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Historical urban centers built in tuff and indoor radon exposure.

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***Abstract* – Several historical urban centers in Italy are renowned for being built into tuff, a porous volcanic rock rich in radionuclides contents. Tuff is among the building materials, counted in the Annex II of the European Directive 59/2013/Euratom, implemented in Italy by Legislative Decree 101/2020, that are subject to the control of the content of natural radionuclides. If threshold levels are exceeded, measures to limit the exposure of the population should be adopted. In historical buildings, tuff can constitute an important secondary source of radon, after soil, in the indoor environment, contributing to its accumulation till levels dangerous for human health. Aim of the study is to analyze the contribution of radon exhalation from walls in tuff which, in some cases, can be the main source. So, an analysis of the fluctuations and accumulation in the indoor environment according to different ventilation rates has been performed in a flat of an old historical building made in tuff located in the old city center of Salerno, as a case study.**

I. INTRODUCTION

Several historical urban centers in Italy and all over world [1] are renowned for being built into tuff, a porous volcanic rock. The Italian regions Tuscany, Umbria, Lazio and Campania claim many beautiful and unique old city centers completely built into tuff rock and on tuff plateau. The medieval hill towns of Pitigliano, Sorano, Manciano, and Civita di Bagnoregio as well as the city of Naples are only a few examples of cities rich in history, culture, and natural beauty, completely built in tuff. This stone has been crucial in the creation of their city center in the course of the decades. The main aesthetic and physical characteristics of tuff stone are a lot influenced by the local geology [2]. Tuff tends to have a beige or light gray colour, but greenish, pink or even yellowish or brown shades may also be present, depending on the environmental conditions and the minerals contained. Its lightweighting and easy workability made it suitable for sculpture and the construction of elaborate architectural details. The high porosity, allowing moisture regulation, made it ideal also for food preservation and wine production in the past. But this stone is rich in natural radio nuclides. This characteristic could represent a problem from a radioprotection point of view.

It is well known that natural building materials, obtained from the earth's crust, such as tuff, may contain traces of ^{238}U and ^{232}Th. The above-mentioned radionuclides decay to radon (^{222}Rn), a radioactive gas whose half-life is 3.82 days. Due to the long half-life, radon can reach and accumulate in closed spaces rising from the underground soil and being produced and exhaled from the walls and floors of the building. The exposure to the inhalation of radon can turn out to be relevant especially in underground and poor ventilated ambient where high concentrations can be accumulated. Prolonged exposure to radon, it's well established to be one of the major risk factors for lung cancer onset [3].

Natural radiation, in general, generates two types of hazards for human health: external exposure due to gamma radiation caused by the cumulative concentration of elements from the uranium, thoron and potassium; and internal exposure due to alpha radiation, which is associated with the inhalation and ingestion of radon and thoron decay products. For this reason, the control of the average annual indoor radon activity concentrations, as well as the control of the content of natural radionuclides in some building materials is regulated by the European Directive 59/2013/Euratom [4], implemented in Italy by the Legislative Decree 101/2020[5].

In this paper, a case study

II. CASE STUDY

The old nucleus of the city of Salerno develops in the maze of alleys of medieval origin. The Roman town of Salernum founded in 197 B.C., started to develop in the Middle Ages under the Longobard domain for about five centuries, starting from 626 A.D., till the Byzantines conquer. During the period of the Longobard Prince Arechi II, who made Salerno one of the seats on his court, the city expanded further. Starting from the sixteenth century, the city was enriched with noble palaces and churches that still constitute the building complex of the town.

In the heart of the city center, very near to the Dome and inside the eastern part of the Roman walls of the 3rd - 4th century, in the district known as "Barbuti" there is the famous street of *Botteghelle* (Figure 1). In the Roman period the street was the connecting pivot between the lower decumanus, via Mercanti, and the upper decumanus, via Tasso. The street is a long thin line made of historical palace built between the sixteenth and seventeenth century, mostly. Along the street many old noble palaces such as Palazzo D'Avossa, one of the largest historical buildings in the ancient Salerno, Palazza Cavaselice and many others rise up. All the palaces are generally characterized by arched entrance portals leading into an internal courtyard with a squared plan and imposing structures with grey tuff walls. The width of the walls is generally very impressive starting from 70-80 centimeters in the basement till 50-60centimeters to the upper floors.

Fig.1 Botteghelle street, Salerno, Italy.

These massive walls made of tuff can constitute an important source of radon to indoor living and working environment.

In order to assess and isolate the contribute of the building materials to the indoor levels in this typical historical palaces a campaign measurement was performed in a residential building in Botteghelle street by using a portable radon detector equipped with special accessories to directly and continuously measure radon emitted by the walls.

A. Materials and methods

A residential flat in the old urban center of Salerno was chosen for measuring and modelling the indoor radon activity concentration determined by the exhalation from tuff. In order to isolate the contribute from soil and building material it has been chosen a flat on the fourth and last floor of an old noble building located in Botteghelle street (Figure 2). The flat is made up of two bedrooms, an opens space with living room and kitchen and two bathrooms. The indoor environment of the flat is well ventilated and bright thanks to the abundant presence of windows in the ceiling and into the walls.

Fig.2 View from the flat in Botteghelle street.

Radon measurements in indoor air and building material in different conditions, were performed in order to compare experimental results with the calculated ones by the application of the S.I.R.E.M. model, developed by some of the authors [6]. Building materials surface emissions measurements were performed and included in the model too.

The radon measurements were carried out by means of a portable electronic device manufactured by DURRIDGE Inc. [7] and in compliance with the internal procedures of the Ambients and Radiations (Amb.Ra) Laboratory of the

University of Salerno, Italy, ISO 9001:2015 certified.

Measurements of the emission from building materials were performed on the perimetral wall (in grey tuff), using the DURRIDGE Surface Emission Chamber (Figure 3), in order to assess the emissions into the room from building materials. In this configuration, the instrument returns, directly, the exhalation from the surface measured in Bq/m^3, a kind of data extremely convenient for the model analysis. This measurement configuration provides a more realistic assessment of the indoor radon concentration with respect to the laboratory evaluation of the exhalation rate in samples because, on site, the emission from walls is strongly affected by the presence of plaster, humidity, aging, “walls breathability’, etc. [8].

According to the model method, for the assessment of the indoor radon, measurements should be performed after a defined period from 48hours to 10 days by keeping the door and windows closed, in order to detect the maximum reachable level of concentration in the room. The aim is to estimate radon ingrowth in the room in low ventilation conditions, qualitatively.

In this condition of ‘closed room’, the dominant mechanism of radon entry is the diffusion mechanism, caused by the difference of the radon concentrations in the air and the radon sources (soil or building materials). Under equilibrium conditions for the radon accumulation due to the diffusion mechanism of entry with constant ventilation conditions in the room, an equilibrium radon concentration, C_{eqD} is obtained:

$$C_{eqD} = E_D/\lambda \qquad (1)$$

Where, in Equation (1), E_D, expressed as the sum of all the radon fluxes from the various surfaces, is the total rate of diffusion radon entry into the room, and λ is the global air exchange rate in the room [8].

Fig.3 Experimental layout for on-site measurements of Radon Emanation by Building Materials

All these measurements were carried out not only for monitoring purposes, but also to propose the use of a model describing radon dynamics for the calculation of the global air change in the room. Since the test room was selected in a flat at the last floor, it was assumed that the soil does not contribute to the indoor radon accumulation and the algorithm was constructed from the data reported in Table 1, which basically describes the diffusion entry into the room from a source of radon [8].

Table 1. Input parameters of the model

Parameter	Description
V_i	Volume of the room
S_{bm}	BM surface area
C_i	indoor radon concentration
C_{eq}	equilibrium indoor radon concentration
E_D	total rate of diffusion radon entry
C_{BM}	BM radon concentration
λ_{rn}	Radon decay constant
λ	ventilation rate factor

The indoor radon concentration in various conditions of ventilation was measured with the continuous radon monitor (DURRIDGE RAD7), above described. E_D can be calculated as the sum of radon fluxes through the surfaces and λ could be indirectly calculated through the model by inputting the experimental values of the indoor radon concentration, C_i.

III. RESULTS

The results of the measurements campaign performed are reported in Tables 2–4. Table 2 reports the result of the radon activity concentrations emitted by the surface of the wall, a 50 cm grey tuff wall covered by 2 cm of plaster. Table 3 reports the results of the indoor radon activity concentrations in the room reached by taking closed door and windows for 10 days and, then, the one reached 30 min after opening the window. In Table 4 values reached by taking closed door and windows in the room for 48 hours and then reached 30 min after opening the window is reported.

The results obtained by the analytical model are reported in Table 5 and graphically represented in Figure 4.

Table 2. Building materials measurements data

Protocol name	Duration [hh:mm]	^{222}Rn [kBq/m3]
user	02:00	0.16 ± 0.05

Table 3. Indoor measurements data (first campaign)

Protocol name	Duration [hh:mm]	^{222}Rn [kBq/m3]
GRAB	00:30	0.34 ± 0.111
GRAB	00:30	0.23± 0.006

Table 4. Indoor measurements dat (second campaign)..

Protocol name	Duration [hh:mm]	^{222}Rn [kBq/m3]
GRAB	00:30	0.20 ± 0.0921
GRAB	00:30	0.15± 0.0772

According to the model method the radon activity concentrations measured after 10 days of ‘closed room’ can be assumed as the indoor radon concentration at the equilibrium. In this hypothesis it is 0.34 ± 0.11 kBq/m^3 and the corresponding calculated value of λ, equal to 0.086, could be considered to be the ‘leakage’ of the room corresponding to the air exchange rate through walls, doors, and windows or more correctly, is the infiltration i.e. the unintentional flow of air through cracks and openings in the room's envelope. So, the lambda value has to be intended as the infiltration in an unoccupied room, since during this phase door and windows where put closed completely. Considering that the structural typology of old buildings allows less infiltration compared to the new one because of the presence of very massive wall whose width is generally two or three times more than the typical wall in bricks and concrete, the value is quite compatible with the values presented in literature for apartments built after 1970s ranging instead with minimum values, reached with all windows closed from 0.16 ± 0.04 to 0.37 ± 0.1 per hour [9-10]. Starting from this data for the calibration of the model, results seems to return reasonable values of the fluctuations of the indoor radon activity concentration according to typical values of natural ventilated indoor environments.

Table 5. Calculation of the ventilation rate factor, λ by converging indoor ^{222}Radon activity concentration by experimental and modelled measurements

^{222}Rn Activity Concentration [kBq/m^3]	^{222}Rn Activity Concentration [kBq/m^3]	λ ventilation rate [h^{-1}]
0.34 ± 0.11	0.35± 0.01	0.086
0.23± 0.006	0.23± 0.007	0.13
0.20± 0.009	0.20± 0.006	0.15
0.15± 0.077	0.15± 0.005	0.20

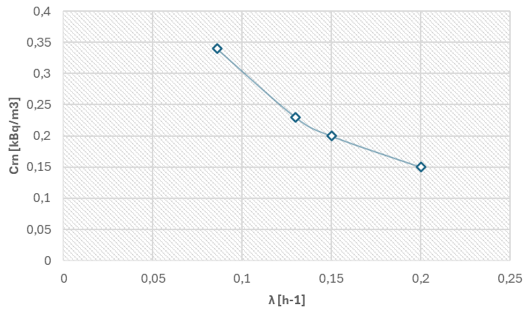

Fig.4 ventilation rate factor, λ, trend by converging indoor 222Radon activity concentration by experimental and modelled measurements

IV. CONCLUSION

Several historical urban centres in Italy are renowned for being built into tuff, a porous volcanic rock rich in radionuclides contents. According to the European Directive 59/2013/Euratom, implemented in Italy by Legislative Decree 101/2020, tuff is listed among the materials that can constitute a hazard for human health due to their high natural content of radionuclides.

This research presents an experimental study aimed at monitoring radon concentrations in buildings made of tuff and analysing the radon dynamics in the indoor environment according to air exchanges in the room. Radon activity measurements were performed using a portable radon detector.

The results show that not-negligible indoor concentrations of radon can be found indoors due to the presence of emitting building materials. By taking door and window closed for ten days threshold values defined by legislation (300Bq/m^3) are overcome. By opening windows radon concentrations are almost halved in half an hour but anyway more than 100 Bq/m^3 which is the recommended value by OMS [1]. The study showed that some building materials such as tuff are an important source of Radon affecting the indoor environment. Therefore, monitoring should not only be limited to lower floors such as basement and ground floor. The results also support that the lower floors are exposed to higher radon accumulation compared to the upper floors, considering not only the presence of soil as additional source but also due to the presence of more massive walls and lower ventilation than upper floors according to the typical structural features. Model analysis demonstrates instead that indoor radon levels fluctuate a lot according to occupants' behaviour (door and windows openings) and that high radon levels can be easily controlled with systematic opportune ventilation rates. Results confirm similar studies performed in other areas putting in evidence the complexity of the management of radon indoor concentration because affected not only by endogenous factors like life habits relative to ventilation and conditioning of the apartments, but also by exogenous factors [11].

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REFERENCES

[1] Siegesmund, S., Pötzl, C., López-Doncel, R. et al. Overview and quality assessment of volcanic tuffs in the Mexican building heritage. Environ Earth Sci 81, 426 (2022). https://doi.org/10.1007/s12665-022-10530-6

[2] Barbero-Barrera, M.M.; Flores-Medina, N.; Moreno-Fernández, E. (2019) Thermal, physical and mechanical characterization of volcanic tuff masonries for the restoration of historic buildings. Mater. Construcc. 69 [333], e179. https://doi.org/10.3989/mc.2019.12917

[3] World Health Organization. WHO handbook on indoor radon: a public health perspective. Geneva, Switzerland: World Health Organization, 2009.

[4] European Directive 59/2013 EURATOM. Online https://eur-lex.europa.eu/legal-content/IT/TXT/PDF/?uri=CELEX:32013L0059 (last access 20/05/2025)

[5] Italian D.Lgs. 101/2020 https://www.gazzettaufficiale.it/eli/id/2020/08/12/20G00121/sg (last access 20/05/2025)

[6] Mancini, S., Vilnitis, M., Todorović, N., Nikolov, J., and Guida, M., 2022. Experimental studies to test a predictive indoor radon model. International Journal of Environmental Research and Public Health, 19(10), 6056

[7] Durridge Company RAD7Manual (2015).Durridge Company, Inc. USA

[8] Yarmoshenko, I., Malinovsky, G., Vasilyev, A., & Onishchenko, A., 2021. Model of radon entry and accumulation in multi-flat energy-efficient buildings. Journal of Environmental Chemical Engineering, 9(4), 105444.

[9] de Jode M. Long term monitoring of CO2 levels and ventilation rates in a naturally ventilated residential apartment, Indoor Environments, Volume 1, Issue 3, 2024,100030, ISSN 2950-3620 doi.org/10.1016/j.indenv.2024.100030.

[10] Howard-Reed C, Wallace LA, Ott WR. The effect of opening windows on air change rates in two homes. J Air Waste Manag Assoc. 2002 Feb;52(2):147-59. doi: 10.1080/10473289.2002.10470775.PMID: 15143789

[11] Soldati, G., Ciaccio, M.G., Cannelli, V. et al. Assessment of indoor radon levels at multiple floors of an apartment building in the historic center of Rome (Italy): a comprehensive study. Environ Sci Pollut Res 31, 61660–61676 (2024). https://doi.org/10.1007/s11356-024-35266-7