Natural Radioactivity and Radon in Building Materials

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Abstract. Most building materials of natural origin contain small amounts of Naturally Occurring Radioactive Materials (NORM), mainly radionuclides from the ^{226}Ra and ^{232}Th decay chains and ^{40}K. Building materials of natural origin reflect the geology of their site of origin. The average ^{226}Ra, ^{232}Th and ^{40}K activity concentration in the Earth's crust is 35, 30 and 400 Bq/kg. Industrial waste or by-products containing high concentrations of NORM, e.g. fly ash, coal slag, phosphogypsum, are extensively used in building materials. Several surveys were conducted at different locations worldwide to characterize the activity concentrations of NORM and the radon exhalation rate from raw materials and building materials. The external radiation exposure, caused by the gamma emitting radionuclides, is assessed either by direct exposure measurements or by mathematical calculations. The evaluation of the internal radiation exposure, due to ^{222}Rn exhaled from building materials into the room air, is more complicated and may strongly depend on environmental parameters, e.g. the ventilation rate. The correlation between the radon exhalation rate measured under laboratory conditions and the in-situ wall exhalation rate is not fully understood. Regulation on the radioactivity in building materials is based on dose criteria for controls and on exemption levels. Internal dose limits from ^{222}Rn exhaled from building materials should be kept consistent with national action levels for indoor radon. Setting a low reference radon concentration for building materials will enable to account for contributions from other sources without exceeding the action level.

KEYWORDS: NORM, building materials, radon exhalation, natural exposure.

1. Introduction

Man is continuously exposed to ionizing radiation from Naturally Occurring Radioactive Materials (NORM). The origin of these materials is the Earth's crust, but they find their way into building materials, air, water, food and the human body itself. The worldwide average indoor effective dose due to gamma rays from building materials is estimated to be about 0.4 mSv per year [1]. In many parts of the world, building materials containing radioactive material have been used for generations. As individuals spend more than 80% of their time indoors, the internal and external radiation exposure from building materials creates prolonged exposure situations [2].

Most building materials of terrestrial origin contain small amounts of NORM, mainly radionuclides from the ^{238}U and ^{232}Th decay chains and the radioactive isotope of potassium, ^{40}K. The external radiation exposure is caused by the gamma emitting radionuclides, which in the uranium series mainly belong to the decay chain segment starting with ^{226}Ra. The internal (inhalation) radiation exposure is due to ^{222}Rn, and marginally to ^{220}Rn, and their short lived decay products, exhaled from building materials into the room air.

Generally, natural building materials reflect the geology of their site of origin. The average activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in the Earth's crust are 35, 30 and 400 Bq/kg respectively [1]. However, elevated levels of natural radionuclides causing annual doses of several mSv were identified in some regions around the world, e.g. in Brazil, France, India, Nigeria, Iran.

Recycled industrial by-products containing Technologically Enhanced Natural Occurring Radioactive Materials (TENORM) are extensively used in the construction industry. Coal ash, produced as waste in the combustion of coal, is used as an additive to cement, in concrete and in some countries bricks are made from fly ash. Coal slag is used in floor structures as insulating filling material. Phosphogypsum, a by-product in the production of phosphorous fertilizers is used as building material, and red mud, a waste from primary aluminum production, is used in bricks, ceramics and tiles [3, 4].

Doses from the gamma radiation and the radon indoor concentration are assessed by means of direct exposure measurements or by mathematical calculations.

The increased tendency in the building material industry to use industrial wastes as substitutes for natural products, having relatively high activity concentration of NORM, and the increased exposure caused by them are the driving force for the development of standards and guidelines.

This paper reviews the current state of the knowledge on activity concentrations of natural radionuclides in building materials and some dose assessment approaches. A review of some national regulations and standards is presented with a special focus on radon.

2. NORM in building materials

During the last three decades, there has been an increasing interest in the study of the radioactivity of different building materials. Several national surveys were conducted to establish the radioactivity concentrations in raw material, industrial by-products and building materials and their radon exhalation rate [5 – 25]. The production process and the origin of the raw materials are the most important factors that determine the radionuclide activity concentrations in the construction materials.

Different types of building materials were found to contain radionuclide concentration of over two to three orders of magnitude.

In order to compare the specific activities of materials containing different amounts of ^{226}Ra, ^{232}Th and ^{40}K, an index, called the radium equivalent concentration Ra_{eq} was defined based on the fact that 370 Bq/kg of ^{226}Ra, 259 Bq/kg of ^{232}Th and 4810 Bq/kg of ^{40}K produce the same gamma dose rate [26]. Therefore, the Ra_{eq} of building material can be written as:

$$Ra_{eq} = C_{Ra} + 1.43C_{Th} + 0.077C_{K} \qquad (1)$$

where C_{Ra}, C_{Th} and C_K are the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K, respectively, in Bq/kg.

The raw materials commonly used in the construction industry may contain NORM at different activity concentrations according to their place of origin. Tables 1 and 2 present ranges of activity concentration of the natural radionuclides in natural raw materials and industrial by-products used in the construction industry.

Table 1: Activity concentration range of commonly used natural raw materials.

Material	**^{226}Ra [Bq/kg]**	**^{232}Th [Bq/kg]**	**^{40}K [Bq/kg]**
Sand quartz	3 - 39	3 - 56	12 - 1008
Basalt	10 - 22	10 - 21	231 - 420
Gravel	10 - 33	ND - 33	14 - 9333
Limestone	ND - 24	ND - 11	ND - 205
Clay	32 - 53	41 - 75	518 - 843
Wood	ND - 10	ND - 4	4 - 166

Table 2: Activity concentration range of commonly used industrial by-products containing TENORM.

Raw material	**^{226}Ra [Bq/kg]**	**^{232}Th [Bq/kg]**	**^{40}K [Bq/kg]**
Fly ash	67 - 760	48 - 232	221 - 735
Zircon	3300 - 3900	680 - 750	45 - 56
Red mud	122 - 568	219 - 496	5 - 101
Phosphogypsum	600 - 1500	ND - 160	ND - 300

2.1 ^{226}Ra, ^{232}Th and ^{40}K concentrations in building materials

The activity concentrations of NORM in building materials vary according to the type and origin of the building material. The typical activity concentration [Bq/kg] in the most common building materials in Europe, e.g. concrete and sand-lime bricks is 40, 30 and 400 and 10, 10, 330 for ^{226}Ra, ^{232}Th and ^{40}K, respectively [5]. Tables 3 and 4 present typical values of NORM in masonry used, both as structural materials and covering layers.

Table 3: Activity concentration range (Bq/kg) of common building materials.

Building material	**^{226}Ra [Bq/kg]**	**^{232}Th [Bq/kg]**	**^{40}K [Bq/kg]**
Concrete	18 - 67	3 - 43	16 - 1100
Light weight concrete	10 - 60	6 - 66	51 - 870
Bricks	7 - 140	8 - 127	227 - 1140
Gypsum	1 - 67	0.5 - 190	22 - 804
Cement	13 - 107	7 - 62	48 - 564

Table 4: Activity concentration range (Bq/kg) of selected covering building materials.

Building material	**^{226}Ra [Bq/kg]**	**^{232}Th [Bq/kg]**	**^{40}K [Bq/kg]**
Ceramics	25 - 193	29 - 66	320 - 1049
Granite	ND - 160	ND - 354	24 - 2355
Tiles	33 - 61	45 - 66	476 - 788
Marble	1 - 63	0.4 - 142	9 - 986

2.2 Radon exhalation from building materials

The radon emanation power or emanation coefficient, denoted by ε, is defined as the fraction of ^{222}Rn produced by the disintegration of ^{226}Ra in the grains of the material that can escape from it. The emanation power is dimensionless and ranges from 0 (no radon escapes from the material) to 1 (all radon escapes). The rate of radon exhalation is proportional to the gradient of the radon concentration in the internal pores [27].

$$E = -D \cdot \left. \frac{dC}{dx} \right|_{x=l} \quad (2)$$

Where D is the effective diffusion coefficient and dC/dx is the change in the radon concentration.

The principal factors affecting the radon exhalation rate (from a building material) per unit activity concentration of ^{226}Ra are the porosity and the density of the material, the diffusion coefficient, the water content, the age and the composition of the material (as seen in equation 3).

For the following boundary conditions: C(l)=C(-l)≅0 and $\left(\frac{dC}{dx}\right)_{x=0} = 0$ the radon exhalation rate E becomes:

$$E = \varepsilon \cdot C_{Ra} \cdot \rho \cdot \sqrt{\frac{\lambda D}{p}} \cdot \tanh\left(\sqrt{\frac{\lambda p}{D}} \cdot l\right) \quad (3)$$

Where ρ is the density, l is the half thickness of the material, p is the porosity of the material, λ is the decay constant of ^{222}Rn and $\varepsilon \cdot C_{Ra}$ is the effective radium concentration (the fraction of the total radium which contributes to radon exhalation).

Radon exhalation from building materials has been studied since the early 70's as one of the contributors to the indoor radon concentration [28 – 29]. In Hong Kong and the Netherlands was found to be the major contributor to the population radon dose [30 - 31].

The radon exhalation rate from concrete varies according to the age of the concrete, the water content and the addition of fly ash. The exhalation increases almost linearly with the moisture content up to 50-60%, peaks at 70-80% and decreases steeply for higher moisture levels [32]. The addition of fly ash to concrete generally increases the ^{226}Ra activity, while the radon exhalation rate slightly increases or even decreases [33 – 35].

Several methods for exhalation measurements have been developed, as opposed to the well established gamma spectrometry procedures for the measurements of ^{226}Ra, ^{232}Th and ^{40}K. Measurements of radon from the exhaling area into a closed chamber, purge and trap of the radon, radon flux measurements from the material surface and *in-situ* measurements have been reported.

2.2.1. Closed chamber method

The closed chamber method is based on the measurement of the radon activity exhaled from the building material into an airtight closed chamber.

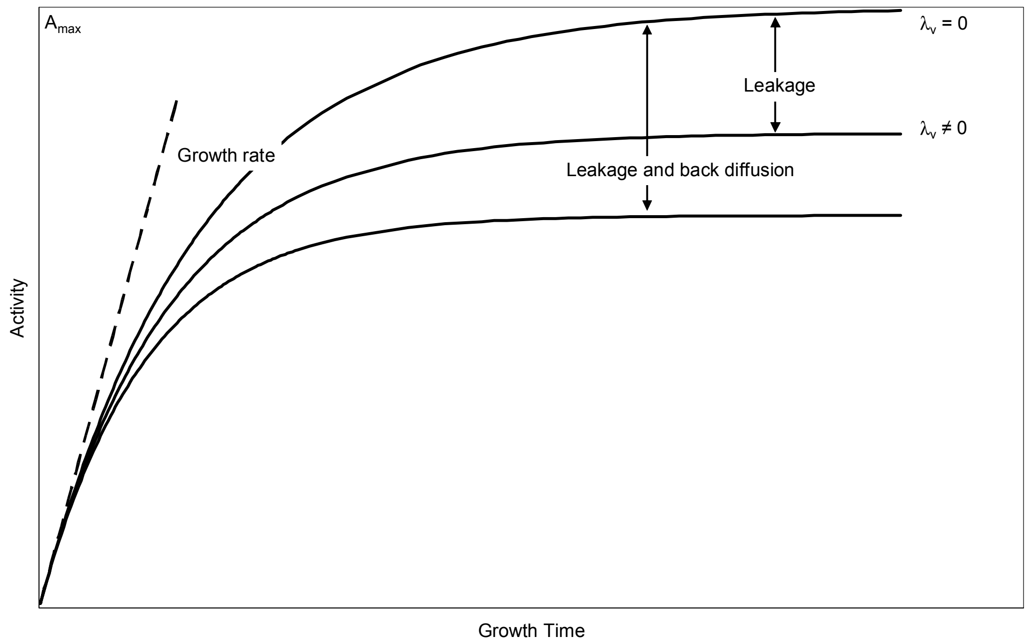
The radon concentration *N* in a closed chamber will grow with time according to the equation:

$$\frac{dN}{dt} = \frac{c}{V} - (\lambda + \lambda_v)N \qquad (4)$$

Where *V* is the container volume, *c* the total exhalation rate of the sample, λ is the radioactive decay rate and λ_v is the leakage or ventilation rate. If *c* is assumed to be constant and independent of *N* (free exhalation rate) the solution of equation 4 expressed as activity (*A*) and seen in Fig. 1 is:

$$A(t) = \frac{\lambda}{\lambda + \lambda_v} \cdot \frac{c}{V} \cdot \left(1 - e^{-(\lambda + \lambda_v)t}\right) \qquad (5)$$

Figure 1: Radon activity ingrowths in a closed chamber as a function of time.



If the exhalation is depressed due to back diffusion the equilibrium value will be lower than the maximum expected. The total exhalation rate is then calculated by the first part of the in-growth curve (which can be approximated by a linear fit) [36]. It follows, however, from the theory, and it has also been documented experimentally [37], that *c* will decrease as *N* increases, because of so-called back diffusion. The decrease in *c* depends upon the properties of the material and upon the ratio of the sample volume to the free space volume.

The radon is then measured by different means: collecting on activated charcoal [38], use of an electret ion chamber detector [39], solid state detectors or a continuous radon monitor (CRM). Only the last method, CRM, enables accounting for effects of leakage and back diffusion.

Radon exhalation from the cross sectional surfaces of the material must be prevented in order to simulate, as much as possible, exhalation from the wall. This is done by tightly covering the cross sectional surfaces with rubber and steel plates or other sealing materials so that only the two opposite surfaces of the material remain free to release radon [40].

2.2.2. Purge and trap method

The purge-and-trap method (required by the Dutch standard NEN 2001b) consists of enclosing the sample in a container from which the exhaled radon is continuously purged with nitrogen gas at a relative humidity of 50% and 20°C [41 – 42]. The exchange rate of the sample container has to fulfill the following relationship:

$$\frac{V_S}{V} \times \frac{\lambda}{\lambda + \lambda_v} < 0.1 \qquad (6)$$

where V_S is the volume of the test sample in the container. This requirement guarantees that the radon concentration around the sample is sufficiently low to avoid back diffusion and thus ensure that the free radon exhalation is determined. The nitrogen stream from the sample container is directed through a device to trap the radon gas. The trapping device is based on cooled activated charcoal, cooled silica-gel or room temperature activated charcoal.

2.2.3. Radon exhalation from surfaces

The measurement of radon exhaled from the surface of building materials is performed after radon enters into a closed volume as an inverted cup or a semi hemispherical container. The method uses either the linear increase in the concentration of the radon and radon decay products or the integral radon concentration in the closed volume to determine the exhaled radon rate [43 – 45]. Another approach consisting of measuring the radon directly from the surface using an activated charcoal canister was used in as study to evaluate the reduction of the exhalation rate from concrete by covering materials [46].

2.2.4. In-situ radon exhalation measurements

In-situ measurements performed directly from the wall or in a sealed room give the closest values to the true exhalation rate of radon into the room. These measurements are rather difficult to perform and few building materials, such as concrete, gypsum slabs or covering materials, were investigated. The exhalation rate was determined from the radon concentration growth curve. Measurement of the exhalation directly from the wall demands the container to be clamped against the material surface with a special rack, or against the opposite wall, ceiling or floor with a long rod. The difficulty with these measurements is the fact that because radon is collected from only one side of the slab, back diffusion of radon exists from the container to the slab, especially if the measured material has a high porosity [40].

Measurements of the exhalation rate in a sealed room are possible when the ventilation rate in the room is very low (less than 1 air exchange every few hundred hours). Measurements were conducted in shielded spaces, which are rooms made of massive concrete equipped with an airtight steel door and window [47].

The prediction of the radon release from dry building materials using Monte Carlo simulation programs (TRIM) has been reported [48]. The simulation establishes the relations between the emanating rate, surface area, material density, and porosity. It then calculates the radon emanation rate from porous materials.

It is agreed that among commonly used building materials, ordinary concrete has the higher radon emanation coefficient with a mean value around 0.15 (range: 0.1-0.4), while brick and gypsum have lower mean values, around 0.05 and 0.08 respectively [49].

The effects of wall covering on radon emanation have been studied for several materials [50 – 51] and were found to vary according to the permeability of the covering layer. Some plaster and paint will decrease the radon exhalation from painted walls, while at the same time the radon concentration will increase in the wall causing an excess in exhalation from unpainted parts of the wall.

The correlation between the exhalation rate measured under laboratory conditions and the in-situ exhalation rate is not fully understood and may vary significantly from one type of building material to another [52]. Simulation of the in-situ exhalation conditions in laboratory measurements was held by tightly covering the cross sectional surfaces with suitable sealing materials, so that only the two opposite surfaces of the material (the surface facing the room and its opposite) remain free to release radon [40, 53].

3. Dose assessments inside buildings

The external and internal exposures in a dwelling are estimated by using the radionuclide concentrations in the building materials and the radon exhalation rate from them, respectively. Several methods have been developed to assess those exposures.

3.1. Gamma ray exposure

The gamma ray exposure in a room is due to radiation emitted by decay products of the ^{226}Ra and ^{232}Th series and ^{40}K. Koblinger [54] first described a Monte Carlo code, based on basic photon transport models, for the calculation of the exposure rate in a standard room (4m x 5m x 2.8 m) from radionuclides in the wall. This method calculates the uncollided part of the dose, while the collided part can be treated by different approaches: using modified attenuation coefficients during the evaluation of the "optical distance" between the source and the detection point, inserting of build-up factors specially devised for this purpose or describing photon scattering effects by Monte Carlo simulations [55].

The dose calculation based on attenuation and build-up of photons from proposed by Stranden [56] and modified by Mustonen [57] is described by the following expression:

$$\dot{X} = \frac{kA\rho}{4\pi} \sum_i E_i N(E_i) \mu_a(E_i) \int \frac{B(E_i, s)}{l^2} e^{-d_i} dV \qquad (7)$$

Where $\dot{X}$ is the exposure rate, k is a coefficient of units conversion, A is the activity concentration of the radionuclide, ρ is the material density, E_i is the photon energy, $N(E_i)$ is the number of photons emitted per disintegration, $\mu_a(E_i)$ is the linear attenuation coefficient in air, $B(E_i,s)$ is the build-up factor at energy E for distance s, l is the distance from the source point and d_i is the distance the photon travels in the building material. The integration is performed on the volume of the walls.

Another approach developed in the Netherlands for the calculation of the dose rate in a dwelling takes into account the characteristics of every specific house (the construction parts, the building materials used, the internal partitioning, doors and windows, etc,) as independent factors affecting the dose rate [58].

The absorbed dose is calculated according to:

$$\dot{D} = \left\{ \sum_{i=1}^{6} \left[F_{dose} \times F_1 \times F_2 \cdots F_n \right]_i \right\} F_{zoning} \times F_{adjac} \qquad (8)$$

Where i is the index of the construction part in the dwelling (4 walls, floor and ceiling), F_{dose} is the dose factor of each radionuclide, F_1 to F_n are the subsequent correction factors belonging to construction part i, F_{zoning} is a correction factor for the internal zoning, F_{adjac} is the contribution from adjacent floors and dwellings. Among the correction factors belonging to each construction part (F_1,..,F_n), F_{Rn} is the radon release factor, F_{equil} accounts for the effect of ^{222}Rn exhalation on the dose rate, $F_{const,i}$ is the correction factor for the surface density of part i, $F_{dimens,i}$ is the relative dose contribution of part i, F_{leave} acounts for the attenuation of the outer leave, $F_{do/wi,i}$ are the areas of doors and windows.

Maduar and Hiromoto [59] proposed a numerical method for the calculation of the gamma dose rate in dwellings based upon the definition of volumetric radiation sources, dose factors, attenuation coefficients and build-up factors. The EDVOS (External gamma Doses due to Volumetric Sources) code was used to evaluate the dose conversion factors in different geometries of a single rectangular compartment, by varying the thickness and density of the building material, the compartment dimension and the coordinates of the calculation point. This study shows that the parameters to which the dose conversion factor is most sensitive are the density and thickness of the construction materials.

3.2. **Internal exposure to radon**

The evaluation of the internal dose caused by building materials is more complicated. The general parameters, apart from the exhalation rate of the building material, affecting the indoor radon concentration are the dimensions of the house (surface to volume ratio) and the ventilation rate.

Expressions for the concentration of radon in indoor air from building materials were derived several authors [60 – 61]. The diffusion pathway for ^{220}Rn is about 80 times smaller than for ^{222}Rn and its exhalation can occur only from the outer layer of the material (~1 mm). However, if there is a strong wind, it is quite possible that ^{220}Rn atoms are forced out from deeper layers of the wall, causing the exhalation to increase [60]. The indoor radon concentration in equilibrium is:

$$C = \frac{E \cdot S}{V \cdot (\lambda + \lambda_v)} + \frac{C_o \cdot \lambda_v}{\lambda + \lambda_v} \qquad (9)$$

Where E is the specific exhalation rate, S is the total wall, floor and ceiling area, V is the room volume, λ is the radon decay constant C_o is the outdoor radon concentration and λ_v is the ventilation rate.

In general, ventilation is the key factor that affects the indoor radon concentration and, on the average, an air-conditioned room has a higher radon concentration than a non-air-conditioned room in the same category of building, and the use of the building may slightly influence the radon concentration [62].

4. Regulations

The use of industrial by-products and residues containing elevated concentrations of radioactive material in building materials is increasing due to economic and environmental reasons. The national regulatory authorities should ensure that "annual doses are restricted to a few mSv for the worst-case scenarios" [63].

A practical approach would be to treat exposure situations resulting from radioactive building materials as existing exposure situations rather than as planned exposure situations. In fact, most uses of building materials, even of those using NORM residues (e.g., coal ash), are de-facto existing exposure situations which can only be sensibly addressed by the use of reference levels or building codes, thus regarding them as a special case of NORM situations or by treating radioactive building materials as a general commodity [63].

Control on the radioactivity of building materials can be based on dose criteria for controls and on exemption levels. The dose criteria used for control should be defined as the excess exposure caused by building materials, i.e. the background dose from natural radionuclides in the local typical environment need to be subtracted. For the external gamma radiation, the "local typical environment" can be defined either as the average dose received outdoors, or as the average dose received in a house built from materials with 'typical' activities [52].

For the radon pathway, the evaluation of the excess dose caused by building materials is more complicated. Since most of the indoor radon at ground level is from the underlying soil, the contribution of building materials must be evaluated by using some theoretical model and general assumptions on the parameter values affecting the indoor radon concentration.

Another approach for considering the radon pathway is to limit the amount of ^{226}Ra in the building material so that the indoor radon concentration cannot rise above some pre-set level even under unfavorable conditions. The reference radon concentration for this purpose could be the lower limit of the action level for radon in dwellings (200 Bq/m^3) recommended by the ICRP [64], or some fraction of it. This will enable contributions from other sources, especially from the underlying soil, without exceeding the action level [52]. In Hong Kong a high-rise building action level of 200 Bq/m^3 was proposed for existing buildings and 150 Bq/m^3 for new buildings [65].

The national median exposure level must be taken into account when setting a dose criterion. Countries with median excess gamma dose of 0.2 mSv arising from building materials may consider a dose criterion of, let say, 0.5 mSv, while this dose criterion will be unfeasible for countries having a median of 0.4 mSv, causing economically and socially intolerable situations because approximately 30% of the building materials on the market would be deemed unsuitable for building purposes [52, 66].

The regulation standards commonly include an activity concentration index I as follows [67]:

$$I = \frac{C_{Ra}}{A_{Ra}} + \frac{C_{Th}}{A_{Th}} + \frac{C_K}{A_K} \tag{10}$$

Where C_x represents the activity concentration of radionuclide x in the building material and A_x is the activity concentration of radionuclide x, which cause a predetermined dose.

4.1. The European recommendations

The European Commission (EC) set guidelines on the radiological protection principles concerning the natural radioactivity of building materials (RP-112 document) for the Member States [5]. Doses to members of the public should be kept as low as reasonably achievable. However, since small exposures from building materials are ubiquitous, control should be applied on exposure levels which are above typical levels of exposures and their normal variations.

Control should be based on a dose criterion which is established considering the overall national circumstances. Within the EU, doses exceeding 1 mSv/y should be taken into account from the radiation protection point of view. Investigation levels can be derived for practical monitoring purposes, presented in the form of an activity concentration index as in equation 10. The following activity concentration index (*I*) is derived for identifying whether a dose criterion is met:

$$I = \frac{C_{Ra}}{300\,Bq/kg} + \frac{C_{Th}}{200\,Bq/kg} + \frac{C_K}{3000\,Bq/kg} \qquad (11)$$

where C_{Ra}, C_{Th}, C_K are the ^{226}Ra, ^{232}Th and ^{40}K activity concentrations (Bq/kg) in the building material. The activity concentration index shall not exceed the values presented in Table 5.

Table 5: Limits of the activity concentration index.

Dose criterion	**0.3 mSv/y**	**1 mSv/y**
Materials used in bulk amount, e.g. concrete	$I \leq 0.5$	$I \leq 1$
Superficial and other materials with restricted use: tiles, boards, etc.	$I \leq 2$	$I \leq 6$

Small and unavoidable exposures need to be exempt from any control. A uniform exemption level would allow free movement of most building materials within the EU.

Some traditionally used natural building materials, used for decades or centuries, contain natural radionuclides at levels such that the annual dose of 1 mSv might be exceeded. In these cases, the detriments and costs of giving up the use of such materials should be analyzed, taking into account and should consider financial and social costs and benefits.

4.2. National regulations

Some EU Member States and non EU countries have established national regulations for limiting exposure to the public from radioactivity in building materials. Countries having low radioactivity background levels, such as Denmark, the Netherlands and Israel generally choose a stricter dose criterion [66]. In Denmark and in Israel an excess dose of 0.3 mSv/y was applied. Whereas the dose criterion only refers to gamma radiation in Denmark [66], it includes internal exposure from radon in Israel [53].

The Dutch regulations, which are still in preparation, use a complex approach based on the implementation of the dose criterion to the specific design building and the building materials to be used. In that way all the relevant parameters influencing the radiation exposure of the inhabitants are taken into account. Those parameters are the surface density, the radon exhalation rate (or emanation coefficient), the cover materials, etc.

The Austrian and the Israeli regulations also take into account the surface density of the building material.

In the Austrian case the surface density is considered only for ^{226}Ra and ^{222}Rn pathways in dense materials as can be seen in the activity index expression [69]. A default radon emanation coefficient of 0.1 is first used to calculate the activity concentration index. Measurement of the radon emanation coefficient is required only for building material not complying with the index [70].

$$\frac{C_K}{10000} + \frac{C_{Ra}}{1000}(1 + 0.15\varepsilon\rho d) + \frac{C_{Th}}{600} \le 1 \quad (12)$$

The Israeli standard requires measurement of the emanation coefficient for every building material following a detailed procedure for pre-conditioning the building material and measurement method [53]. The activity concentration expression for building materials is:

$$\frac{C_K}{A_K(\rho d)} + \frac{C_{Ra}}{A_{Ra}(\rho d)}(1 - \varepsilon) + \frac{C_{Th}}{A_{Th}(\rho d)} + \frac{\varepsilon \cdot C_{Ra}}{A_{Rn}(\rho d)} \le 1 \quad (13)$$

Where $A_x(\rho d)$ is the activity concentration limits at surface density ρd for radionuclide x.
For covering building materials the expression should be ≤ 0.8.

The majority of the EU Member States comply with the recommendations in the RP-112 document, some of them implementing it into their national regulations [71]. Some EU States as in Poland, has stricter activity concentration limit for ^{226}Ra than in the RP-112 recommendation (200 Bq/kg instead of 300 Bq/kg) in order to assure indoor radon concentrations lower than 200 Bq/m^3 [72].

Some regulations address the radioactivity of waste materials and industrial by-products specifically, but others do not distinguish between building materials containing waste materials and regular building materials [66].

5. Summary and conclusions

Most building materials contain small amounts of NORM reflecting the geological variation of their site of origin. Several surveys were conducted at different locations worldwide to characterize the activity concentration of NORM and the radon emanation from building materials.

The recycling of industrial waste or by-products containing TENORM is extensively used in the construction industry. The use of fly ash, coal slag, phosphogypsum, red mud and other industrial by-products in building materials and the increment in radiation exposure from these materials it has been of concern for several years.

Assessments of the external radiation exposure to inhabitants of dwellings are performed by means of mathematical calculations. The evaluation of the internal radiation exposure to ^{222}Rn due to building materials is more complicated. The correlation between the exhalation rate measured under laboratory conditions and the *in-situ* exhalation rate is rather poor and not fully understood and may significantly vary from one type of building material to another.

National and international regulations and guidelines treat radioactivity in building materials as existing exposure situations rather than as planned exposure situations. Controls on the radioactivity concentration of building materials are based on dose criteria and on exemption levels. The dose criterion is established considering the overall national circumstances but it is thoroughly accepted that external doses exceeding 1 mSv/y should be taken into account from the radiation protection point of view.

Internal dose limits from ^{222}Rn exhaled from building materials should be kept consistent with national action levels for indoor radon. Setting a lower reference radon concentration for building materials will enable contributions from other sources, , e.g. the underlying soil, groundwater supply, outdoor radon, without exceeding the action level.

Restricting the use of certain building materials might have significant economical, environmental and social consequences at a local or national level. Such consequences, together with the existing national levels of radioactivity in building materials, should be assessed and considered when establishing binding regulations.

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