to observe that there is not always a clear correlation between thickness and radon diffusion resistance. An example of this is in Figure 14 where the radon barriers from Table 2 are compared. However, these barriers are all made of different polymeric materials, which makes it difficult to draw reliable conclusions. As the other characteristics of the materials also determine the radon resistance.

A user of radon barriers should be looking for a radon barrier with high radon diffusion transmittance and low air permeance. If only looking at these metrics Juta is the best one when it comes to radon diffusion resistance and Canes radon barrier is the clear favorite for air tightness. If air permeance and radon diffusion resistance are being considered at the same time, then Canes, as well as Jackon A and B radon barriers seem to have a satisfying value for both qualities. However, when making this comparison, metrics such as watertightness, tensile strength, cost, durability, and more are not taken into consideration. Therefore, it is hard to determine what is the “best” one. A consumer should be determined by what they are looking for specifically and know what their house needs, in order to be sure, they choose the right barrier for them.

Knowing and looking at the typical radon diffusion resistance and air tightness, it is also possible to compare these values directly to other materials given in Table 3. As mentioned, the pool of materials with a given radon resistance in earlier works is limited, and the air resistance for these materials was even harder to find. So, the airtightness and radon resistance are not given for all materials. Firstly, looking at the materials in Table 3, the radon diffusion resistances seem to vary greatly from 10^4 to 10^8 (s/m). This makes sense as the materials alter in their commercial use as building parts. However, as can be seen, some commonly used materials in house construction do well in this comparison, as the materials with the highest radon resistance are BM, PVC, and EPDM. The most surprising result might be that cardboard has such a high radon resistance; however, this material is likely to have a smaller amount of potential as a radon barrier as it is not airtight or water resistant without any type of sealing or additives (GWP group, 2018).

PVC is a type of polyethylene but specialized as it is a durable thermoplastic. It is commonly used as membranes for flat roofs (PlastechPlus, 2018). As radon barriers are not the standard radon protection system in the world, there was not sufficient available information about why PVC-plastic is not used instead of PE. The main reason that was available simply stated that it is more expensive (Legacy building solutions, 2017), however the same source also stated that PVC has a longer lifespan and is more water tight than PE (Brennan, 2018). However, another source says that PVC is more toxic than PE both to the environment and humans. This is because PVC can increase the risk of cancer and is also the least recyclable type of all plastics. Additionally, if PVC catches on fire, it can release dioxin- like compounds which are extremely toxic chemicals (Garratt, 2023).

7. Durability of state-of-the-art barriers

All the radon barriers are made of some kind of polymeric material and should therefore have a high life expectancy as the longest lasting plastics can take up to 500 years before they decompose (Chariot energy, 2021). This is one of the reasons why polymeric materials are used in buildings. However, if the radon barriers are damaged during assembly, creating small punctures in the barriers, they will not pass the NBI 167/02 air permeance test (SINTEF, 2016).

There was no research on radon barriers durability in the building foundations available. However, even if the radon barrier is perfectly assembled in the building, it will possibly be subjected to some wear and tear by the building's movement. This could deteriorate the material and make it prone to further tearing. Based on the previous statement one could make the general assumption that a thick material with high tensile strength would probably have a higher durability, compared to the same material if it was thinner. Furthermore, these two components generally correlate, as can be seen in Figure 18.

Another factor to consider is the frailty of commercial radon barriers. If a house owner makes changes and drills down to the foundation to install an interior wall one could easily by mistake rip holes or rifts in the sheet. Especially if the product is right under the floor covering. Resulting in significantly higher radon gas leakage into the building envelope.

8. Installation of commercial radon products and other materials as radon barriers

All the different radon barriers in Table 2 are resistant to moisture and can be placed in the different principal usage groups by SINTEF, depending on their approval. These usage groups are groups which determine the placement of the radon barriers in different height levels in the foundation, see Figure 19 (Byggforskserien, 2018).

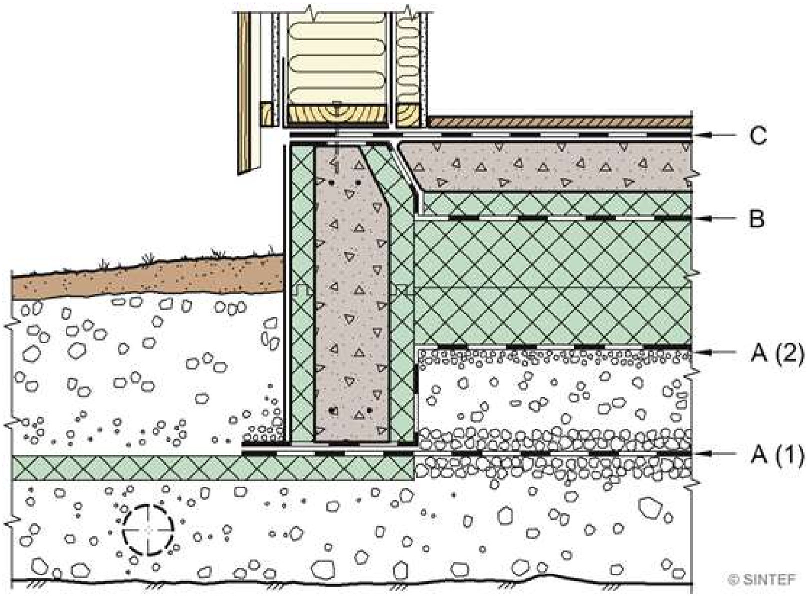


Figure 19: Different usage groups for radon barriers (Byggforskserien, 2018)

Furthermore, it is a difficult process to replace a plastic radon barrier which is already incorporated in the foundation like with these usage groups. As the removal process required would need a significant amount of energy and resources to replace which would not be sustainable. However, the materials in Table 3 are not approved by SINTEF or standardized for radon protection purposes and how deep in the foundation these materials should be placed is therefore unknown. Some of the materials in Table 3 cannot repel moisture and could swell up and possibly rot such as cardboard and gypsum likely will, unless treated with a special coating. Additionally, the four different kinds of concrete in Table 3 can all form cracks which would have a huge impact on the radon diffusion resistance and the air tightness. The last type of concrete, aerated concrete has a low density and a porous structure, that makes radon diffusion resistance low and makes it an ineffective radon barrier. It is also important to notice in Table 3 and in chapter 5, that aerated concrete has a thickness of 100 mm and common concrete only has 22 mm and that the difference in thickness impacts the radon diffusion resistance value. This means that it would take approximately 4 times the thickness for aerated concrete to achieve the radon diffusion resistance value for common concrete. However aerated concrete is not commonly used in the foundation in buildings, but commonly shaped as blocks for usage in walls. Using blocks also means that mortar must be applied between the blocks, which could further influence air permeance and radon levels inside the building. No type of mortar has been tested in this study.

Heavy concrete is commonly used in radiation shielding facilities and for ballasting pipelines and should therefore not crack easily. Most of the radon barriers with a technical approval for short TG from SINTEF can be found in Table 2 to have a radon diffusion resistance of approximately $5.0 \cdot 10^7$ (s/m). 100 mm heavy concrete gives a radon diffusion resistance of $2.042 \cdot 10^7$ (s/m) which comes close to the value of the radon barriers in Table 2. If the thickness of heavy concrete is increased, it could be at the same radon diffusion resistance as the radon barriers. However, the cost of concrete increases depending on its density and heavy concrete has a wide range of density from the lowest of 2600 to 8900 kg/m^3 as mentioned previously in chapter 3.2. Therefore, common radon barriers are often the cheapest alternative. Also, polymer concrete is close to the radon diffusion resistance TG approval with a value of $1.0394 \cdot 10^7$ and a thickness of 40 mm, which is lower than 100 mm for heavy concrete. All the different thicknesses of concrete are the reason Table 4 and Figure 20 exists.

Table 4: Four types of concrete compared with the same thickness (100 mm)

Concrete	**Radon diffusion coefficient (m^2/s)**	**Radon diffusion length (m)**	**Radon diffusion resistance (s/m)**
Common	$1.23 \cdot 10^{-7}$	$(24.2\text{-}27.1) \cdot 10^{-2}$	$7.5 \cdot 10^{5}$ (Am)
Aerated	$1.3 \cdot 10^{-6}$	$800 \cdot 10^{-3}$	$7.7 \cdot 10^{4}$ (Am)
Polymer	$<10^{-12}$	$7 \cdot 10^{-3}$	$5.5 \cdot 10^{13}$ (Am)
Heavy	$7.0 \cdot 10^{-9}$	$60 \cdot 10^{-3}$	$2.0 \cdot 10^{7}$ (Am)

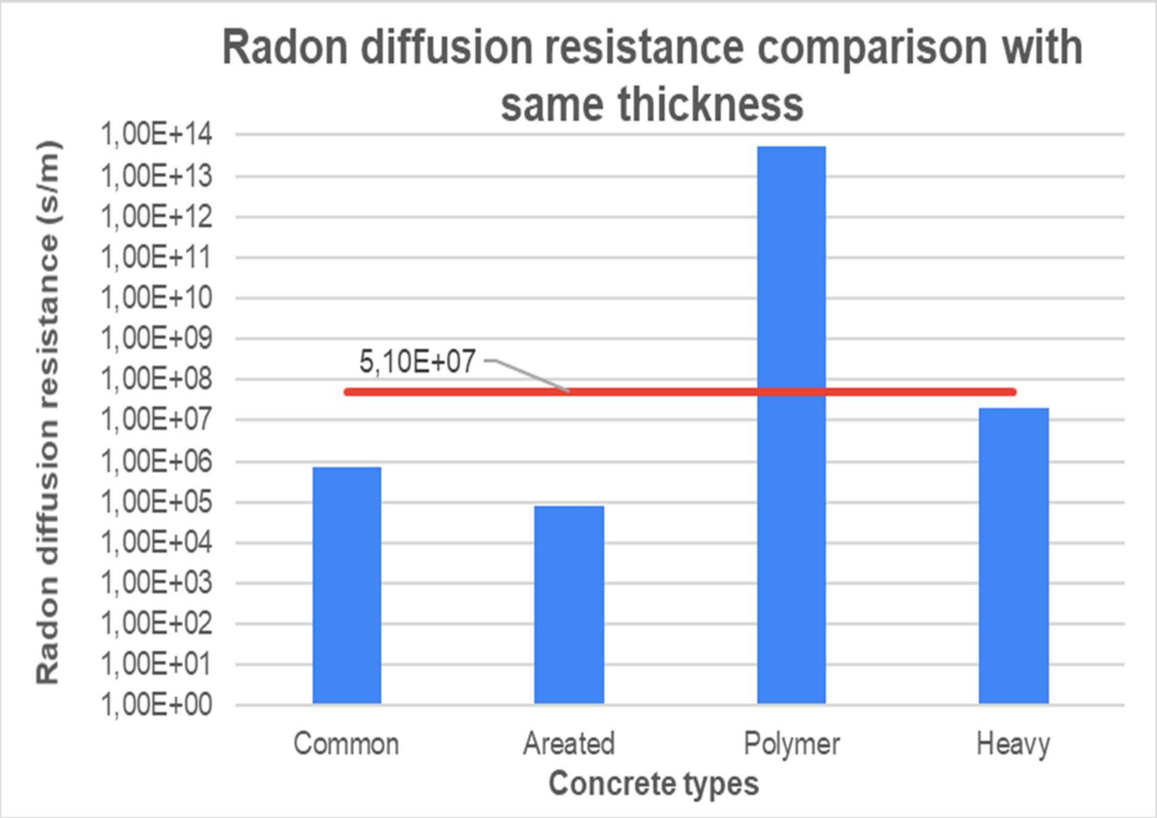


Figure 20: concrete compared with the same thickness of 100 mm. Where the orange line is the minimum value for SINTEF technical approvals.

In Figure 20 a logarithmic scale was used for the radon diffusion resistance axis. This is because polymer concrete had a drastically higher value than the other materials. Which means that polymer concrete is by far the most radon diffusion resistant material of the four concretes. Considering that polymer concrete is known and used for what was mentioned earlier, this matches well with the results. However, what is the least amount of concrete necessary to get a radon tight layer?

9. Testing radon tightness based on alternative model

As previously stated, a material can be checked if it is "radon tight" by looking at thickness and diffusion length. If the thickness of a material is 3 times the diffusion length, then it is "radon tight" as only 5% of the initial radon will pass through the materials. The term "radon tight" is somewhat misleading as a material categorized as radon tight in the Table 5, does not mean that the material will protect from 100% of radon gas. Additionally, in a situation where a radon source is particularly strong, only 5% of the initial gas, can lead to a very high concentration of radon accumulating and remaining withing the building envelope. The radon tightness has been tested in the table below:

Table 5: Testing materials from Table 3 for radon tightness

Materials:	**Thickness of sample (mm)**	**Radon diffusion length (mm)**	**Is the sample "radon tight"?**	**Thickness needed for sample to be "radon tight"**
Common concrete	22	242-271	No	726-813
Heavy concrete	100	60	No	180
Aerated concrete	100	800	No	2400
Polymer concrete	40	7	Yes	-
Limestone	150	400	No	1200
Brick	150	400	No	1200
Gypsum	100	1100	No	3300
Bitumen membrane	4	3.25	No	9.75
EPDM	6	11	No	33
Cardboard	56	29	No	87
PVC	0.6	1.5	No	4.5
Aluminum foil	0.01	1.9	No	5.7

As can be seen, all materials are not "radon tight" with the thicknesses that they have in Table 3, except for polymer concrete. However, values are close such as heavy concrete, where it shows that only 180 mm of heavy concrete is enough to be "radon tight". What turns out to be the least "radon tight" is gypsum where the diffusion length is 11 times the length of the sample. This means that to make pure gypsum “radon tight”, it needs to be 3.3 meters long. In addition to these materials there is much potential in other technologies shown in the next chapter, that could potentially replace the radon barrier products that exist today.

10. Possible solutions and future perspectives

10.1 Limitations of the state-of-the-art products

Even as the state-of-the-art products today do their job efficiently and relatively reliably there is also a significant number of improvements that can be made in the future, especially when it comes to research regarding durability and the long-term consequences of using these products. There are multiple theoretical alternatives and improvements to the radon barriers that are available today.

10.2 Self-healing concrete

As mentioned, microcracks in concrete are a problem for radon tightness in houses. Additionally, these rifts often worsen over time. If the cracks could heal themselves, concrete could be a permanent solution to prevent radon gas in houses. Self-healing, also called autogenous healing, is the ability for concrete to heal itself.

The Romans were well ahead of their time for engineering and construction, as their projects have survived for two millennia. Many of these structures were built with concrete, for example the Pantheon with the largest unreinforced concrete dome in the world, that was built in 128 C.E., and is still intact. While many modern concrete structures have collapsed after a few decades. This ability of the concrete to survive for so many decades likely come from the fact that roman concrete often had white chunks referred to as “lime clasts” (Chandler, 2023; Seymour et al., 2023).

By studying the samples of old Roman concrete, it was discovered that the white inclusions were made of different forms of quicklime also called calcium carbonate. Additionally, a spectroscopic examination also provided clues that the old concrete had been made at extreme temperatures. Hot mixing was the key to the super- durable nature of the concrete. The benefits of hot mixing are firstly that the increased temperature drastically reduces curing and setting times since all the reactions are accelerated, which allows for much faster construction. Secondly when the overall concrete is heated to high temperatures, it allows a chemical process that is not attainable if only slaked lime is incorporated in the concrete, creating high-temperature-associated compounds that would not otherwise form (Chandler, 2023; Seymour et al., 2023).

In the hot mixing process, the lime clasts establish a brittle nanoparticulate architecture. Creating a simply fractured and reactive calcium source. It was proposed that this could provide self-healing capabilities. When tiny cracks begin to form within the concrete, they can travel through the lime clasts. The lime clasts can react with water which creates a calcium- saturated solution. This solution can recrystallize as calcium carbonate and quickly fill the crack or react with pozzolanic materials to further strengthen the composite material. These chemical reactions happen spontaneously and can therefore automatically heal the cracks before they worsen (Chandler, 2023; Seymour et al., 2023).

Through the examination of concrete cracks in ancient Roman samples, calcite was found filling the cracks. To test this, concrete was intentionally cracked and water was run through these cracks. After two weeks the cracks had healed, and the water could no longer flow (Chandler, 2023; Seymour et al, 2023). If radon barriers were switched out with ancient Roman self-healing concrete, it is possible the main challenges of radon permeability could be solved. However, it is not known if cracks filled with calcite have sufficient capabilities to withstand radon diffusion and air permeance. Additionally, water or rainwater will sometimes not come in contact with concrete and therefore also make self-healing inaccessible. As mentioned earlier, many modern-day constructions crumble after a few decades. If concrete structures could stand for hundreds of years, it would make modern buildings more sustainable. Potentially this can be used for entire buildings, not just radon protection purposes.

10.3 Self-healing membranes

Most radon barriers are made of polymeric materials such as polypropylene or polyethylene, which is seen in Table 2. These barriers are excellent for expulsion of moisture and gasses. However, research regarding the durability of radon barriers is inadequate. Therefore, assuming that the radon barrier is exposed to some aberration from laborers installing the material or natural conditions, its quality could be compromised. This weakening can lead to water damage on constructions and radon leaking through the barrier. However, replacing a radon barrier is a costly operation. Therefore, polymeric materials constructed with self-healing capabilities could be highly attractive.

Research is presently being done on self-healing technology for plastic materials. In addition, there are many different methods for self-healing polymers and elastomers. There are also gas barriers available with self-healing properties on the commercial market. Permagard has a gas barrier called Newton HydroBond 403, where the gas membrane features a locking fleece on the inner surface and an external hydrophilic coating. The hydrophilic layer provides self- healing capabilities if the membrane is punctured. The membrane locking fleece prevents water leakage as it becomes fully encapsulated and engaged into the newly placed concrete (Permagard, 2023). Another example of a self-healing membrane is the Sika BentoShield Max LM, which is specialized for below ground structures. This product can be seen in Figure 21. The function of this waterproof shield is also engineered to include protection of the concrete structure itself against potentially harmful influences of aggressive natural mediums such as gasses in soil, groundwater, or seawater. Its self-healing properties come from the unique swelling performance of sodium bentonite with high- strength polypropylene geotextiles (Building Trust Sika, 2023). However, this barrier has only a guarantee of water tightness for 10 to 15 years depending on what kind of system it's being used for (Building Trust Sika, 2023). Since it is expected that a building should last 50-100 years, depending on what kind of materials used, this would not be a sustainable radon solution.

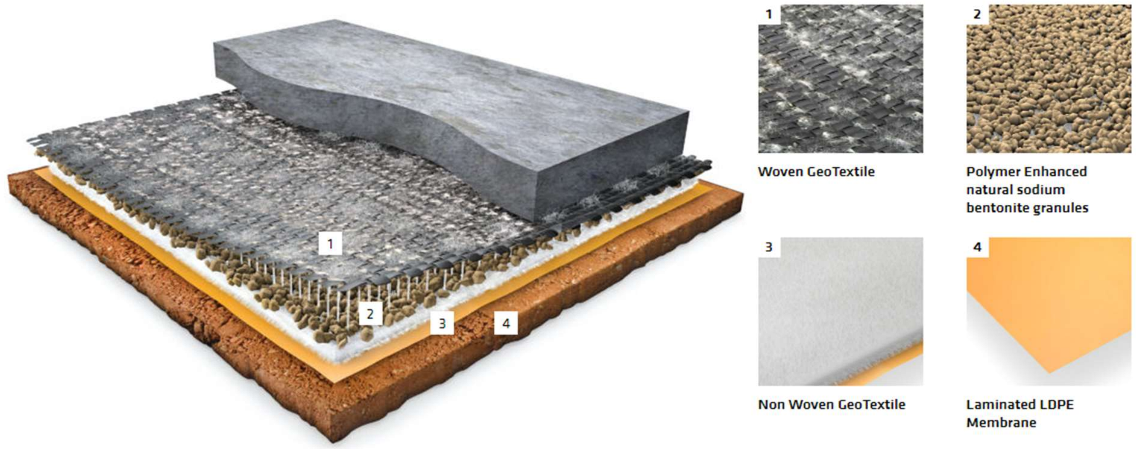


Figure 21: structure (left) and materials (right) of Sika BentoShield Max LM (Sika, 2023).

Another example of a self-healing membrane is the BPA- DualProof S membrane system. It consists of a special non-woven barritex fleece, which is co- extruded with a highly flexible water and gas resistant PVC membrane. In the barritex fleece is a polymer mix, which includes an absorber impregnated in the PP- fleece. The BPA- DualProof S membrane system can be used both as pre- applied and post-applied. When used post-applied the sealing effect is achieved from two functions. The first sealing function lies in the high- density PVC- membrane, and the second sealing function is only activated if the membrane is damaged, and the incoming water activates the swelling non- woven geotextile. If the water penetrates the PVC- membrane, the water reactive polymer swells thus creating an extremely tight, gel- like film which permanently seals the concrete structure. Both BPA- DualProof S membrane and Newton HydroBond 403 have no guarantees for the longevity of the barriers (BPA waterproofing systems, 2023). Additionally, all 3 of these self- healing membranes have to be placed in a wet environment to self-heal, which means that the self-healing ability might not activate if the environment is too dry.

10.4 Bio-based plastics

Plastic is one of the most commonly used materials in the world as it is used for a large variety of purposes. This is because plastic can be modified in various ways that impact the shape, thickness, flexibility, hardness, durability, and strength. However, plastic is known to be an unsustainable material and often has a short usability, and the world has begun to look for a different solution.

There have been multiple methods and studies to try to find a substitute for plastic and one of these is bio-based plastics. There are several different types of bioplastics, some that are biodegradable and some which are not. These polymers are produced from biological materials or renewable feedstock (Atiwesh et al., 2021). The non-biodegradable ones are more applicable for use in the building industry, as there are very few instances where one would want a building material to degrade easily.

The process of producing bioplastics is very easy to do and replicate as can be seen in Murray-Smith's video on how to make bioplastic. (Murray-smith, 2020) As this is a cheap and easy process it is likely a larger number of bioplastics will be used in the building business in the future. The use of bioplastics in the building sector is something that is also presented by (Siracusa & Blanco, 2020) in their article about bioplastics, where they estimate that around 4% of bioplastics in the future will be used in the building/construction business. Furthermore, there seems to be little other information available about the application for bioplastics being used for radon protection as the bioplastic business is fairly new and small. As well as the fact that soil depressurization is the most common worldwide method of radon protection, instead of the radon barriers that are commonplace in Norway. This has likely contributed to little or no research into if bioplastics can be used as radon barriers or not. The future of sustainable radon protection might be in the bioplastics industry, but the application for this is currently unknown in the aspects of efficiency, economy, and sustainability. This must be researched before bioplastic radon barriers become commercial.

11. Conclusions

There are several types of radon barriers that exist today, by using the principles from Bjørn Petter Jelle's 2012 article, it has been observed that there are especially two values of great significance for radon protection capabilities in materials. The most important qualities for radon barriers are that they should be as airtight and radon tight as possible. This thesis has compared several state-of-the-art barriers and determined which are optimal for different uses or have different limitations. Juta's barrier has the best radon tightness, Canes radon barrier is optimal for the least amount of air permeance and Canes, Jackon A and B radon barriers have the better combined results for both radon tightness and air tightness. These outcomes can also be seen in graphs which visualize the forementioned tables. This can help determine what radon barrier is best suited for a user and should help readers see the potential of alternative materials for radon protection. Additionally, some sources stated that there could be some potential in PVC in replacing PE as it has a longer lifespan and better water tightness capabilities. However, other websites were more negative to this material as it is toxic if it catches on fire and is one of the least recyclable types of plastic. Concrete also has the potential to be airtight and radon tight enough to be sufficient, however concrete tends to be inconsistent as the casting process execution is vital to a satisfactory result. In addition, concrete tends to crack under pressure or by aging. Even small holes and microcracks can lead to a significant leakage of radon gas into houses. The last part of the thesis mentions new technology and the possibilities that the future holds for radon protection. Self- healing ancient Roman concrete has been rediscovered, where cracks could be healed to retain the concrete's structure. This self-healing concrete needs to be tested for radon protection to make sure that it is applicable as a barrier. In addition, some state-of-the-art barriers have also been developed to self- heal. Both self-healing concrete and membranes needs water to activate their self-healing properties, which could make it challenging to implement them for optimal function. Furthermore, how long the self-healing membranes last is unclear. The last technology explored was bio-plastics. Bio plastics may have potential to be used in the building industry in the future, but because this technology is new, its applicability and potential challenges remain undetermined.

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