RadoNorm
Managing risks from radon and NORM

Deliverable D5.7

Research paper in a scientific journal describing obtained results

Work Package 5 Mitigation

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Executive Summary

A summary of the results was produced in a paper titled "The influence of radon penetration through joints on the overall radon barrier properties of waterproof membranes" as part of subtask 5.2.4 of the RadoNorm project. The article was published in the Journal of Building Engineering (Impact Factor 7.4; CiteScore 11.5; Elsevier B.V.) on August 30, 2024.

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Appendix A. Copy of the article

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The influence of radon penetration through joints on the overall radon barrier properties of waterproof membranes

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A R T I C L E I N F O

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A B S T R A C T

Waterproofing membranes with a proven ability to prevent radon penetration are commonly used to provide basic protection of buildings against radon from the subsoil. The goal of our research was to find out which types of joints of the pre-applied membranes are radon-tight and which, on the other hand, are radon permeable. Another goal was to find out how significant radon penetration through the joints can be, and how it can affect the ability of the whole radon-proof course to prevent radon penetration into the house. Six types of joints were investigated by determining the radon diffusion coefficient. Four of these types had a radon diffusion coefficient up to three orders of magnitude greater than the membranes themselves. A procedure was proposed for taking into consideration the high radon diffusion coefficient of joints in the calculation of the radon resistance of the whole radon-proof course. It has been proven that leaks in the joints can reduce the radon resistance of the whole radon-proof course by two to three orders of magnitude. For this reason, the course may not meet the minimum radon resistance requirements. Numerical simulation revealed that the leaks were due to the use of unsuitable sealing materials and technologies. A correct sealing technology for problematic joints was designed and subsequently verified.

1. Introduction

Radon penetrating from the subsoil into buildings is considered to be one of the main causes of lung cancer. Many building codes and standards [1,2,18] therefore require new buildings with habitable space to be protected against radon. In countries where buildings are normally protected against soil moisture or underground water by continuous waterproofing, the waterproof course also provides basic protection against radon from the subsoil. The waterproof course can be made up of seamless coatings in the form of paints, sprays and screeds, or it can be laid out from pre-applied membranes based on bitumen, polymers or composite materials [4]. The ability of a given waterproofing product to prevent radon penetration is verified by determining the radon diffusion coefficient or the radon resistance. The radon diffusion coefficient is a material characteristic independent of thickness that describes the ability of radon to diffuse through a given material. It is determined mostly on the basis of the amount of radon passing through the tested material [8,11,13–16]. Since 2017, the ISO/TS 11665-13 [6] test standard has also been available. Radon resistance is a product characteristic that expresses how effectively a given product of a given thickness can prevent the diffusion of radon [9]. It is a parameter according to which individual products can be compared with each other. A higher value indicates a more effective barrier. An overview of the values of the radon diffusion coefficient and of radon resistance in individual types of waterproofing products,

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depending on their chemical composition, is given, for example, in Refs. [5,10].

There is currently no European or international standard that specifies how to design waterproof membranes as radon barriers. The method for designing the membranes varies from country to country according to national regulations and technical standards. In general, procedures are available prescribing either the maximum value of the radon diffusion coefficient [1,18], or the minimum thickness of the membrane [11], or the minimum value of the radon resistance [2,17]. The applicability and reliability of these design procedures is discussed in detail in Ref. [7]. Regarding radon resistance, various minimum values apply. For example, according to the SINTEF guidelines for approval of radon membranes [17] the radon barrier must have radon resistance greater than 50 Ms/m (megasecond per meter = 10^6 s/m; unit is defined by equation (5)). In the Czech Republic, according to standard CSN 730601 [2], the minimum radon resistance values range from 2 Ms/m to 300 Ms/m depending on the type of house, the intensity of its ventilation, the radon potential of the subsoil and the presence of other radon control technologies.

The effectiveness of the waterproof course in ensuring a low radon concentration in a building varies. Some works document high efficiency, e.g. publication [12] mentions that in 96 % of the houses protected by the membrane, the radon concentration was below the action level. On the other hand, the WHO [19] warns that the effectiveness can be highly variable. The explanation for the differences in effectiveness cannot be found in the waterproof products themselves. Their barrier properties are tested and, if used appropriately, guarantee a low concentration of radon in a building. A weak point is the poor quality of the application due to non-compliance with technological procedures and the possibility of damage and puncturing during subsequent work. The influence of pinholes and other imperfections in membranes on the value of the radon diffusion coefficient was studied in Ref. [3]. The authors of the study confirmed a significant deterioration of barrier properties depending on the number and the diameter of pinholes, and on the self-healing properties of the membrane.

Radon can also penetrate through leaks in the joints between the individual membranes and in the penetrations of the installation lines. Until now, unfortunately, only the radon resistance of the membranes themselves, not their joints, has been tested. Therefore, we decided to test the radon tightness of common types of joints between different material variants of pre-applied membranes. The goal of our work was to identify the types of leaky joints, find out the causes of leaks and determine how these leaks can affect the ability of the whole waterproof course to prevent radon penetration into a building. Experimental measurements and numerical modeling of radon diffusion through the joint samples were used to reveal the factors affecting the radon tightness of joints.

2. Materials and methods

2.1. *Tested types of joints*

In our work, we studied the radon-tightness of six types of joints that occur most often in practice. In Fig. 1, they are shown under letters a) to f). Torching or hot air welding (Fig. 1a) are standard technologies used for sealing joints between bitumen or polymer membranes. Torching brings the bitumen into a liquid state, and during hot air welding the polymer is similarly brought into a plastic state. Subsequent compression results in a homogeneous joint. Polymer membranes thinner than 0.5 mm cannot usually be welded by hot air, and therefore additional sealing tapes, sealants or adhesives are used to join them. Fig. 1b shows a variant of the joint with a sealing tape pasted over the top surfaces of the membranes. Fig. 1c shows another variant with a sealing tape placed between the membranes. Some polymer films have a permeable layer (geotextile, non-woven fleece, bentonite, self-adhesive coating, etc.) on the bottom surface. A joint using a sealing tape or an adhesive inserted between the films is shown in Fig. 1d. Fig. 1e shows a joint according to Fig. 1d, which is additionally sealed with a tape pasted over the top surfaces of the membranes. The last variant, in Fig. 1f, illustrates a joint between self-adhesive bitumen membranes with the top surface sanded (a mineral powder on the top surface).

2.2. *Test samples*

Since our laboratory is not equipped with the necessary material and welding devices to perform all types of joints, the joints were prepared by professional representatives of the manufacturers of waterproofing membranes according to the manufacturers' technical manuals. The production of joints by professionals is an attempt to ensure that any leaks are not due to faulty execution. However, it can be expected that the manufacturers paid more careful attention to the correct execution of the joints than is common in practical applications. The resulting tightness should therefore be viewed as the maximum possible.

Test samples measuring 135 × 325 mm were cut from each supplied membrane with a joint executed in such a way that it was in the middle of the sample and perpendicular to the longer side of the sample. From each waterproofing product, three samples of the

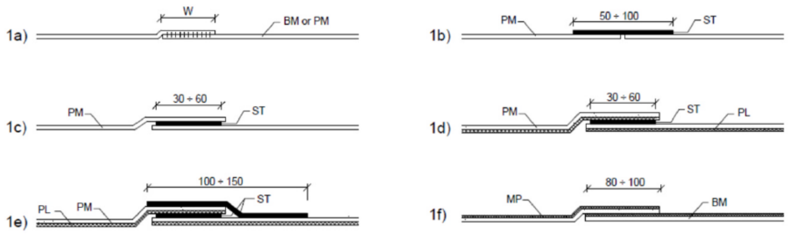

Fig. 1. Schematic illustrations of studied membrane joints (W - minimum joint width, which is 80–100 mm for BM or 30 mm for PM, BM – bitumen membrane, PM – polymer membrane, ST – sealing tape, PL – permeable layer, MP – mineral powder).

membrane itself and three samples with a joint were tested.

2.3. Experimental determination of the radon diffusion coefficient

The radon diffusion coefficient was determined on samples of the membrane itself and on samples of the membrane with a joint. The tightness of the joint can be evaluated by comparing these two values. If the result is greater for the joint than for the membrane, and the difference is greater than the measurement error, it is considered that the joint is not tight. This assessment is reinforced by the fact that a properly tight joint should have a diffusion coefficient smaller than that of the membrane itself, since the part of the sample with the joint has a greater thickness. The reduction in the value of the radon diffusion coefficient caused by the increased thickness of the sample was never greater than 25 %. Therefore, this effect cannot mask more significant leaks in the joints, which are manifested by an increase in the diffusion coefficient by one or more orders of magnitude.

The experiments were carried out on a measuring device that allows three samples to be measured at the same time and under the same conditions. The tested samples were placed between the flanges of the source and receiver containers pre-coated with a sealant. Each sample has an effective area exposed to radon of 293 cm^2; the volume of the receiver container is 2700 cm^3. A diagram of the device is shown in Fig. 2. The source container was connected by a closed circuit with an artificially produced and certified RF100 radon source. Continuous monitoring of the radon concentration in the source container was provided by an ionization chamber operating in current mode that was part of the closed circuit. The radon concentration in the receiver containers was continuously measured using TSR 4 radon detectors, which were inserted into each receiver container. From the known courses of the radon concentration on both sides of the sample, the thickness of the sample and its effective area, the radon diffusion coefficient was determined using IterRn software [20]. The calculation procedure in this software is based on repeated numerical solution of standard one-dimensional partial differential equation of transient radon diffusion:

$$D \cdot \frac{\partial^2 C}{\partial x^2} - \lambda \cdot C = \frac{\partial C}{\partial t} \tag{1}$$

where D is the radon diffusion coefficient [m^2/s], C is the radon concentration in the sample [Bq/m^3], x is the distance from the surface of the sample exposed to radon [m], t is time [s], and λ is the radon decay constant [s^{-1}]. The resulting value of the diffusion coefficient is considered to be the value for which the calculated increase in the radon concentration in the receiver container has a minimum deviation from the measured increase. The whole procedure used in the IterRn software including an overview of initial conditions, boundary conditions and the method of numerical solution is described in detail in Ref. [8].

2.4. Numerical simulation

Numerical modeling was used not only to explain the measured values, but also to extend the findings to other variants and combinations of thicknesses, widths, and diffusion coefficients of sealing tapes. Modeling thus made it possible to understand broader contexts and gain a more general view of the issue. Obtaining similar knowledge through experiments alone would be very time-consuming.

An improved version of TransRn software [20], which we initially developed back in 2004, was used for the numerical modeling of radon diffusion through joints. However, since two-dimensional diffusion occurs at the joints due to the use of various sealing tapes and sealants, the original tool for one-dimensional calculations was modified to allow the solution of two-dimensional transient radon diffusion governed by equation:

$$D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2}\right) - \lambda \cdot C = \frac{\partial C}{\partial t} \tag{2}$$

where x and y are coordinates of a point [m] where the radon concentration is being calculated.

Initial and boundary conditions for equation (2) are the same as for equation (1), i.e. the radon concentration in the sample is 0 Bq/m^3 at the beginning of the calculation and the boundary conditions on surfaces exposed to the source and to the receiver containers

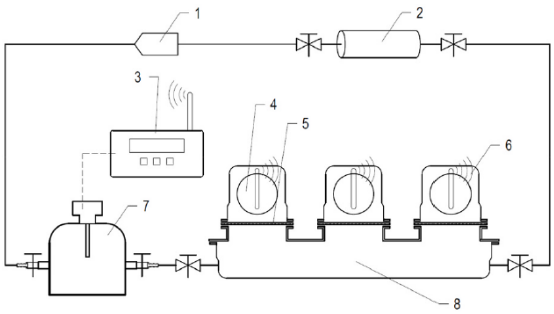

Fig. 2. Schematic drawing of the measurement device (1 – flow pump, 2 – flow through radon source, 3 control unit, 4 – wireless radon detector TSR 4, 5 – tested sample, 6 – receiver container, 7 – ionization chamber, 8 – source container).

have the following general form:

$$-D\frac{\partial C}{\partial x} = h \cdot (C_s - C_a), \tag{3}$$

where h is the radon transfer coefficient [m/s], C_s is the radon concentration on the sample surface [Bq/m^3] and C_a is the radon concentration in the container [Bq/m^3]. While the C_s value is the result of calculation, the C_a value can be either measured radon concentration in the source container or calculated radon concentration in the receiver container. The latter is always time-dependent because radon concentration in the receiver container gradually rises. It can be calculated for the time step *(i)* from the previous step *(i-1)* using equation (4)

$$C_a = C_{rc,i} = C_{rc,i-1} \cdot e^{-(\lambda+n)\cdot\Delta t} + \frac{E_{i-1}\cdot A}{V.(\lambda+n)} \cdot \left(1 - e^{-(\lambda+n)\cdot\Delta t}\right) \tag{4}$$

where C_{rc} is the radon concentration in the receiver container [Bq/m^3], n is the air change rate in the receiver container [s^{-1}], Δt is the time difference between time steps [s], E is the radon exhalation rate from the sample to the receiver container [Bq/(m^2. s)], A is the area of the sample [m^2] and V is the volume of the receiver container [m^3].

Described boundary condition is applied to the bottom side (contact with the source container) and to the upper side (contact with the receiver container). Adiabatic condition (no radon diffusion flux) is used on the left-hand and right-hand sides of the sample.

The numerical solution of equation (2) was derived by means of the finite element method, using the Galerkin approach. Initial and boundary conditions for equation (2) – briefly described above – are more discussed in Ref. [8], together with an explanation of how the time-dependent boundary conditions must be treated in the numerical solution of equation (2).

The finally developed software was used to model the processes that occur in the above-described measuring device when measuring the radon diffusion coefficient. The entered sample area and the volume of the receiver container therefore correspond to the actual dimensions. The boundary condition on the upper surface of the joint reflects the gradually increasing concentration of radon in the receiver container as expressed by equation (4). However, unlike real measurements, the boundary condition on the lower surface of the joint assumes a constant radon concentration in the source container of 10 MBq/m^3. The uniform concentration on the lower surface allows the importance of individual parameters for the tightness of the joint to be evaluated. Numerical modeling was used to predict the time evolutions of the radon concentration in the receiver container and the radon exhalation rate from the surface of the sample into the receiver container for each type of joint.

In addition to other parameters, radon resistance was used to evaluate the radon tightness of the joints. This was calculated according to equation (5) from the values of the radon diffusion coefficient determined during experimental tests [9]. In the case of numerical modeling, the radon resistance was calculated using final steady state values (i.e. values at the end of the calculation period, when steady-state diffusion is reached) of the radon exhalation rate into the receiver container and the radon concentration in the source container (equation (6)).

$$R_{Rn} = \frac{\sinh(d/l)}{\lambda \cdot l}\ [\mathrm{s/m}] \tag{5}$$

$$R_{Rn} = \frac{C_s}{E}\ [\mathrm{s/m}] \tag{6}$$

where d is the thickness of the membrane [m], l is the radon diffusion length calculated from the radon diffusion coefficient [m], C_s is the steady state radon concentration in the source container [Bq/m^3], E is the steady state radon exhalation rate from the sample into the receiver container [Bq/m^{2}s], and R_{Rn} is the radon resistance [s/m].

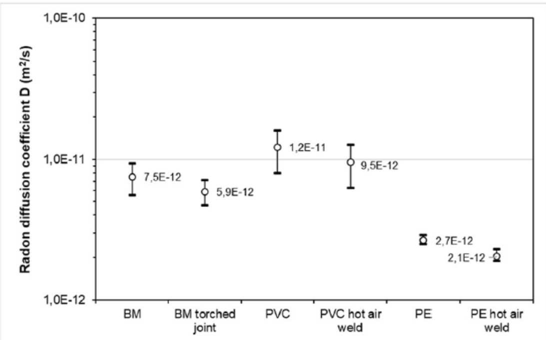

Fig. 3. Values of the radon diffusion coefficient (AM ± SD) measured for different membranes and their welded joints. The chart uses data from eight bitumen membranes BM, four flexible PVC membranes and four polyethylene membranes. For each product, the value of the diffusion coefficient of the joint was lower than that of the membrane itself.

3. Results and discussion

3.1. Welded joints

Both mathematical modeling and experimental measurements on welded joints (Fig. 1a) showed that the radon supply rate to the receiver container and the resulting radon concentration in the receiver container were lower compared to the values for samples without joints. The resulting value of the radon diffusion coefficient for the joint was always lower than its value for the membrane itself (Fig. 3). This means that the joint does not reduce the radon resistance of the whole membrane. Such results are due to the fact that the sample is twice as thick in the area of overlap. As can be seen from Fig. 3, the radon diffusion coefficient is reduced by less than 25 %. Since leaky joints show an increase in the radon diffusion coefficient of up to two orders of magnitude, this means that greater joint thickness cannot mask joint leaks. No significant differences were registered between flame welding of bitumen membranes and hot air welding of polymer membranes. It follows that correctly executed welded joints do not reduce the barrier properties of radon-proof membranes.

3.2. Joints sealed with a top tape

At the joints sealed with the top tape, a strip several mm in width is formed, where the tape is the only barrier (Fig. 1b). The radon tightness of the joint is thus determined by the barrier properties of the sealing tape given by its thickness and the radon diffusion coefficient. Sealing tapes can differ in material composition. Butyl tapes, PE tapes with self-adhesive treatment, tapes consisting of PE, bitumen or Al layers, or tapes combining layers of different polymers are most widely used. Depending on the material composition, the radon diffusion coefficient of the sealing tape can range from 10^{-10} to 10^{-14} m^2/s (Table 1).

Numerical modeling showed that a significant deterioration of the barrier properties of the membrane occurs when the top tape has a radon diffusion coefficient two to three orders of magnitude greater than that of the membrane itself. At the same time, the thickness of the tape does not play such an important role. This is documented in Fig. 4, which shows the increase in radon concentrations in the receiver container depending on the radon diffusion coefficient of the top tape D_{tape} and its thickness. For D_{tape} one order of magnitude greater than D_m, the steady state concentration in the receiver container is less than twice the concentration corresponding to the membrane without the joint. If D_{tape} is two orders of magnitude greater than D_m, the concentration in the receiver container is 10 times greater, and for D_{tape} three orders of magnitude greater than D_m, the concentration is even 90 times greater than for a membrane without a joint. A greater value of the radon diffusion coefficient of the tape D_{tape} causes an increase in radon exhalation into the receiver container (Fig. 5). Consequently, the radon resistance of the joint decreases, as it is inversely proportional to the radon exhalation rate in accordance with equation (6). For tapes with a high value of the radon diffusion coefficient, the drop in radon resistance can be very significant.

The results of the numerical simulation were confirmed by measurements on samples of a composite membrane combining PE and Al layers. The total thickness of the membrane was 0.4 mm. The membrane was exposed to a radon concentration in the source container of 9.6 MBq/m^3. Fig. 6 shows the values of the radon diffusion coefficient determined for the membrane itself and two joints sealed with either butyl tape or PE tape. The experiment confirmed that thicker butyl tapes provide greater joint tightness than thin PE tapes. It is worth noting that, for the joint sealed with PE tape, the measured value of the diffusion coefficient was almost three orders of magnitude greater than for the membrane without a joint. Such an increase in the values indicates a radon leaky joint, which is manifested by a significant decrease in the radon resistance of the tested samples (up to six orders of magnitude).

3.3. Joints sealed with a tape placed between membranes

Self-adhesive butyl tapes 30–60 mm in width and 1–3 mm in thickness are most often used to seal the joints shown in Fig. 1c. If the tapes are inserted between clean polymer foils, the surface of which is free of dust, the joint is usually tight. Although butyl tapes have a diffusion coefficient up to one order of magnitude greater than standard polymer foils, the width of the tape is large enough to prevent radon from diffusing across the tape. The radon diffusion coefficient measured on samples with a joint coincides with the coefficient of the membrane within the measurement error. Dimpled membranes are an exception to this rule. Due to the presence of dimples, only tapes with a width of around 5–10 mm can be used to seal the joints. This type of tape is not able to transfer the dilation movements of inflexible, rigid and tough dimpled membranes made of HDPE. As a result, the tape easily peels off from the membrane and the joint becomes leaky. This was confirmed experimentally by measuring the radon diffusion coefficient. The value for the joint was two orders of magnitude greater than for the membrane itself (Fig. 7). Unfortunately, there is no reliable sealing technology for sealing the joints of dimpled membranes.

In addition, this method of sealing joints is not suitable for polymer foils that have a permeable layer on the underside (Fig. 1d). The permeable layer can be formed by a geotextile, a non-woven fleece, bentonite, a self-adhesive coating, etc. The sealing tape is thus not inserted between the foils, but between the foil and the permeable layer through which radon can penetrate. Significant radon

Table 1
Typical thicknesses and radon diffusion coefficients D_{tape} of sealing tapes.

Material	Thickness [mm]	D_{tape} [m^2/s]
Al + butyl tape	1.5–2.5	$3.0 \times 10^{-14} - 3.0 \times 10^{-13}$
Butyl tape	1.0–2.0	$3.0 \times 10^{-12} - 3.0 \times 10^{-11}$
PE + bitumen tape	1.5	$7.0 \times 10^{-12} - 3.0 \times 10^{-11}$
Self-adhesive PE tape	0.2–0.5	$6.0 \times 10^{-12} - 1.0 \times 10^{-10}$

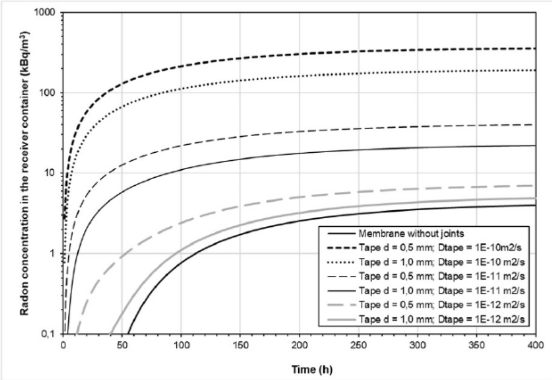

Fig. 4. Time evolution of the radon concentration in the receiver container in dependence on the radon diffusion coefficient of the tape D_{tape} and the tape thickness. The result of the numerical simulation for a sample of the membrane with $D_m = 1 \times 10^{-13}$ m^2/s and thickness $d = 0.5$ mm exposed to a constant radon concentration in the source container $C_s = 10$ MBq/m^3.

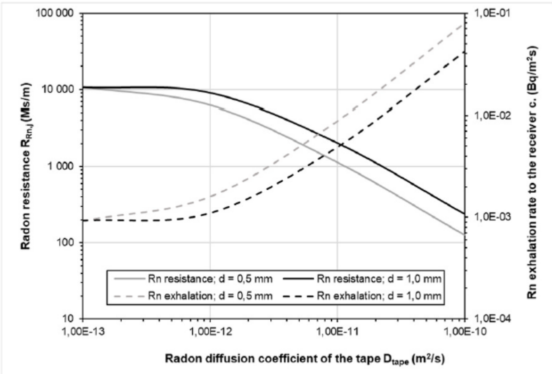

Fig. 5. Radon exhalation rate into the receiver container and radon resistance of the joint in dependence on the radon diffusion coefficient of the tape D_{tape} and the tape thickness. The result of the numerical simulation for $D_m = 1 \times 10^{-13}$ m^2/s, membrane thickness $d = 0,5$ mm and $C_s = 10$ MBq/m^3. The radon resistances of the joint were calculated according to relationship (6).

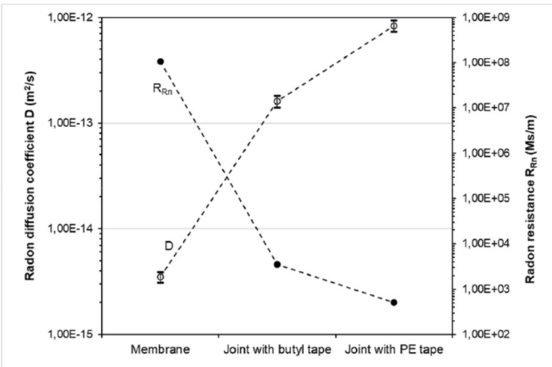

Fig. 6. Values of the radon diffusion coefficient (AM ± U) measured for the PE/AL membrane and its joints sealed with two different top tapes. Radon resistances were calculated from the arithmetic means of the radon diffusion coefficient values according to relationship (5). The expanded uncertainties of measurement ± U are the product of standard measurement uncertainties and the expansion coefficient k = 2, which provides a confidence interval of approx. 95 %.

diffusion through the permeable layer was confirmed by experimental measurements of the radon diffusion coefficient for various polymer foils and their joints sealed with tape inserted between the foils (Fig. 7). From the measured values, it follows that an increase in the radon diffusion coefficient and a decrease in radon resistance by one to three orders of magnitude were recorded for the joints

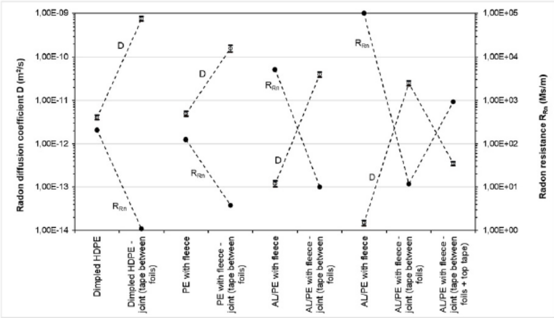

Fig. 7. Values of the radon diffusion coefficient (AM ± U) measured for different foils and their joints sealed with tapes placed between foils. Radon resistances were calculated from the arithmetic means of the radon diffusion coefficient values according to relationship (5).

compared to the values of the foil itself. The radon tightness of a joint sealed with tape inserted between foils with a permeable layer on the underside can be increased by using a top tape applied over the upper surfaces of the foils, as shown in Fig. 1e. Fig. 7 documents that the top tape reduces the value of the radon diffusion coefficient and increases the radon resistance by up to two orders of magnitude compared to a joint sealed only with a tape placed between the foils.

Numerical simulation was used to study the factors affecting the amount of radon diffusing through the permeable layer. It turned out that the most important role is played by the radon diffusion coefficient of the permeable layer, its thickness, and the width of the sealing tape, which determines the distance that the radon must diffuse through the permeable layer to penetrate from one side of the joint to the other. If we recognize that this distance, together with the radon diffusion coefficient of the permeable layer, determines the radon resistance of this layer, the radon resistance of joint $R_{Rn,j}$ can be expressed as a function of the radon resistance of the permeable layer. Fig. 8 shows that the steepest increase in the radon resistance of the joint occurs when the radon resistance of the permeable layer increases from 0.1 Ms/m to 10 Ms/m. The graph can also be used to determine the radon resistance of the permeable layer so that the radon resistance of the joint meets the requirements for the whole radon-proof course.

3.4. *Joints between self-adhesive bitumen membranes*

Membranes with a self-adhesive layer on the underside are able to form radon-tight joints if their topside is made of a smooth asphalt layer or a polymer film. However, if their topside is covered with mineral powder or sand (Fig. 1f), the self-adhesive layer adheres only to the top grains of sand without filling the gaps between the lower grains. Empty gaps between the grains allow radon to penetrate the joint. The correct solution is to seal the joints of the self-adhesive bitumen membranes by torching, which ensures fusion of the bitumen masses from both membranes (the molten bitumen must fill all the gaps between the grains). A comparison of the values of the radon diffusion coefficients measured on torched joints and on self-adhesive joints is provided in Fig. 9. It is clear that torched joints can have a radon diffusion coefficient that is up to four orders of magnitude lower than that of self-adhesive joints. In the case of radon resistances, the difference can be even more significant - it can exceed five orders of magnitude. Greater differences occur with membranes with a very low radon diffusion coefficient, such as membranes with Al foil.

3.5. *The influence of leaky joints on the overall barrier properties of membranes*

The above-mentioned values of the radon diffusion coefficient and radon resistance concerned either only the membrane itself or the joint itself. In real practice, there is a certain length of joints on each surface covered with waterproofing. It is clear that leaky joints influence the value of the radon diffusion coefficient of the whole waterproof course. The overall value of the radon diffusion

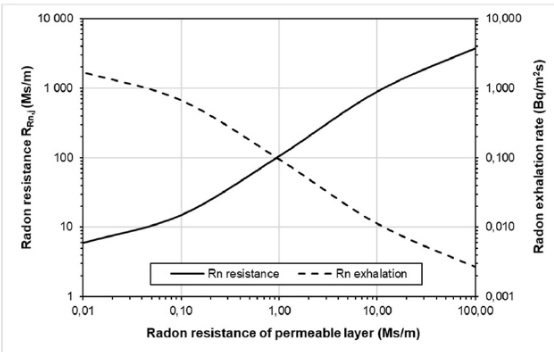

Fig. 8. Correlation between the radon resistance of the permeable layer and the radon resistance of the joint sealed with tape inserted between the foils with the permeable layer on the underside. The radon resistances of the joint were calculated according to relationship (6).

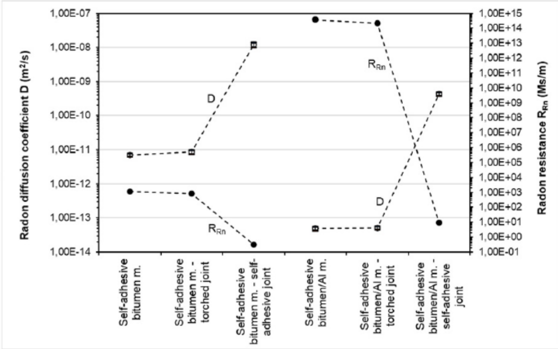

Fig. 9. Values of the radon diffusion coefficient (AM ± U) measured for different self-adhesive bitumen membranes and their torched joints and self-adhesive joints. Radon resistances were calculated from the arithmetic means of the radon diffusion coefficient values according to relationship (5).

coefficient D_o must lie between the values for the membrane itself and for the joint. It is important to know this value for the correct design of waterproofing, which also fulfills the radon proofing function.

The overall value D_o depends on the ratio of the total length of the joints to the total area of the waterproofing course. This ratio is influenced by the distance between the joints, which corresponds to the production width of the membranes. Heavy membranes, such as bitumen membranes, are produced with a width of 1 m, and lighter polymer membranes can be several meters wide. Avoiding the need to calculate the total length of the joints, it is sufficient in most cases if we replace the above-mentioned ratio with the ratio $1/i$, which expresses the area of the membrane corresponding to 1 m of joint length (Fig. 10). Another parameter that enters into the calculation of D_o is the diffusion coefficient of joint D_j. This value was measured on a sample with a certain area A_s and a certain joint length r_s. These data are part of the calculation, as they are used to convert the measured diffusion coefficient of the joint to the membrane area corresponding in a real situation to 1 m of joint length. The resulting formula for calculating the overall radon diffusion coefficient is therefore as follows:

$$D_o = D_m + (D_j - D_m) \cdot \frac{A_s}{r_s} \cdot \frac{r_m}{A_m} \simeq D_m + (D_j - D_m) \cdot \frac{A_s}{r_s} \cdot \frac{1}{i} \ [\mathrm{m}^2 / \mathrm{s}] \qquad (7)$$

where D_o is the overall radon diffusion coefficient of the whole waterproof course [m^2/s], D_m is the radon diffusion coefficient of the membrane [m^2/s], D_j is the radon diffusion coefficient of the joint [m^2/s], A_s is the area of the test sample [m^2], A_m is the area of the membrane [m^2], i is the distance between joints [m], r_s is the joint length in the area of the test sample [m], and r_m is the length of the joint in the area of the membrane [m]. For our measuring device, $A_s/r_s = 0.27$ m.

The calculation of D_o according to equation (7) makes sense, of course, only if $D_j > D_m$. If the measurement shows that $D_j < D_m$, which can happen with tight joints, then $D_o = D_m$. Furthermore, it should be noted that the calculation using the ratio $1/i$ does not consider the transverse joints of the membranes, nor other joints, for example around penetrating structures. The actual D_o will therefore be slightly larger than the calculated D_o.

Fig. 11 graphically illustrates the influence of D_j on D_o according to equation (7) for a standard membrane with $D_m = 1.0 \times 10^{-12}$ m^2/s and for different joint distances. It can be seen from the figure that for $D_j = 1.0 \times 10^{-11}$ m^2/s and $i = 1$ m, D_o is more than three times larger and for $i = 3$ m it is almost two times larger than D_m. However, if D_j is two to three orders of magnitude larger than D_m (such large differences have really been measured - see Figs. 6, 7 and 9), D_o differs from D_m by the same number of orders. For example, for $i = 1$ m and $D_j = 1.0 \times 10^{-10}$ m^2/s, resp. $D_j = 1.0 \times 10^{-9}$ m^2/s, D_o is 28 times, resp. 270 times larger than D_m. Such a large increase in the radon diffusion coefficient must necessarily result in a decrease in the ability of the membrane to prevent radon penetration. This can be expressed by the decrease in radon resistance, which is recorded in Fig. 12.

Although it is generally true that the effect of leaky joints decreases with increasing distance between joints, the drop in the radon resistance of the whole waterproof course is very significant, especially for i up to 3 m. A leaky joint can thus cause the radon resistance of the whole waterproof course to drop below the minimum radon resistance value required by some technical regulations and standards. For example, the waterproofing product according to Fig. 12 does not meet the minimum radon resistance of 50 Ms/m according to the SINTEF requirements [17], nor the minimum resistance of 300 Ms/m according to the Czech standard CSN 73 0601 [2], for certain values of D_j at a joint distance of up to 3 m. It can be concluded that a leaky joint may exclude the use of some waterproofing products as a radon barrier.

4. Conclusions

Experimental determination of the radon diffusion coefficient on different types of membrane joints has helped to identify joints that do not have sufficient tightness against radon penetration. Significant radon leaks were discovered at the following joints - joints of polymer membranes sealed with a top tape, joints of polymer membranes with a permeable layer on the underside sealed with a tape placed between membranes, joints of dimpled membranes, and self-adhesive joints of bitumen membranes with a sanded topside. Tests have shown that the radon diffusion coefficient for these joints is one to three orders of magnitude greater than the value for the

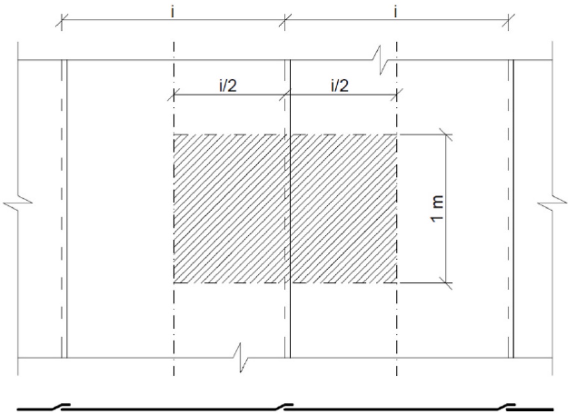

Fig. 10. The area of the membrane corresponding to 1 m of joint length for joint distance *i*.

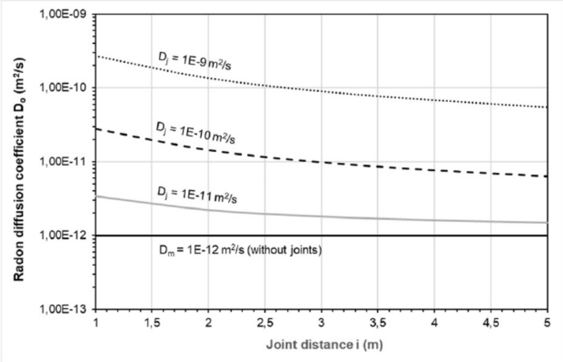

Fig. 11. The influence of D_j on the radon diffusion coefficient of the whole waterproof course D_o in dependence on the distance between the joints.

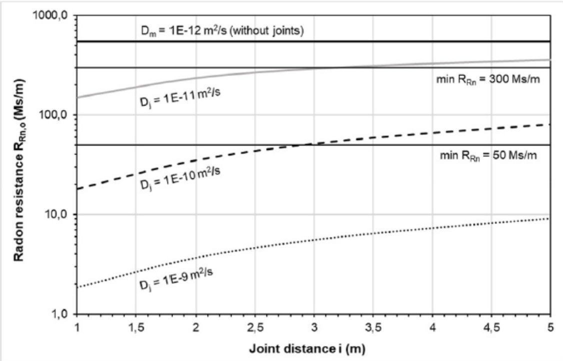

Fig. 12. The influence of D_j on the radon resistance of the whole waterproof course $R_{Rn,o}$ in dependence on the distance between the joints. Radon resistances were calculated according to relationship (5) for membrane thickness $d = 0.5$ mm. A comparison is made with some minimum values of radon resistance according to legislative regulations.

membrane itself. Since the samples of the tested joints were made by professionals from the companies producing or supplying the membranes, the high values of the radon diffusion coefficient for the joints cannot be explained by bad execution of the joints. In addition, the increased values were confirmed for different material variants (different membranes and different sealing tapes) of each joint. The reasons for the high values of the radon diffusion coefficient of joints were explained by numerical simulation and lie in the use of unsuitable sealing tapes (with a small thickness and a high radon diffusion coefficient), or in the choice of a bad sealing technology (joining membranes over permeable layers).

In general, joints between polymer membranes sealed with various sealing tapes were found to be the most problematic. In addition to the factors studied in our research, leaks in these joints can also be caused in practice by poor adhesion of the tape to a dusty, dirty, or wet membrane surface. Another factor that can negatively affect the tightness of the joint is the formation of air bubbles, cavities and channels between the tape and the membrane, which are the result of uneven stretching of the tape during its application. Therefore, great attention should be paid to observing the correct implementation technology and using only sealing tapes with suitable parameters. Thicker butyl tapes and higher quality composite tapes should be preferred to thin PE tapes. Joints of membranes with a permeable layer on the underside should be sealed with a top tape.

On the other hand, it has been shown that torched joints of bitumen membranes and hot-air welds of polymer membranes have excellent radon tightness. The radon resistance of these joints is the same as for the membranes. Therefore, whenever possible, this method of joining should be preferred.

The new finding of our research is that not all standard types of joints that are commonly used for joining membranes protecting buildings against moisture are also suitable for protecting buildings against radon. If a membrane is also to fulfill the function of a barrier against radon, manufacturers must pay more attention to the development and verification of sealing materials and joint technologies. We propose that in the future only such waterproofing products should be certified as a radon barrier that demonstrates sufficient radon resistance not only of the membrane itself, but also of the joints. This will require testing laboratories to be equipped with suitable measuring equipment that can be used to measure larger samples with joints.

The results of our research should also be considered in the design of radon-proof courses. As has been shown, leaky joints can significantly impair the ability of the membrane to prevent radon penetration by reducing its overall radon resistance. If a building code or standard prescribes a minimum radon resistance value, this value should apply to the whole radon-proof course, not just to the membrane itself. The radon resistance value of the whole radon-proof course can be determined by the procedure described in this paper. Another way to take membrane joints into account in the design of radon-proof courses is to minimize the total length of the joints by using membranes with larger production widths.

The radon tightness of penetrating installation lines should be given the same attention as is given to joints. Since a range of materials are used in membranes, sleeves and collars, this is a topic for a separate investigation.

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CRediT authorship contribution statement

Martin Jiránek: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Conceptualization. **Veronika Kačmaříková:** Writing – original draft, Visualization, Resources, Investigation. **Zbyněk Svoboda:** Writing – original draft, Software, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] Building Regulations 1997, Technical Guidance Document C, Site Preparation and Resistance to Moisture, 2008.
[2] Czech Technical Standard ČSN 73 0601 Protection of Buildings against Radon from the Soil, Czech Standardization Agency, 2019.
[3] T. Dobrovolný, M. Jiránek, J. Krejsová, The influence of pinholes in waterproofing materials on the value of the radon diffusion coefficient, Radiat. Protect. Dosim. 191 (2) (2020) 238–243. https://doi:10.1093/rpd/ncaa160.
[4] Ulli Heinlein, Karl-Christian Thienel, Thomas Freimann, Pre-applied bonded waterproofing membranes: a review of the history and state-of-the-art in Europe and North America, Construct. Build. Mater. 296 (2021) 123751, https://doi.org/10.1016/j.conbuildmat.2021.123751. ISSN 0950-0618.
[5] J. Chen, J. Ly, E. Schroth, et al., Radon diffusion coefficients of vapour barrier membranes used in Canadian building construction, Radiat. Environ. Biophys. 48 (2009) 153–158, https://doi.org/10.1007/s00411-009-0212-5.
[6] ISO/TS 11665-13 (E), Measurement of Radioactivity - Air: Radon 222 - Part 13: Determination of the Diffusion Coefficient in Waterproof Materials: Membrane Two-Side Activity Concentration Test Method, 2017.
[7] M. Jiránek, New, efficient and generally applicable design of radon-proof insulations — a proposal for a uniform approach, Radiat. Protect. Dosim. 177 (2017) 121–124, https://doi.org/10.1093/rpd/ncx139.
[8] M. Jiránek, Z. Svoboda, Transient radon diffusion through radon-proof membranes: a new technique for more precise determination of the radon diffusion coefficient, Build. Environ. 44 (2009) 1318–1327. https://doi:10.1016/j.buildenv.2008.09.017.
[9] M. Jiránek, Z. Svoboda, A new approach to the assessment of radon barrier properties of waterproofing materials, Radiat. Protect. Dosim. 177 (2017) 116–120, https://doi.org/10.1093/rpd/ncx140.
[10] M. Jiránek, V. Kačmaříková, Radon diffusion coefficients and radon resistances of waterproofing materials available on the building market, J. Environ. Radioact. 208–209 (2019) 106019, https://doi.org/10.1016/j.jenvrad.2019.106019.
[11] G. Keller, B. Hoffmann, T. Feigenspan, Radon permeability and radon exhalation of building materials, Sci. Total Environ. 272 (2001) 85–89.
[12] Selim M. Khan, James Gomes, Daniel R. Krewski, Radon interventions around the globe: a systematic review, Heliyon 5 (2019) e01737, https://doi.org/10.1016/j.heliyon.2019.e01737.

[13] A. Maier, et al., Method for measurement of radon diffusion and solubility in solid materials, Nucl. Instrum. Methods Phys. Res., Sect. B 416 (2018) 119–127. https://doi:10.1016/j.nimb.2017.12.008.
[14] Beatriz Ruvira, Beatriz García-Fayos, Belén Juste, José Miguel Arnal, Gumersindo Verdú, Determination of the radon diffusion coefficient of thin polyethene and aluminium foils used as single or multilayer configuration barriers, Radiat. Phys. Chem. 200 (2022) 110329, https://doi.org/10.1016/j.radphyschem.2022.110329. ISSN 0969-806X.
[15] Piotr Szajerski, Arkadiusz Zimny, Numerical analysis and modeling of two-loop experimental setup for measurements of radon diffusion rate through building and insulation materials, Environ. Pollut. 256 (2020) 113393, https://doi.org/10.1016/j.envpol.2019.113393. ISSN 0269-7491.
[16] Michael Schubert, Diana Altendorf, Holger Weiß, A straightforward approach for assessing the effectiveness of membrane materials as radon (222Rn) barriers, Isot. Environ. Health Stud. 58 (3) (2022) 301–310. https://doi:10.1080/10256016.2022.2058500.
[17] SINTEF, Guidelines for SINTEF technical approval for radon membranes (2012).
[18] Spanish Ministry of Public Works and Transport, Basic document DB-HS on health and safety, Section 6 - Protection against Radon, Technical Building Code, 2019, pp. 138–184.
[19] WHO Handbook on Indoor Radon. A Public Health Perspective, WHO, 2009. ISBN 978 92 4 154767 3.
[20] Z. Svoboda, M. Jiránek, Software Packages TransRn & IterRn, Czech Technical University, Prague, 2004-2021.