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Factors Affecting Indoor Radon Levels in Buildings Located in a Karst Area: A Statistical Analysis

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Abstract: In this paper, the averages annual radon concentrations in buildings placed in a karst area are analyzed in order to understand which factors may affect the occurrence of high levels of radon indoor. Statistical analysis on the radon dataset is performed using analytical factors described by two or three levels according to the characteristic of the measured buildings. The factors that determine higher radon levels in terms of arithmetic mean (AM) at ground floor (GF) are mainly the presence of sedimentary calcareous rock (SCR) in walls and the direct attack or crawl space as type of foundation. At first floors (FF), the presence of walls of only SCR showed radon levels higher (in terms of AM) than the one found for walls of mixed typology. These outcomes suggest that in karstic area buildings with SCR as the main construction material and direct attack or crawl space as the type of foundation, can be considered as radon-prone buildings. Moreover, this study confirms the need to measure radon levels not only at below ground floor and at GF, but also at FF and above for buildings in karst areas with construction materials including SCR blocks.

Keywords: karst region; indoor radon; construction materials; foundation type; SSNTD

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1. Introduction

Radon (^{222}Rn) is a colorless, odorless, and chemically inert radioactive natural gas that comes from the decay of radium (^{226}Ra) present in bedrocks and soils, well water, and building materials, and tends to accumulate to harmful levels in indoor environments, such as homes and office buildings [1,2]. The accumulation of radon inside buildings is a consequence of technological progress: insulation work, tightly closed windows, and poor ventilation of the rooms lead to an increase in the concentration of radon inside [3,4]. Several epidemiological studies have found a statistically significant connection between radon exposure and lung cancer risk [5–8].

The monitoring and control of the concentration of indoor radon in dwellings and workplaces is a very important issue worldwide, for such reason it is also important to understand which factors may affect the occurrence of high levels of indoor radon [9,10]. To investigate the influence of different factors on indoor radon concentrations, several studies considered measurements at different locations and different story levels inside buildings; moreover, some authors have also taken into account other factors, such as building materials and improvements, and the use and age of the building. In several EU countries, radon concentrations higher than the reference levels applied in the respective country were reported [11–15].

A previous paper [16] reported the results of a radon survey carried out in a high number of buildings placed in a small part of an Italian karst area to evaluate the variations of indoor radon concentrations. These buildings present different characteristics in terms of year of construction, materials used, building size, and type of fixtures and heating system. In this paper, the averages of annual radon concentrations are further analyzed in order to understand which factors (e.g., materials of construction, direct connection to the underground/ground floor or presence of crawl space) may affect the occurrence of high levels of indoor radon in buildings. The association between the story level of the monitored room and concentration levels across rooms belonging to various buildings were investigated. The radon concentrations were also compared to the national and international reference levels.

2. Materials and Methods

2.1. The Radon Survey and the Sample

INAIL and UniSalento conducted a radon survey on 54 buildings of UniSalento from March 2018 to April 2019. Salento is a karstic area in the Apulia region (Southeast Italy). This area is characterized by a subsoil of limestone, dolomite, and gypsum, and presents lot of sinkholes, caves, and underground drainages [17]. The buildings measured in this survey are placed mostly in the city of Lecce (50 buildings) but also in more distant municipalities (4 buildings). In order to ensure a higher homogeneity of the sample and to minimize confounding factors, the analysis here reported examines only the 50 buildings located in the city of Lecce.

The average radon activity concentration was measured by NRPB/SSI passive dosimeters coupled with CR-39 (Intercast, Europe) as detectors, for two consecutive semesters (March–October and October–April) by means of the analytical procedure described in Leonardi et al. [18] and references within. This device, according to the protocol adopted in our laboratory, has an LLD in terms of radon exposure of 14 kBqhm^{-3}. The uncertainties associated to this device, taking into account also the calibration uncertainty, varies from 14% to 10% (with k = 2) for exposure from ~100 kBqhm^{-3} to 3000 kBqhm^{-3}, respectively. Moreover, due to the holder diffusion half time, greater than a few minutes, this device is not sensitive to ^{220}Rn [19].

A dosimeter or multiple dosimeters (for large rooms) were placed in all rooms below ground and at ground floor. Some rooms at upper floors (mostly at first floor) were also monitored. In each room, the annual average radon value has been computed as weighted arithmetic mean on the number of exposure days in each sampling period.

2.2. Data Analysis Description

The sample consists of buildings that can differ in year of construction, construction materials, and type of foundation. These characteristics, summarized in Table 1, represent the analytical factors [20] described by two or three levels and considered in the present analysis.

The natural stones used in the building material in this region are generally calcarenites, sedimentary calcareous rocks characterized by high porosity, named "Pietra Leccese", "Pietra Mazzara", and "Carparo". These last two types are characterized by low contain of radium-226 (a tenth of Bq/kg), coarse grain, and are frequently used as building materials, for example, in the construction of roof vaults (Pietra Mazzara) and for the load-bearing structures of the building or as cladding material (Carparo) [21].

In the first part of this analysis, only radon levels at GF (excluding mezzanine) have been analyzed. The sample is thus reduced from 50 to 49 buildings because one building only has the underground floor. For each building, the radon level at GF is the arithmetic mean of the annual average radon value of all the rooms located at GF.

Table 1. Factors and levels considered in the analysis.

Id. Number	Factor	Id. Number	Level
F1	*year of construction*	L1 L2	pre-1960 post-1960
F2	*materials of construction*	L1 L2 L3 L4	SCR mixed typology-CI mixed typology-C mixed typology-IT
F3	*type of foundation*	L1 L2 L3	direct attack [1] crawl space or technical void slab foundation
F4	*typology of construction*	L1 L2	presence of BGF [2] absence of BGF

[1] No insulation between subsoil and building base. [2] Included underground floor and basement.

The construction techniques used in the analyzed buildings are different since the year of construction varies over a very wide range (from 1170 to 2017). Hence, for this factor (F1) two levels, which are distinctly separated in the construction techniques, were considered (pre-1960 and post-1960): a further annual division was not considered because it would not provide any benefit to the analysis leading only to not very populated numerous levels.

Since some buildings showed inhomogeneous characteristics, some factors, such as the type of foundation and the typology of construction, are not uniform throughout the entire building. In these cases, for example, when the BGF was present only in a portion of the building, the building has been separated in two or three sub-buildings, each one considered as a single structure with homogenous factors. Due to this, the sample size increases from 49 to 63 building-units.

In the second part of the analysis, radon values at FF have been compared to those at GF. In this case, the sample size is reduced from 63 to 36 building-units because the FF is not present in all buildings. As for GF, for each building, the radon level at FF is the arithmetic mean of the annual average radon value computed for all the rooms located at that floor.

2.3. Statistical Analysis

Statistical analysis was performed with IBM SPSS version 25.0 [22]. Descriptive statistics, in terms of AM, median, SD with the formula of the corrected sample, minimum value (min), maximum value (max), and CV = SD/AM has been applied to the overall set of building radon values at GF and FF, and the set of radon values at GF and FF divided into levels for each factor (as described previously).

The Shapiro–Wilk test has been applied to each level of all factors in order to evaluate the normality of distribution in the analyzed dataset. For each factor, at least one level has been found to be non-normal. For this reason, non-parametric tests, the Mann–Whitney test or the Kruskal–Wallis [23] have been used for comparing levels of the same factor, respectively, in case of two or three. Moreover, in the case of three levels, since the Levene test of Homogeneity of Variance has been found to be statistically significant, multiple pairwise comparisons on the levels have been performed by means of the Games–Howell test [24]. p-values < 0.05 were considered significant.

Bivariate logistic regression [25,26] has been applied to examine how the factors F2 and F3 affect the risk of having high radon concentration at GF. The general model relation of the bivariate logistic regression is

$$P(y) = a_0 + a_1\, x_1 + \ldots + a_n\, x_n \tag{1}$$

where the term a_0 is a constant, the terms $a_1, \ldots, a_n$ are the constant coefficients, which explain the dependence probabilistic relation of the dichotomous variable y as function of the predictor variables $x_1, \ldots, x_n$, respectively. Interactions between variables $x_1, \ldots, x_n$ can also be considered. P in Equation (1) stands for statistical probability.

For the present analysis, the model tested is

$$P([Rn] > 300) = A + B \cdot F2 \cdot F3 \tag{2}$$

with A model constant and B constant coefficient of the predictor variable $F2 \cdot F3$. This model tests the likelihood of having radon levels (in terms of annual mean concentration—$[Rn]$) above 300 Bq/m^3. $[Rn]$ is a continuous variable but this statistical test requires it to become a dichotomous one. To address this issue, the radon level has been dichotomized by assigning value 0 if its value is below 300 Bq/m^3 or value 1 if it is greater than 300 Bq/m^3 which is the Italian radon reference level [27] for the protection from radon exposure at workplaces [28,29]. Consequently, the bivariate logistic regression analyzes the radon levels as dichotomized dependent variable in terms of chosen factors as predictor variables. The predictive power of the models implemented into the bivariate logistic regression has been measured by means of Nagelkerke R^2 values [30].

3. Results

3.1. Radon Distribution at Ground Floor

The distribution of radon levels at GF is described in Table 2. They are ranged on a wide interval of values from 45 Bq/m^3 to 1072 Bq/m^3. The AM, equal to 218 Bq/m^3, is far above the median, 121 Bq/m^3, with a SD of 216 Bq/m^3.

Table 2. Descriptive statistics of radon levels at GF.

N	Min	Max	AM	Median (CI 95%)	SD	CV	$[Rn]$> 300 Bq/m^3
	Bq/m^3					%	
63	45	1072	218	121 (101; 148)	216	99	22

The wide range of radon values strongly depends on the construction characteristics of the buildings, as it can be observed in Table 3. In fact, the GFs of buildings constructed before 1960 (F1L1) show radon levels distributed from 98 Bq/m^3 to 1072 Bq/m^3 with an AM of 389 Bq/m^3, a median of 380 Bq/m^3, and a SD of 273 Bq/m^3. On the contrary, the GFs of buildings constructed after 1960 (F1L2) report radon values distributed on a smaller range from 45 Bq/m^3 to 438 Bq/m^3 with lower AM, median, and SD, respectively corresponding to 120 Bq/m^3, 99 Bq/m^3, and 72 Bq/m^3.

The difference in the distribution of radon levels between pre-1960 (F1L1) and post-1960 (F1L2) is extremely significant with $p < 0.001$. In Table 4, all statistical testing results are shown.

A similar trend is also found if the dataset is observed in terms of materials of construction because all buildings constructed with walls of only SCR (F2L1) are pre-1960 (19 out of 23 pre-1960 buildings have only SCR blocks). Therefore, the distributions of radon levels of buildings constructed pre-1960 or post-1960 reflect the distributions of radon levels in buildings constructed with only SCR (F2L1) or mixed typology (F2L2 and F2L3), respectively. It is noteworthy that higher AM or median values are found in the case of only SCR (F2L1) compared to mixed typology with concrete and SCR (F2L2) or concrete without SCR (F2L3) with high statistical significance ($p = 0.001$ or $p < 0.001$, respectively, in Table 4). See also Figure 1a for an immediate comparison between levels. Moreover, the

CV value, as measure of the spatial variability at GF, sharply decreases, from about 60% for F2L1 and F2L2 to about 20% for F2L3 which does not contain SCR. The case of mixed typology with iron and SCR (F2L4) shows a radon level of 79 Bq/m^3, which is intermediate between the case of only SCR (F2L1) and the other cases of mixed typology. However, it is a single case.

Table 3. Descriptive statistics of radon concentrations at GF subdivided in factors and levels as described in Table 1. Levels with the same letter in brackets show data distribution with statistical significance according to the testing results showed in Table 4.

Factor/Level	N	Min	Max	AM	Median	SD	CV
				Bq/m^3			%
F1L1 (a)	23	98	1072	389	380	273	70
F1L2 (a)	40	45	438	120	99	72	60
F2L1 (b,c)	19	98	1072	437	420	277	63
F2L2 (b)	24	45	438	141	115	90	64
F2L3 (c)	19	70	148	103	99	22	21
F2L4	1	79	-	-	-	-	-
F3L1 (c)	15	98	796	345	338	227	66
F3L2 (d)	33	45	1072	212	118	230	109
F3L3 (c,d)	15	51	279	104	84	59	57
F4L1	27	45	1072	217	101	262	121
F4L2	36	79	796	218	127	178	82

Table 4. Statistical comparisons and testing results between radon levels at GF. Bold numbers highlight results with statistical significance. The level 4 of factor 2 is excluded because it is a single case.

Factor	MW Test	KW Test	LtHoV	GH Test
F1	**<0.001 (L1–L2)**	-	-	-
F2		**<0.001**	**<0.001**	**0.001 (L1–L2)** **<0.001 (L1–L3)** 0.218 (L2–L3)
F3		**<0.001**	**0.010**	0.164 (L1–L2) **0.003 (L1–L3)** **0.042 (L2–L3)**
F4	0.134 (L1–L2)	-	-	-

If radon values at GF are observed as a function of the factor F3, the type of foundation (see also Figure 1b), buildings with slab foundation (F3L3) show the lowest radon levels in terms of AM, median, and SD if compared to crawl space/technical void (F3L2) and direct attack (F3L1) with statistical significance (p = 0.042 and p = 0.003, respectively; see Table 4). The difference between crawl space/technical void and direct attack is not statistically significant (p = 0.164, see Table 4).

The last factor examined is the typology of construction (F4): radon levels at GF are compared based on the presence of below ground floor (BGF in the following). The two distributions of values show similar AM but with a higher median where there is no BGF (F4L2). Ranges of values are wide in both cases, but SD and CV are higher in buildings with BGF (F4L1). The presence of the BGF seems to work as an insulation from the subsoil and affects the spatial variability, increasing the spread of radon levels around AM. Conversely, the absence of BGF lead to higher but less dispersed radon values. However, statistical testing does not give significance, as reported in Table 4.

In order to evaluate how specific combinations of factors could affect the radon levels, the factor "materials of construction" (F2) has been analyzed in combination with the factor "type of foundation" (F3). The descriptive statistics and the statistical comparisons are reported in Tables 5 and 6, respectively, where the Games–Howell test has been applied because the Kruskal–Wallis test and the Levene test of Homogeneity of Variance have been found to be statistically significant with $p < 0.001$.

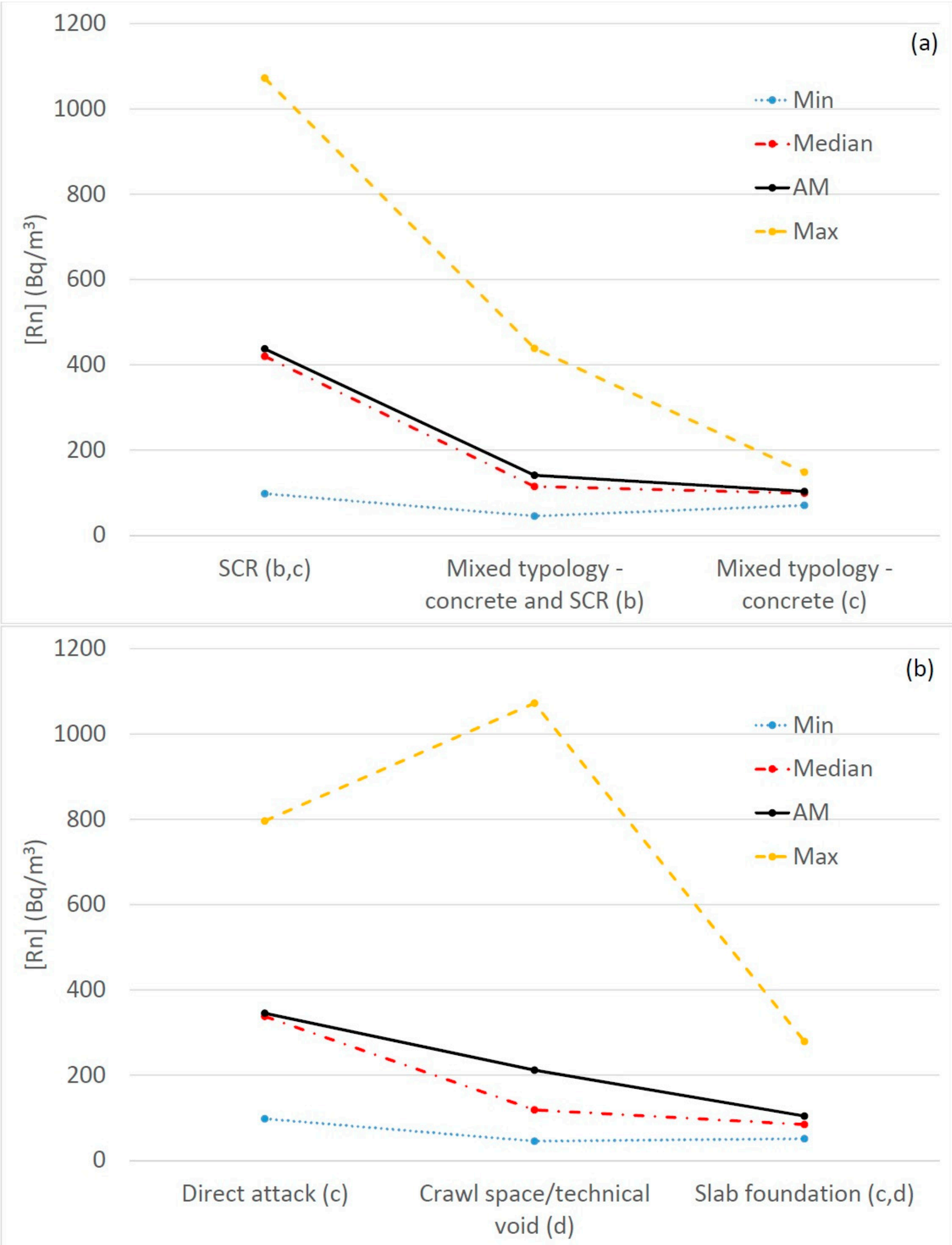

Figure 1. Values of min, median, AM, and max of radon levels at GF subdivided for (**a**) material of construction (F2L1, F2L2, F2L3), (**b**) type of foundation (F3L1, F3L2, F3L3) as reported by Table 3. The levels that share the same letter in brackets show data distribution with statistical significance according to the testing results showed in Table 4.

Table 5. Descriptive statistics of radon levels at GF subdivided for combination of materials of construction (F2) and type of foundation (F3). The levels that share the same letter in brackets show data distribution with statistical significance according to the testing results showed in Table 6.

Factor/Level	N	Min	Max	AM	Median	SD	CV
				Bq/m^3			%
F2L1–F3L1 (a, b, c, d)	12	98	796	394	394	228	58
F2L1–F3L2 *	7	108	1072	510	488	354	69
F2L2–F3L1 (a)	3	101	183	148	161	42	29
F2L2–F3L2	10	45	438	170	152	116	68
F2L2–F3L3 (b)	11	51	279	112	84	68	60
F2L3–F3L2 (c)	16	79	148	107	105	21	20
F2L3–F3L3 (d)	3	70	92	82	84	11	13

* Crawl space, no technical void.

Table 6. Statistical comparisons with the Games–Howell test and testing results for combination of materials of construction (F2) and type of foundation (F3) at GF. Bold numbers highlight results with statistical significance.

GH Test	F2L1–F3L2 *	F2L2–F3L1	F2L2–F3L2	F2L2–F3L3	F2L3–F3L2	F2L3–F3L3
F2L1–F3L1	0.982	**0.046**	0.097	**0.016**	**0.014**	**0.008**
F2L1–F3L2 *		0.244	0.301	0.181	0.171	0.140
F2L2–F3L1			0.998	0.897	0.689	0.392
F2L2–F3L2				0.800	0.622	0.301
F2L2–F3L3					1.000	0.785
F2L3–F3L2						0.178

* Crawl space, no technical void.

In Table 5, radon levels at GF are subdivided according to materials of construction (F2) and type of foundation (F3). Regarding materials of construction, the levels considered are SCR (F2L1), mixed typology with concrete and SCR (F2L2), mixed typology with concrete and no SCR (F2L3), while about the type of foundation the levels considered are direct attack (F3L1), crawl space/technical void (F3L2), and slab foundation (F3L3). F2L4—mixed typology with iron and SCR as single case is excluded.

The combination of walls with only SCR (F2L1) and direct attack (F3L1) shows higher radon levels with statistical significance if compared to:

- walls of mixed typology with concrete and SCR (F2L2) combined to direct attack (F3L1)—$p = 0.046$
- walls of mixed typology with concrete and SCR (F2L2) combined to slab foundation (F3L3)—$p = 0.016$;
- walls of mixed typology with concrete and no SCR (F2L3) combined to crawl space/technical void (F3L2)—$p = 0.014$
- walls of mixed typology with concrete and no SCR (F2L3) combined to slab foundation (F3L3)—$p = 0.008$.

Other combinations do not show statistical significance. However, it is worth noting that the highest radon levels in terms of AM and median are shown by the combination of walls with only SCR (F2L1) and crawl space (in the specific case of walls with only SCR, there is no combination with technical void) (F3L2).

In order to further investigate the effect of crawl space combined to walls of only SCR on radon levels, the bivariate logistic regression has been applied. For this test, the combination between the factor levels SCR (F2L1) and direct attack (F3L1) or mixed typology of construction materials (F2L2 and F2L3) and any type of foundation (F3L1 or F3L2 or F3L3) has been chosen as the reference interaction. To apply the bivariate logistic regression, radon level at GF has been treated as dichotomous variable by assigning value 0 if it is below 300 Bq/m^3 or value 1 if it is above 300 Bq/m^3 (dependent variable). In this way, the test helps to understand which, among the analyzed factors (independent variables), lead to radon levels above the European Union and Italian reference levels for radon in workplaces [28,29]. Results are shown in Table 7.

Table 7. Bivariate logistic regression for radon levels at GF. B represents the coefficients of Equation (2). Nagelkerke R^2 value: 0.20.

Factor/Level	B	SE	*p*	Exp(B)	CI (95%)
F2L1–F3L1 or F2L2/F2L3–F3L1/F3L2/F3L3	Ref.				
F2L1–F3L2 *	2.57	0.91	0.005	13.06	(2.18; 78.05)

* Crawl space, no technical void.

According to the model presented in Equation (2), a positive B value of 2.57 confirms that the combination of walls with only SCR (F2L1) with crawl space (F3L2) increases the likelihood of having radon levels exceeding 300 Bq/m^3 with high statistical significance (p = 0.005). In particular, the likelihood of having such radon levels raises by about 13 times if compared to any other combination (the reference). This model explains 20% of variations in radon levels according to Nagelkerke R^2: it is worth noting that all pseudo-R^2, as Nagelkerke R^2, produce low R^2 values compared to those associated with good fits in least squares regression. Therefore, the combined presence of SCR, as unique building material, with crawl space seems to make buildings more radon-prone than other combinations.

3.2. Radon Distribution at First Floor

The distribution of radon levels at first floor (FF) are described in Table 8.

Table 8. Descriptive statistics of radon levels at FF.

N	Min	Max	AM	Median (CI 95%)	SD	CV	[Rn]> 300 Bq/m^3
	Bq/m^3					%	
36	65	688	179	103 (96;121)	173	97	17

The values range between 65 Bq/m^3 and 688 Bq/m^3, with AM of 179 Bq/m^3, median of 103 Bq/m^3, and SD of 173 Bq/m^3. These values are lower than ones at GF discussed previously (see Table 2), however, it is worth noting that the two groups are not homogeneous since not all 63 buildings with GFs have also FFs. The subdivisions of radon levels for factors and levels and the statistical comparison are shown in Table 9 with Figure 2 and Table 10, respectively. The behavior of radon levels respect to the factors F2 and F3 at FF is similar to the one at GF. The radon levels, in terms of AM and median, at FF are higher for F2L1 (walls of only SCR) than for F2L3 (concrete and no SCR) with statistical significance (p = 0.020). The spatial variability between FFs, expressed as CV, is higher in presence of SCR if compared to absence of SCR (CV = 67% in the first case, CV = 22% in the second case). On the contrary, the differences between the distributions of radon levels for factor F3 are not statistically significant.

Table 9. Descriptive statistics of radon concentrations at FF subdivided levels of factors, as materials of construction (F2) and type of foundation (F3), as reported in Table 1. The levels with the same letter in brackets show data distribution with statistical significance according to the testing results showed in Table 10.

Factor/Level	N	Min	Max	AM	Median	SD	CV
				Bq/m^3			%
F2L1 (a)	10	101	688	348	300	233	67
F2L2	11	65	487	134	100	120	90
F2L3 (a)	15	75	155	98	93	21	22
F3L1	6	100	688	341	231	272	80
F3L2	21	75	531	166	102	150	91
F3L3	9	65	165	100	93	33	33

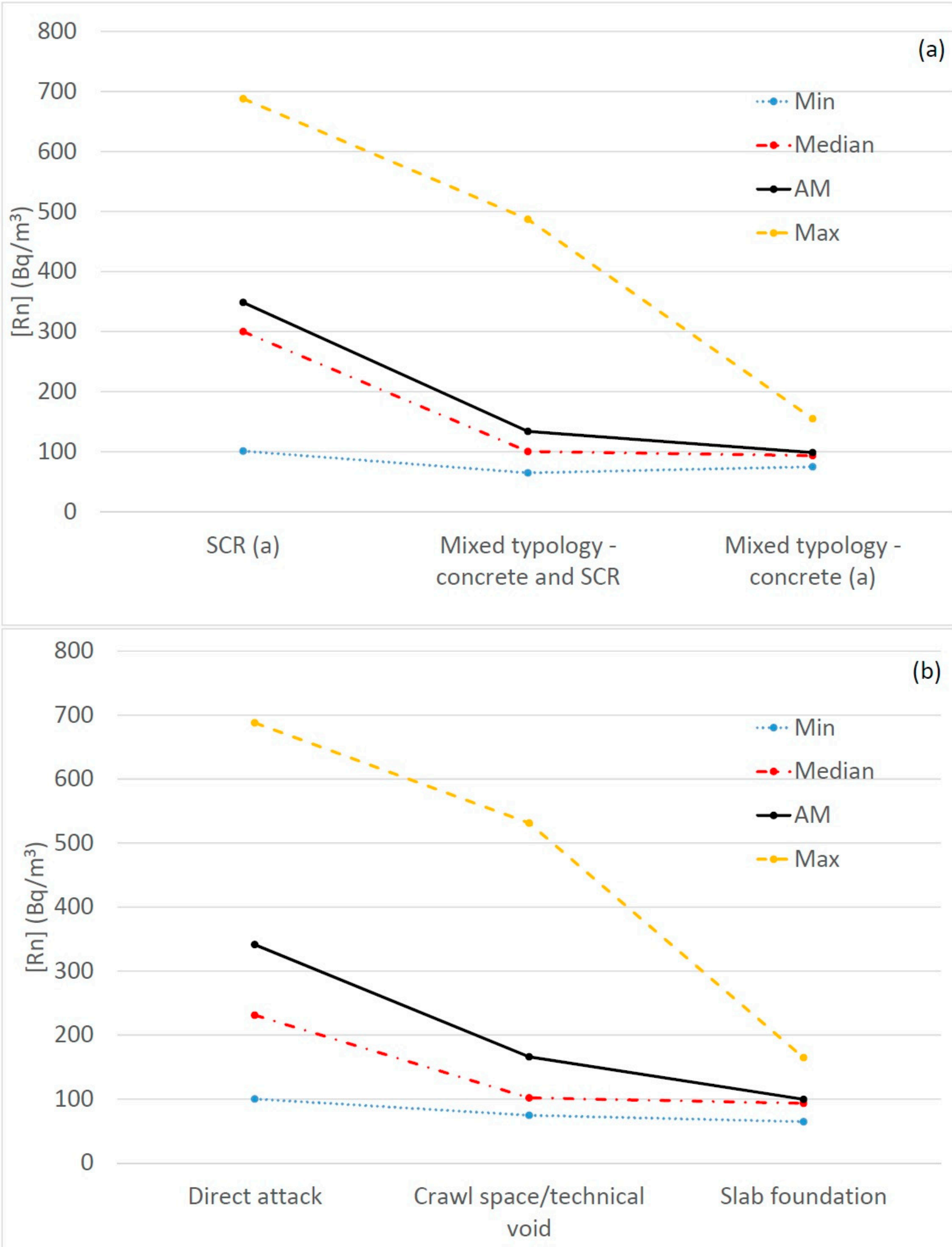

Figure 2. Values of min, median, AM, and max of radon levels at FF subdivided for (**a**) material of construction (F2L1, F2L2, F2L3), (**b**) type of foundation (F3L1, F3L2, F3L3) as reported in Table 9. The levels that share the same letter in brackets show data distribution with statistical significance according to the testing results showed in Table 10.

Table 10. Statistical comparisons and testing results between radon levels at FF. Bold numbers highlights results with statistical significance.

Factor	KW Test	LtHoV	GH Test
F2	**0.001**	**<0.001**	0.052 (L1–L2) **0.020** (L1–L3) 0.613 (L2–L3)
F3	**0.031**	**0.001**	0.350 (L1–L2) 0.168 (L1–L3) 0.155 (L2–L3)

Table 11 shows the descriptive statistics of radon levels at FF for combinations of materials of construction (F2) and type of foundation (F3) as identified in the sample. In particular, for materials of construction (F2), the levels are SCR (F2L1), mixed typology with concrete and SCR (F2L2), and mixed typology with concrete and no SCR (F2L3), while for type of foundation (F3), the levels are direct attack (F3L1), crawl space/technical void (F3L2), and slab foundation (F3L3).

Table 11. Descriptive statistics of radon levels at FF subdivided for combination of materials of construction (F2) and type of foundation (F3).

Factor/Level	N	Min	Max	AM	Median	SD	CV
				Bq/m^3			%
F2L1–F3L1	5	127	688	390	308	273	70
F2L1–F3L2 *	5	101	531	307	292	208	68
F2L2–F3L1	1	100	-	-	-	-	-
F2L2–F3L2	4	88	487	193	99	196	101
F2L2–F3L3	6	65	165	100	90	39	39
F2L3–F3L2	12	75	155	98	96	21	22

* Crawl space, no technical void.

According to the statistical comparisons (not reported in the present paper), there is not a specific combination with statistically significant differences in the distribution of radon levels. However, it is worth noting that the statistical significances could be affected by the reduced number of radon data at FFs (36) and by the further numerical subdivision in factors and levels.

4. Discussion and Conclusions

The first part of data analysis focused on the distribution of radon levels in 63 buildings-units by observing how several building characteristics can affect the radon level at GF. The factors that determine higher radon levels in terms of AM at GF with statistical significance are:

- the presence of only SCR (AM = 437 Bq/m^3) in the walls compared with mixed typologies of construction materials such as concrete with (AM = 141 Bq/m^3) or without SCR (AM = 103 Bq/m^3);
- the presence of direct attack (AM = 345 Bq/m^3) or crawl space or technical void (AM = 212 Bq/m^3) as type of foundation compared with slab foundation (AM = 104 Bq/m^3).

If the radon levels at GFs are analyzed by matching the information about the construction materials and the type of foundation, the presence of only SCR in the walls combined to direct attack causes higher radon levels in terms of AM at GF (AM = 394 Bq/m^3) with statistical significance if compared with:

- mixed typology with concrete and infill of SCR combined to direct attack (AM = 148 Bq/m^3) or slab foundation (AM = 112 Bq/m^3);
- mixed typology with concrete without SCR combined to crawl space or technical void (AM = 107 Bq/m^3) or slab foundation (AM = 82 Bq/m^3).

As already mentioned, the SCR blocks used as construction materials for vertical walls have a high porosity and, due to the sedimentary origin, very low natural radioactivity content (comparable to the one found in typical limestone [31]). Despite that, GFs in buildings constructed with only SCR showed the highest radon levels with AM and median exceeding 300 Bq/m^3. In the sample, 19 GFs have only SCR in vertical walls: 12 GFs have direct attack as foundation, while 7 GFs have crawl space. The respective radon distributions show AM and median that are higher in the latter case (AM = 510 Bq/m^3) than in the other (AM = 394 Bq/m^3), although the differences are not statistically significant. However, in the analyzed sample it has been observed with statistical significance that the combination of only SCR walls with crawl space increases the likelihood of having radon levels above 300 Bq/m^3.

In the second part of the analysis, it has been analyzed how construction materials and type of foundation can affect the distribution of radon levels in 36 FFs. FFs with walls of only SCR have shown an AM of radon levels (AM = 348 Bq/m^3) higher than the AM value at FFs with walls of mixed typology without SCR (AM = 98 Bq/m^3), as already observed at GF. If the dataset of FFs is subdivided for type of foundation or for combination of construction materials and foundation, the respective distributions of radon levels do not show statistically significant differences. Though the statistics have been applied to a small number of cases, it could be hypothesized that the materials of construction are the only factor affecting the radon levels at FF.

The karstic origin of both the subsoil and the materials of construction could be responsible for these findings. The high porosity facilitates the transport of radon gas from the subsoil to upper floors of buildings. Indeed, in a karstic area, if local rocks are used as the material of construction, both factors (F2 and F3) concur to enhance radon values at GF: radon migrates from the subsoil via the building foundation and the construction materials, particularly in presence of SCR in vertical walls [32]. At FF, instead, the only component influencing radon levels is the construction material, particularly in the presence of SCR as unique construction material or mixed with concrete.

This hypothesis seems to be supported by both the statistical evidences of the present analysis and the analysis carried out in Leonardi et al. [16] on the same dataset. In that study, a very low spatial variability was found: homogenous radon levels were observed among rooms at all floors of 54 buildings, including 4 buildings far from Lecce and excluded in the present analysis. With statistical significance, the analysis of the radon spatial variability showed more homogeneous values at FF than at GF.

All these outcomes suggest that in karstic areas buildings with sedimentary rock as the main construction material and direct attack or crawl space as type of foundation, can be considered as radon-prone buildings: the combined presence of both factors play a role in the migration of radon, produced in deeper rock strata, within the entire building. Moreover, these findings suggest that in buildings with crawl space, the implementation of ventilation of crawl space can be an effective action to reduce radon levels at ground floor [33], while its effectiveness at first (or at upper) floor is not guaranteed due to the role played by construction materials as main factor affecting the presence of radon.

These findings, finally, suggest the need to measure radon levels not only at BGF and at GF, but also at FF and above when the buildings have been built in karst areas and with construction materials including SCR blocks.

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Nomenclatures

Acronyms and Abbreviations			
AM	arithmetic mean	LtHoV	Levene test of Homogeneity of Variance
BGF	below ground floor	Max	maximum value
CI 95%	confidence interval 95%	min	minimum value
CV	coefficient of variation	mixed typology-C	Mixed typology: concrete, gypsum board; no calcarenite blocks
FF	first floor	mixed typology-CI	Mixed typology: concrete with infill of calcarenite blocks, plaster
GF	ground floor	mixed typology-IT	Mixed typology: iron and calcarenite blocks
GH test	Games-Howell test	MW test	Mann-Whitney test
INAIL	National Institute for Insurance Against Accidents at work	N	number of observations in terms of building-units
		SCR	Calcarenite-sedimentary calcareous rocks
		SE	Standard error
KW test	Kruskal-Wallis test	SD	standard deviation
LLD	Lower Limit of Detection	UniSalento	University of Salento

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