RADON IN SCHOOLS IN A KARST LIMESTONE ITALIAN AREA: CRITICAL ASPECTS OF THE REMEDIATION

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Abstract
Final results of a radon monitoring in 438 public schools located in the province of Lecce (Puglia Region, South Italy) showed an average radon concentration of 215±20 Bq/m^3 and that 7% of schools exceeded 500 Bq/m^3, the Italian action level for radon in workplaces, and consequently requiring remedial actions.
The activity described in the present paper is main elements of the remediation project.
This paper provides a synthesis of the remediation project in a subset of school buildings and relevant critical aspects in particular the influence of the karstic nature of the area and …. .
Moreover, considering new reference level for radon in workplaces, introduced by the new EU Basic Safety Standards, a new analysis of data achieved in the first survey put in evidence that the 20 % of school need to be remediated.

1. Introduction
A radon monitoring in 438 public schools located in the province of Lecce (Puglia Region, South Italy), was carried out in the framework of survey on natural radioactivity. Final results showed an average radon concentration of 215±20 Bq/m^3 (Trevisi et al. 2012), much higher than the one estimated for the whole region (52±2 Bq/m^3) (Bochicchio et al. 2005). In each school– as initial screening– only 3 rooms, randomly selected by the school staff, were measured. The data analysis highlighted that 12% of schools had mean radon levels exceeding 400 Bq/m^3 and that 7% of schools exceeded 500 Bq/m^3, the Italian action level for radon in workplaces (2000, Legislative Decree n. 241 2000), and consequently requiring remedial actions. For this reason, a plan of radon remediation in schools has been designed and carried out. In the same survey, the low value of indoor gamma dose rate (=29 nGy/h) (Trevisi et al. 2010) and the sedimentary origin of local building materials, confirmed that the main radon source is the subjacent soil gas.
The activity described in the present paper is the result of collaboration between the Department of Physics of the University of Salento (identified as "contact point"), the Department of Medicine, Epidemiology, Occupational and Environmental Hygiene of INAIL-Research Sector, and the Department of Architecture of the University of Ferrara. The working group set up a remediation project to reduce indoor radon levels in schools. The main elements of the remediation project included measurement protocols for radon control technologies and preparation of technical documents concerning radon control systems suitable to the characteristics of the building (type of foundation, bulk building materials, age of construction, etc.). The project also foresaw training courses for building professionals (e.g. municipal engineers, mitigation contractors, etc.) and all stakeholders involved in the implementation of radon prevention and remediation.
This paper provides a synthesis of the remediation project in a subset of school buildings and relevant critical aspects. Moreover, an analysis of data achieved in the first survey is given to evaluate future perspectives coming from the implementation of the new reference level for radon in workplaces, introduced by the new EU Basic Safety Standards (CE, 2014).

Table 1 gives a basic information about the characteristics of the remediated schools (hereafter identified by an ID) in terms of type of school (kindergarten, primary, secondary, etc.), type of foundation, structural building materials, and year of construction. Some schools are historic buildings, where the introduction of radon control systems needed to account for architectural constraints. Most of the remediated schools are kindergartens since kindergartens had had the highest radon levels both as arithmetic mean (AM=246±17 Bq/m^3) and as geometric mean (GM=192 Bq/m^3) (Trevisi et al. 2012).

Table 1
Description of the remediated schools.

Type of school	School ID	Town (municipality)	Foundation	Year of construction	Structural building materials	Rooms (n)
Kindergartens	1	Racale	crawl space	1980	concrete	5
Kindergartens and primary school	2	Casarano	crawl space	1962	concrete	15
Kindergartens	3	Poggiardo	crawl space	1980	concrete	4
Kindergartens	4	Surbo	foundation wall	1985	concrete	10
Kindergartens	5	Giorgilorio	foundation wall	2004	concrete	5
Kindergartens	6	Matino	foundation wall	1980	concrete	6
Kindergartens	7	Ugento	crawl space	1981	concrete	7
Kindergartens	8	San Donato	foundation wall	1980	concrete	8
Kindergartens	9	Castro	foundation wall	1970	concrete	8
Kindergartens	10	Galugnano	crawl space	1980	tuff	3
Secondary school	11	San Donato	crawl space	1940	tuff	11
Secondary school	12	Lecce	crawl space	1900	tuff	11
Primary school	13	Lecce	crawl space	1920	tuff	16
Secondary school	14	Carmiano	crawl space	1965	concrete	7
Primary school	15	Cavallino	crawl space	1920	tuff	13
Kindergartens	16	Vitigliano	crawl space	1800	tuff	2
Kindergartens and primary school	17	Lecce	crawl space	1897	tuff	40

2. Materials and methods

2.1. Measurement protocol
Radon measurements support building remediation: so a protocol was set up taking into accounts the experience acquired by many colleagues (Vaupotič and Kobal 2005, Llerena et al. 2010); (Holmgren and Harvela 2012) and the indication given in the "WHO Handbook on Indoor Radon" (WHO, 2009)

The measurement protocol consists in:

- diagnostic test before remediation (six-month long sampling by Solid State Nuclear Track Detectors - SSNTD) to evaluate the average radon concentration in every frequently occupied indoor space (Step 1);
- pre-remediation (Step 2) and post-remediation (Step 3) short-term radon measurement by electret dosimeters (EIC), two weeks long monitoring before and after the remediation;
- remediation test by active monitors (ionisation chamber, Alphaguard, Germany) in a "reference room" to check the effectiveness of remediation system (Step 4);
- post-remediation radon measurement (one year long monitoring by SSNTD divided into two semesters) to verify the overall effectiveness of the remediation (Step 5).

Technical details of radon measurements by SSNTD and EIC have been described elsewhere (D'Alessandro et al. 2010; Mishra et al. 2005; Trevisi et al. 2010).

Furthermore, about EIC, in some schools short-term radon measurements were carried out using pairs of electret dosimeters in two different configurations, SLT and LST, to assess the reproducibility of the technique (Kotrappa et al. 1988); (Kotrappa et al. 1990) and to identify the most appropriate configuration for project objectives. In processing experimental data the indoor gamma-dose rate previously estimated (Trevisi et al. 2010) was used. Measurement uncertainties were calculated in accordance with existing literature (Caresana et al. 2005) and with standard EN ISO/IEC 17025:2005.

2.2. Remediation systems

Taking into account the initial indoor radon concentrations, the building characteristics and, in some cases, the architectural constraints, the most used radon control systems were the active depressurization of the crawlspace (ACD) and the sub-slab depressurization (SSD).

The active crawlspace depressurization (ACD) (where the crawlspace is a space beneath the building in order to protect the house from the moisture coming up from the soil) generally uses the crawlspace volumes to create a vacuum that traps the gas and evacuate it with a pipe to the roof. For radon remediation, ACD system consisted in suction electric fans put just below the remediating room. For the installation, some holes are made on the external wall to intercept the crawlspace. In few cases, i.e. schools ID=10 and ID=11, suitable vent pipes are inserted into the holes and the electric fans are attached at the end of pipes. Depending on the fan model (electrical power=20/40 Watt), it could be necessary to adapt the diameter of the hole, usually of 100-120 mm. Typically, in presence of an half–full crawlspace (filled with coarse material, rubble and waste material), the overall suction power of the system was enhanced.

As for ACD, the sub-slab depressurization (SSD) is another very effective remediation system, which reverse the air pressure difference between the ground under the floor or the slab and the occupied rooms, preventing radon-rich air from entering the building.

The SSD system usually consists in a sump (suction point), a perforated PVC vent pipe (diameter =100 mm) and a fan (electrical power=85 Watt). The sump is 2-3 m deep into the ground, optimally it has to be places at least 80 cm below the foundation level and filled with coarse gravel. To prevent the obstructions of holes, the PVC pipe is coated with a "non-woven" material (Fig.1). The system is very effective, easy to adopt and suitable for areas with high permeability (Trevisi et al. 2008).

Fig. 1. Perforated PVC pipe coated with a “non-woven” material to prevent holes obstructions.

For small school size, in particular in case of kindergartens with less than 10 classrooms, typically 2-3 SSD systems per building were enough to have a decrease of indoor radon levels, since each suction point has normally an action range of 6-8 meters of diameter.
In some cases, architectural constraints led to position sump systems close to the perimeter of the building (instead of the external walls), with a well-known reduction of the overall efficiency of remediation and a probable increase of suction points.
In few cases – where standard passive or active radon control systems failed, the positive pressurisation of classroom (CP) was adopted, as last possible option for radon remediation: an effective positive pressurization of indoor spaces (i.e. classrooms) is an attractive solution since as well as it avoids radon entering, it leads to a dilution of other common indoor pollutants. The positive pressurisation system usually consists in small electric fans placed just below the remediating room: the system works blowing filtered fresh air into the classrooms.
To be effective, however, the positive pressurisation requires the air-tightness of the building shell and further precautions such as the presence of blower-doors as far as detailed management procedure etc. These precautions are very difficult to adopt in case of school buildings. That is the case of school ID=12 and ID=17.

3. Results

The new reference level (300 Bq/m^3 as annual average radon concentration) for the exposure to radon in workplaces, introduced by the EU Basic Safety Standards (CE, 2014) led to update the analysis of data achieved in the first survey.
As reported in previous papers (Trevisi et al. 2012), indoor radon average concentration not exceeds 200 Bq/m^3 in the 66% of schools. The 22% of schools has radon annual averages in the range 200-400 Bq/m^3 and the 7% of schools exceeds the Italian action level of 500 Bq/m^3.
A new analysis put in evidence that the 13% of schools have radon annual averages in the range 300-500 Bq/m^3 with an arithmetic mean±standard error equal to 393±52 Bq/m^3, a median of 390 Bq/m^3 and a geometric mean 389 Bq/m^3: so the overall percentage of schools located in this area that need to be remediated increases to about 20%.

3.1. Main results of six-months radon measurements (Step 1)

The remediation of schools started with an accurate diagnosis, consisting in a new six-months monitoring in all frequently occupied rooms at ground floor (Step 1). Indeed, the previous survey –

as initial screening – considered only 3 rooms randomly selected by school staff. So, for each school the annual average radon concentration was evaluated as arithmetic mean of values measured in three rooms: a synthesis is reported in Table 2.
Table 2 shows also the results of Step 1: for each school the arithmetic mean and the range between the minimum and maximum values are given.
The need to introduce radon control systems is confirmed in all the schools. Indeed, high average radon levels, in the range 241-1672 Bq/m^3, were found. Despite of the school ID 12 has an average of 241±26 Bq/m^3, considering that the maximum of radon concentration found in this school (443 Bq/m3) is above the new reference level (300 Bq/m^3) (CE, 2014) a remedial action should be considered also in this school.
Generally speaking, the average radon concentrations related to three rooms randomly selected and the half-yearly averages related to all rooms are good agreement and often they overlap, taking into account the relative uncertainties and the different monitoring design. Room-to-room radon variations were found in many school buildings as values of the standard deviations (SD) and coefficient of variation (CV) show (see Table 3).

Table 2
Comparison of radon data concerning the two surveys.

School ID	First survey data (3 rooms per building)	Step 1- Diagnostic test results (all rooms per building)	
	Annual average radon concentration±rel.unc.* **(Bq/m^3)**	**Six-months concentration average±rel.unc.* (Bq/m^3)**	**Range (Bq/m^3)**
1	732±52	735±75	633-839
2	1608±100	1672±162	926-2424
3	595±103	906±93	880-956
4	576±31	541±56	458-708
5	625±60	622±64	459-976
6	648±19	938±96	875-1040
7	653±70	651±67	473-881
8	719±10	578±60	523-625
9	635±114	1639±166	1361-1639
10	979±10	1067±109	774-1426
11	870±10	708±73	286-1989
12	508±139	241±26	121-443
13	522 ±71	538 ±56	220-962
14	522±120	1063±108	341-1584
15	485±45	560±58	379-687
16	499±10	478±50	318-637
17	431±19	601±63	238-1267

*rel.unc.= relative uncertainty (k=1)

3.2. Quality control of short-term radon measurements
To record variations of radon levels just before and after remediation works (Steps 2 and 3), passive electret dosimeters were placed in each room. The monitoring duration was compatible with two different configurations of electret devices: SLT and LST. In order to assess the quality of data obtained by the two options and to assess the best configuration for this purpose, initially in each room a couple of electret dosimeters (one for each configuration) was positioned, and in one room an ionisation chamber as a reference monitor was added.

Radon concentration results obtained with SLT and LST electrets are plotted in Fig.2. The angular coefficient of the straight line (see Fig.2), close to 1 (0.909), and the value of the coefficient R^2 equal to 0.99959 confirmed the excellent degree of concordance between the data obtained using both configurations. Therefore, for the purpose of this project, the two configurations were considered “equivalent”.
Furthermore, the comparison between the arithmetic means of radon averages obtained with SLT and LST electrets and those from reference monitor made possible to assure the quality of data provided by electret dosimeters, as shown in Fig.3.
The electret dosimeter is confirmed to be a good tool when radon concentration measurements have to be done simultaneously in many rooms for not too long periods, as during the remediation.

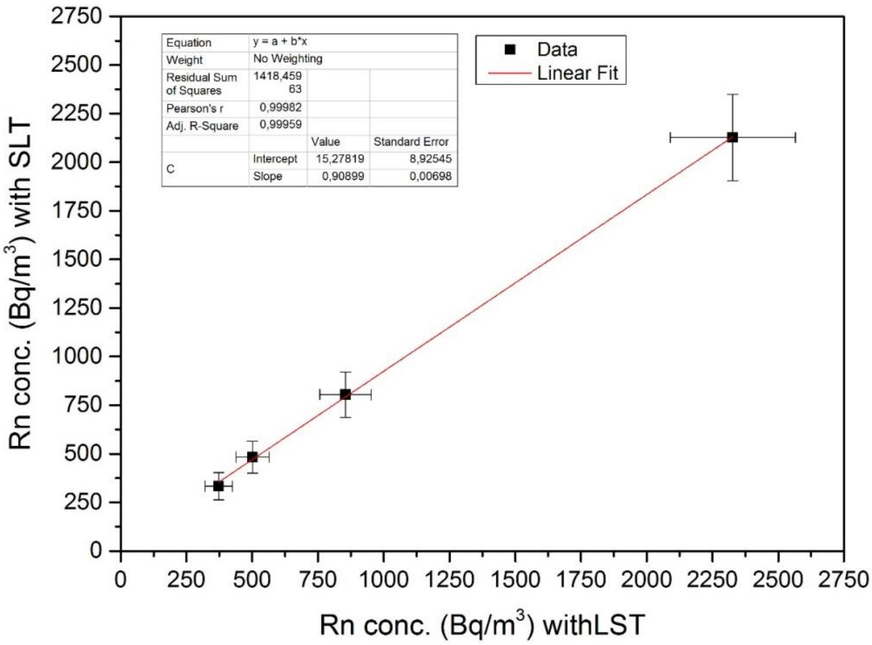

Fig. 2. Correlation of radon data acquired using LST- SLT electrets – School ID=6.

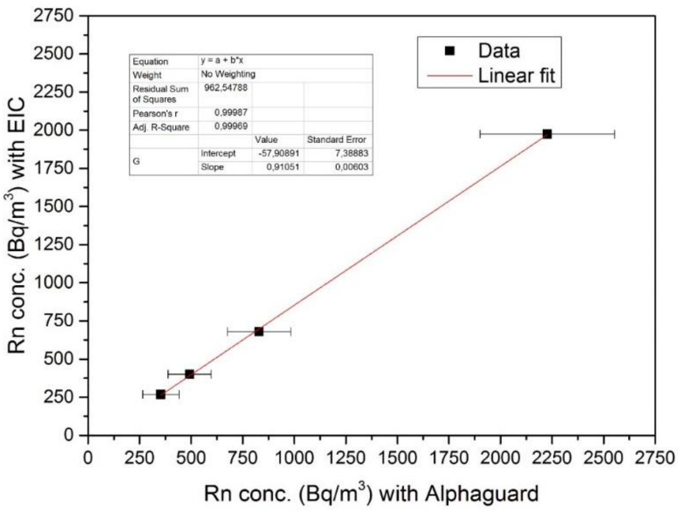

Fig. 3. Correlation between radon data from electret dosimeters (EIC) and from the reference monitor Alphaguard. On the y-axis the arithmetic mean of values achieved with the two types of electrets is shown– School ID=6.

3.3. Results of weekly monitoring – pre and post remediation (Steps 2 and 3)

The results of weekly monitoring by EICs, as arithmetic mean ± standard deviation (AM±SD), are summarised in Table 3. To be more informative, the radon control system adopted in each school is also described. Generally pre-remediation radon average values were scattered, between 337 and 2841 Bq/m^3: lower pre-remediation values (e.g. school ID=4 and ID=11) were found where the pre-remediation weekly monitoring was performed during the warmer season. In the same table post remediation radon average values are reported: they ranged between 84 and 644 Bq/m^3.

Two different criteria were used to quantify and compare the effectiveness of different radon control systems: the *"radon reduction factor"* and the *"efficiency of remediation"*.

The *"radon reduction factor"* is the ratio between the radon concentration before and after remediation (Hogdson et al, 2011). A value greater than 1 indicates a reduction while a value of 1 implies no effect: the greater the number the better the reduction.

The *"efficiency of remediation"* is evaluated in terms of percentage reduction of the radon concentration after the remediation and calculated in the following way:

$$Efficiency\ (\%) = \frac{C_{prior-}\ c_{post}}{C_{prior}}$$

In the first two weeks after the work, the efficiencies varied from 26 to 95% (see Table 3). Looking at the reduction factors, we can observe that in all the cases the factor is more than 1 and the most successful remediation is relative to school ID=6 with a reduction factor of more than 23. More accurate evaluations of the remediation efficiency are based on annual radon averages, reported in Table 4.

Table 3

Radon concentration pre and post remediation (Steps 2 and 3).

ID	Pre-remediation Radon concentration	Post-remediation Radon concentration	Remediation system	Efficiency	Reduction factor
	AM±SD (Bq/m^3)	**AM±SD (Bq/m^3)**		**%**	
1	560±120	132±10	ACD	76%	4.2
2	2049±1151	237±178	ACD	88%	8.6
3	1163±350	348±160	SSD (vertical pipes)	70%	3.3
4	337±75	140±105	SSD (vertical pipes)	58%	2.4
5	995±141	157±55	SSD (vertical pipes)	84%	6.3
6	2841±245	120±24	SSD (vertical pipes)	95%	23.7
7	630±284	84±66	SSD (horizontal pipes)	87%	7.5
8	893±141	151±41	SSD (horizontal pipes)	83%	5.9
9	1144±340	244±111	SSD (vertical pipes)	79%	4.7
10	556±115	282±18	ACD	49%	2.0
11	375±198	214±31	ACD	43%	1.7
12 **	-	-	Classroom pressurization (CP)	-	
13	482±190	355±112	SSD (vertical pipes)	26%	1.4
14	829±392	299±39	ACD	64%	2.8

15	731±453	306±58	ACD	58%	2.4
16	419±265	150±17	Pressurisation of crawlspace	64%	2.8
17	1285±265	644±128	Classroom pressurization (CP)	50%	2.0

** remediation was designed and performed by external designers

Table 4
Radon concentration pre and post remediation (data of long-term monitoring) (Step 5)

	Pre-remediation		Post-remediation				
ID	**AM±rel.unc.* (Bq/m^3)**	**SD (Bq/m^3)**	**AM±rel.unc.* (Bq/m^3)**	**SD (Bq/m^3)**	**CV %**	**Efficiency %**	**Reduction factor**
1	735±75	73	128±17	10.3	8	83%	5.8
2	1672±162	456	339±35	241.6	71	80%	4.9
3	906±96	42.6	76±9	0.6	0.8	92%	11.9
4	541±56	86	103±14	15.6	15	81%	5.2
5	622±64	165	62±8	6.9	11	90%	10.0
6	938±96	76.4	477±50	50.0	40	49%	2.0
7	651±67	161.7	122±14	41.1	34	81%	5.3
8	578±60	51	144±15	19.2	13	75%	4.0
9	1639±166	281.4	311±33	58.6	19	81%	5.3
10	1067±109	331	544±63	81.2	15	49%	2.0
11	708±73	506.2	294±25	165.7	56	59%	2.4
12	241±26	106.4	220±25	98.2	45	8.7%	1.1
13	538±56	130	in progress	-	-	-	-
14	1063±108	272.3	311±11			71%	3.4
15	560±58	166.6	388±117	116.6	30	44%	1.4
16	478±50	225.6	291±55	55.9	19	30%	1.6
17	478±50	212.1	in progress	-	-	-	-

*rel.unc.= relative uncertainty (k=1)

As said before, in Table 4 a synthesis of the results of long term radon measurements, as arithmetic mean (AM) of radon values found in each classroom (Step 5), in comparison with long term pre-remediation data, is shown; furthermore, the effectiveness of different radon control systems in terms of *"radon reduction factor"* and *"efficiency of remediation*" is given. Where the post-remediation value is not reported, the annual monitoring is still ongoing. Analysing overall results, a general reduction of indoor radon levels can be observed: reductions ranged between 8.7% and 92%. The success of remediation in terms of efficiency needs attention since many factors are involved. It can depend on the pre-remediation level of radon: if it is not very high (as in case of school ID=12), it is normal to observe a low efficiency due to mathematical reason, but also because reducing high radon concentration is not so difficult as reducing medium-low levels. Figure 5 shows the radon reduction degree (as efficiency) necessary to achieve a final radon concentration less than or equal to defined levels as function of the initial radon concentration: the continuous and the dashed line consider the reference level of 300 Bq/m^3 and to the Italian action level of 500 Bq/m^3, respectively: plotting the reduction obtained with the initial radon level, it can be evaluated if a certain radon control system is sufficiently efficient (all points on the left side of the curve). In the present remediation project, considering the action level of 500 Bq/m^3, excluding school ID=10, all the remediation are effective; conversely, if the new reference level of 300 Bq/m^3 is considered, in several schools further actions have to be done. Indeed, the schools ID=9 and ID=2, having high values of efficiency of 80% and 81% respectively, present post remediation radon values still exceeding 300 Bq/m^3. Nevertheless, looking at the plot, for schools ID=12 and ID=16, despite the efficiencies achieved are quite low (8.7% and 30%, respectively), the effectiveness of remediation is confirmed: both of schools are on the left side of the continuous line referred to 300 Bq/m^3.

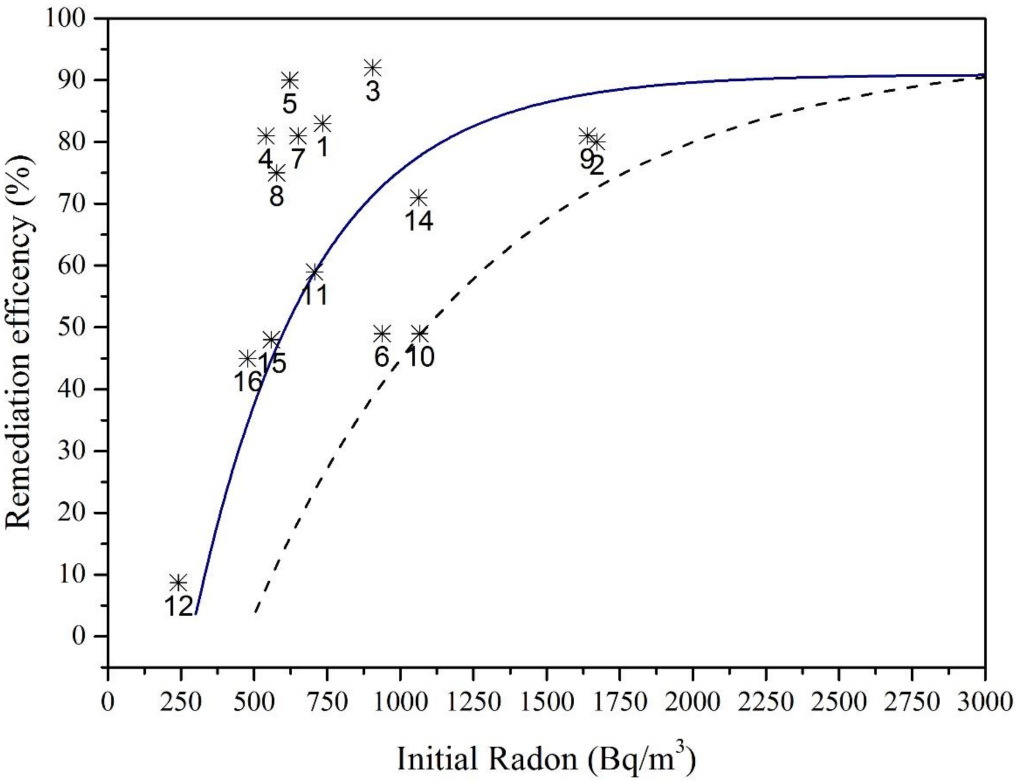

Figure 5. Radon remediation efficiency percentage. Stars represent results from each schools. Continuous and dashed lined: minimum reduction required at any given initial radon concentration to achieve a result below the new BSS reference level (300 Bq/m^3) and Italian action level (500 Bq/m^3) respectively.

4. Discussion

The success of a remediation is affected by many factors: the nature of subjacent soil, the size, the shape and the orientation of the building, the number of suction points, the position of vent pipes or holes in case of active or passive systems respectively, etc.

4.1. First critical aspect: the "karst phenomenon"

In most cases the reductions were in the order of 60-80%, with some cases in which post remediation radon annual concentrations still exceed 300 Bq/m^3: a non-optimal outcome of remediation may be mostly attributable to the permeability of the ground below the buildings. This area (the province of Lecce, Puglia, Italy) is characterized by a complex karst landscape associated with the presence of extensive Plio-Pleistocenic coverage (calcarenites and clay deposits): the "karst phenomenon" can explain the indoor radon average concentration in school (AM=215±20 Bq/m^3) much higher than the one estimated for the whole region (52±2 Bq/m^3) (Bochicchio et al. 2005). Same conclusions were found in the Lithuanian radon survey performed between 1995 and 1998 in 400 houses, where higher indoor radon levels were detected in houses of the Birzai karst region (Morkunas and Akerblom 1999)

The karst characteristics are primarily the product of water dissolving the limestone formations, which exhibit significant fissures and voids. Previous investigations on this geographic area as well studies in other karst regions (Taroni et al. 2010, Hughes et al. 1998; Long et al 2016) indicate the probability of a significant influence by geological and environmental factors on soil gas movement over great vertical and horizontal distances, and the solution cavities can act as very effective conduits for radon. The variability in magnitude and direction of radon movement could provide in drastic and rapid fluctuations in radon concentrations both in subjacent soil gas and indoors.
The karst nature of the site and the large variations in radon entry potential make the choice of effective remediation systems more demanding in terms of identification of potential entry points and driving forces, and of the accurate prediction of system's mechanical performance characteristics like magnitude and extent of pressure fields.
In case of remediation by SSD, it was expected some evident difference as consequence of the position of vent pipes - horizontal or vertical - in terms of reduction percentage (efficiency) or in terms of more homogeneous indoor radon levels within remediated schools. Actually, experimental data did not confirm the hypothesis, maybe due to the "karst phenomenon", but further analysis will be performed at the end of the remediation project.

4.2. Second critical aspect: optimisation of remediation

The optimisation of remediation required a lot of efforts and work, especially if the aim of optimisation are multiple, the first is an improvement of remediation efficiency.
In many schools, as in case of school ID=2, the optimisation consisted in a graduated approach: multiple remediation attempts, which usually starts with a passive ventilation of crawlspace (more easy and more economic to install, with no running cost), wherever it is possible, sometimes supported by a good orientation respect to dominant winds blowing on the building shell. The passive ventilation of crawlspace was done creating holes in a north-south direction: experimental results, evaluated by 3-months of weekly measurements, showed a reduction efficiency widely ranging between 23% to 60%, on the base of the not controllable intensity of the wind. The passive ventilation of crawlspace (see Fig.6) was too much influenced by the wind's fluctuation (in Fig.6 is also visible the effect of strong winds) so, in the second step, the ACD was introduced: since school ID=2 had a partitioned crawlspace, each area was provided by an electric fan just below each classroom. The active systems were equipped with a potentiometer to adapt the fans speed during the hot/cold seasons. The active depressurization of a partitioned crawlspace provided an overall efficiency of about 88% (short term monitoring results – Step 3), and of 96% in the reference room (result of active monitoring – Step 4, see Fig.7). Post-remediation long term radon measurements confirmed a reduction efficiency of 80%.
During the optimisation, many efforts were done to have a good balance between then remediation efficacy and saving energy-related operating costs, accounting for problems due to acoustic and thermal discomfort, too. In the framework of Step 4, radon active monitoring for at least 2-3 weeks let follow continuously the hourly trend of radon level depending on the ON/OFF state of suction fans, order to set the suitable timing protocol. Different timing protocols for the suction fans were tested: continuously, at intervals of about 12 hours (night ON, day OFF) and short cycles (2 hours ON, 30 min. OFF), as already done in some Italian schools (Arrigoni, 2011).
Continuous fan working is certainly the most effective but it does not guarantee a long life for the suction fans and requires a huge consumption of energy; conversely, cycles of about 12 hours ON/OFF provided less satisfactory results, since radon levels often increased too much when the fan was switched off for a such long time. In the actual situation, the best timing was a sequence of 2-4 hours ON/ 30-60 min. OFF. This timing is sufficient to cooldown the electric fan without leading to a strong increasing of indoor radon levels. Figure 7 shows the effects of the suction system on a sample room in school ID=1: a reduction of 90% with continuous suction and of 89% applying ON/OFF cycles of 120/30 min.

4.3. Third critical aspect: architectural constrains in buildings of architectural or historic interest
The radon remediation in case of buildings of architectural or historic interest appeared as a challenge, which required compromise solutions to retain the building's characteristic. In case of historic buildings, indeed, the aim should be to reach the best radon reduction as far as reasonably practicable without damaging their characteristic or causing long term deterioration. So, main key-principles are:

- keep works to the minimum necessary;
- keep intervention to a minimum and help to retain the character of the building;
- avoid inappropriate external interventions.

Especially in these situations, remediation specialists had to agree a solution which achieves an effective reduction in radon level and ensures a professional finish that is both quiet and visually discrete . For these reason in some peculiar situation, the placement of radon sumps and fan units on the exterior of buildings required to be considered more carefully. That is the case of school ID=13, where the suction points were not barycentric respect to the entire building, but excavated in the courtyard, along the external walls (Fig8).

4.4. Fourth critical aspect: management of remediation
The last critical aspect faced in the remediation of public workplaces such as schools is the management over the time, that means maintenance work to guarantee a long term effectiveness and periodically check, especially in case of active systems. In some remediated schools, indeed, radon measurements highlighted increased post remediation levels of radon not due to scarcely effective remediation but due to post remediation technical failure such as the decay of fan performances (mainly due to the presence of dust, dirt and moisture, see Fig. 9 and Fig. 10).
The experience shows that after the remediation, it is necessary to identify a trained person in charge to check periodically if the remediation systems is functioning correctly, following a proper procedure.

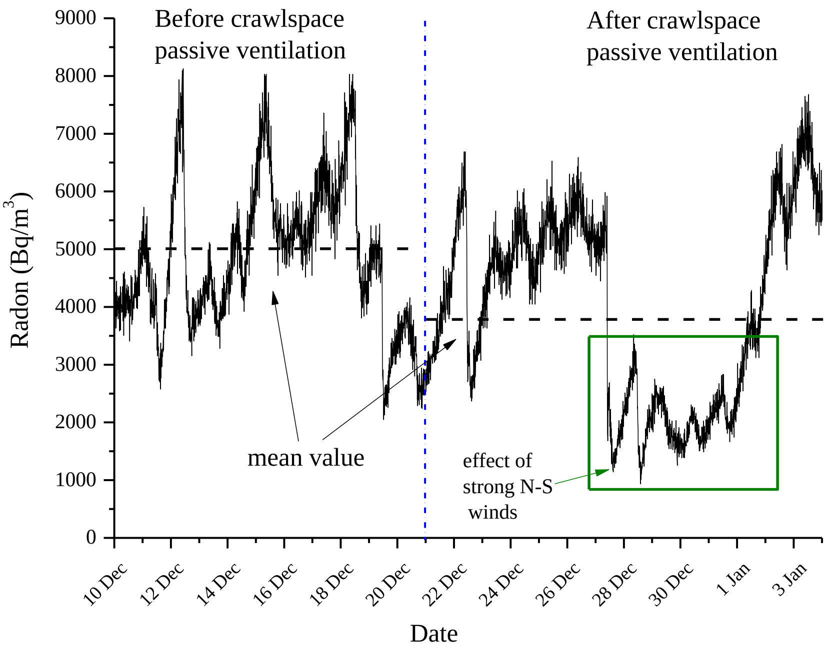

Fig. 6. School ID=2 - reference room. Comparison of results before and after the passive ventilation of crawlspace.

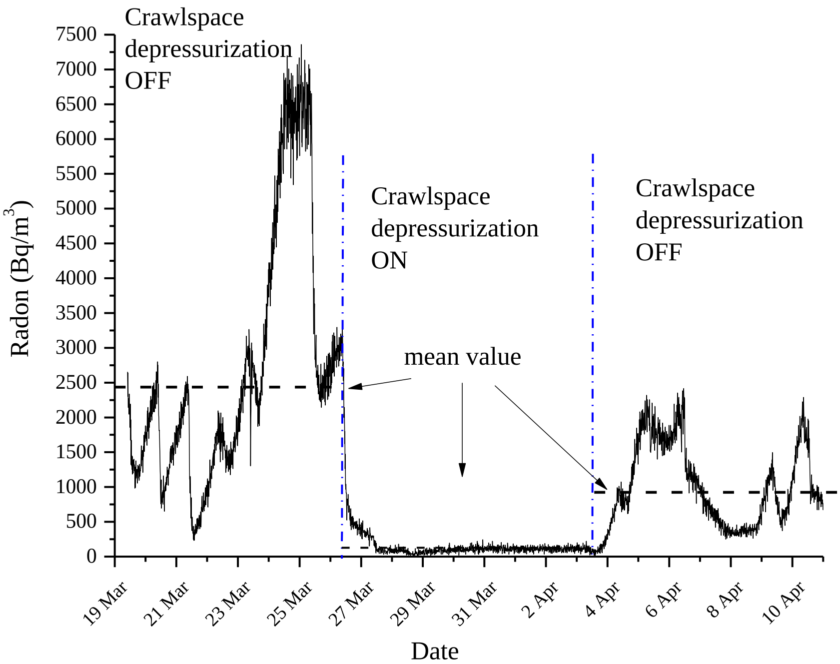

Fig. 7: School ID=2 **-** reference room. Comparison of results before and after the active ventilation of crawlspace.

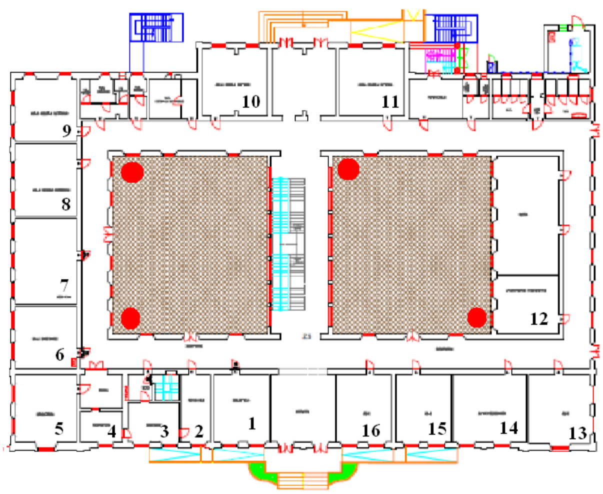

Fig. 8. Sumps and pipes inserted vertically in a position not always barycentric to the building but along the perimeter. School ID=13

4.5 Economic considerations

In the remediation project economic aspects were carefully considered: an evaluation of economic costs of installation, maintenance and running has been done as for ACD as for SSD. A synthesis is given in Table 5.

For SSD systems, the costs of installation varied from 1,000 to 1,500 **€** per suction point (sump and fan), depending on the difficulties regarding the position of the suction system (like easy

accessibility) and nature of the work (type of rock or soil beneath the building, size and direction of the excavation, etc.). For ACD systems, the installation costs varied from 200 to 400 € per suction point (fan).
Moreover, as annual operating costs only the ones related to power consumption were considered since the building heating/cooling loss were considered negligible in a such temperate climate area: for SSD systems they are in the range 100-130 € per fan (power ≅85 Watt) and 25-30 € for ACD (fan power 20 Watt). About maintenance, the average annual cost for SSD is 150 € and about 50 € for ACD: they consider also the replacement of not working fan.

Table 5
Remediation systems and relevant cost – synthesis.

System	**Installation cost**	**Maintenance cost**	**Operating cost/fan**
	€	**€ /y**	
SSD	1000 - 1500	150	100-130
ACD	200 - 400	50	25-30

Fig. 9. Maintenance work are basic for efficiency of the plants, e.g. avoiding obstruction by water and ground.

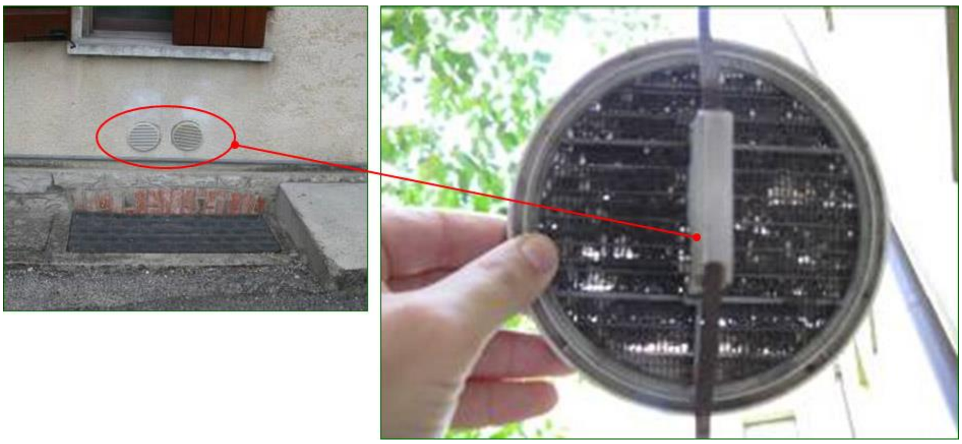

Fig. 10: Maintenance work: dust and dirt and moisture can obstruct the protection grid of the pipes

Conclusions

A new data-analysis put in evidence that about the 20% of schools have radon annual averages exceeding the new reference level of radon in workplaces (300 Bq/m^3) recently introduced by the European Union Legislation. Past estimations considered as remediation school buildings those with radon average levels over 500 Bq/m^3 (Italian action level for workplaces, still in force). So the transposition of the European legislation will lead to the need of remediation in a lot of schools in the same area.

A plan of radon remediation in schools has been designed and realized. This experience further corroborated the fact that radon remediation requires the preparation of measurement protocols and practical intervention protocols, to be developed in conjunction with the technical offices of local authorities. Close collaboration and supervision can guaranty better results.

This paper gives a synthesis of the remediation project in a subset of school buildings and relevant critical aspects: in particular, in the considered schools new long-term monitoring confirmed high levels of radon, as found in the first survey and the need to introduce radon control systems.

The quality control of measurements performed by using EIC confirmed the reproducibility of data acquisition by two different configurations (SLT and LST) and the good concordance of both methods with the results from the reference monitor: electret devices were confirmed as a good tool when radon concentration measurements have to be done simultaneously in many rooms for not too long periods, as during the remediation.

The intervention adopted was mainly the sub-slab depressurization (SSD in 57% of schools), but also the active ventilation of crawlspace (ACV in 21% of schools).

This project let to put in evidence that an effective remediation can be affected by many critical aspects, such as:

- the geologic nature of the area;
- the optimisation of remediation in terms of electric fans operating timing or coexistence of multiple radon control systems;
- economic costs, which consider installation, running and maintenance costs.

The percentages of remediation obtained vary from 48% to 85% on average for schools, and from 24% to 96% for single rooms.

The identification of a trained person in charge to periodically check the good working of the system allow to guarantee a long-term protection from radon exposure.

A major role in the radon behavior observed in these schools, such as large and rapid fluctuations in indoor and subsurface radon concentrations is attributable to the karst characteristics of this area. So, diagnostic and remediation procedures may be inadequate to quantify the magnitude and temporal variation of radon concentrations to design effective radon control systems in areas where Karst geology plays an important role.

References

Arrigoni S., Antonioli L., Capetta C., Cugini A., D’Aloja G., Di Toro M., De Bartolo D., Imbrogno P., Pezzera G., Ratti A., Romanelli M., Zannoni G, 2011. *Risanamenti da radon in edifici* *scolastici in provincia di Bergamo*.12 - 14 October 2011, Proceedings of AIRP –National Radiation Protection Conference. CODICE AGENAS 1031-15033.

2000. Legislative Decree n. 241, 2000, May 26. Attuazione della direttiva 96/29/EURATOM in materia di protezione sanitaria della popolazione e dei lavoratori contro i rischi derivanti dalle radiazioni ionizzanti. *GURI n. 203, 2000, August 31. Ordinary Supp. 140.*

2005. ISO/IEC 17025 General requirements for the competence of testing and calibration laboratories. edited by International Standard.

2009. WHO handbook on indoor radon - a public health perspective. World Health Organization.

Bochicchio, F., G. Campos-Venuti, S. Piermattei, C. Nuccetelli, S. Risica, L. Tommasino, G. Torri, M. Magnoni, G. Agnesod, G. Sgorbati, M. Bonomi, L. Minach, F. Trotti, M. R. Malisan, S. Maggiolo, L. Gaidolfi, C. Giannardi, A. Rongoni, M. Lombardi, G. Cherubini, S. D'Ostilio, C. Cristofaro, M. Pugliese, V. Martucci, A. Crispino, P. Cuzzocrea, A. S. Santamaria, and M. Cappai. 2005. "Annual average and seasonal variations of residential radon concentration for all the Italian Regions." *Radiation Measurements* 40 (2-6):686-694.

Caresana, M., F. Campi, M. Ferrarini, L. Garlati, and A. Porta. 2005. "Uncertainties evaluation for electrets based devices used in radon detection." *Radiation Protection Dosimetry* 113 (1):64-69.

D'Alessandro, M., F. Leonardi, S. Tonnarini, R. Trevisi, and M. Veschetti. 2010. "Development of a framework of quality assurance practices for a radon passive dosemeter service." *Journal of Radiological Protection* 30 (2):149-159.

Holmgren, Olli, and Hannu Harvela. 2012. Assessment of Current Techniques Used for Reduction of Indoor Radon Concentration in Existing and New Houses in European Countries. Finland, Helsinki: Radiation and Nuclear Safety Authority- STUK.

Kotrappa, P., J. C. Dempsey, J. R. Hickey, and L. R. Stieff. 1988. "An electret passive environmental 222Rn monitor based on ionization measurement." *Health Physics* 54 (1):47-56.

Kotrappa, P., J. C. Dempsey, R. W. Ramsey, and L. R. Stieff. 1990. "A practical E-PERM(TM) (electret passive environmental radon monitor) system for indoor 222Rn measurement." *Health Physics* 58 (4):461-467.

Llerena, J. J., D. Cortina, I. Durán, and R. Sorribas. 2010. "An approach to the subslab depressurization remedial action in a high 222Rn concentration dwelling." *Journal of Environmental Radioactivity* 101 (3):219-225.

Mishra, R., C. Orlando, L. Tommasino, S. Tonnarini, and R. Trevisi. 2005. "A better understanding of the background of CR-39 detectors." *Radiation Measurements* 40 (2-6):325-328.

Trevisi, R., A. Caricato, M. D'Alessandro, M. Fernández, F. Leonardi, A. Luches, S. Tonnarini, and M. Veschetti. 2010. "A pilot study on natural radioactivity in schools of south-east Italy." *Environment International* 36 (3):276-280.

Trevisi, R., F. Leonardi, C. Simeoni, S. Tonnarini, and M. Veschetti. 2012. "Indoor radon levels in schools of South-East Italy." *Journal of Environmental Radioactivity* 112:160-164.

Vaupotič, J., and I. Kobal. 2005. "Radon exposure in Slovenian kindergartens and schools." *International Congress Series* 1276:375-376.

Taroni, M., Bartolomei, P., Esposito, M., Vaccaro, C., 2010. High Radon concentration in the karst area of south Puglia, Italy. Geophysical Research Abstracts Vol. 12, EGU2010-11112, 2010 EGU General Assembly 2010.

Hughes, J.R., Turk, B., Cardwell, R., 1998. Karst geology, radon fluctuations. and implications for measurement and mitigation. ……

Morkunas, G. and Akerblom, G., 1999. The results of the Lithuanian Radon Survey. Proceedings of the Conference "Radon in the Living Environment", 19-23 April 1999, Athens, Greece, 61-70.

Hodgson, S., Zhang, W., Bradley, E., Green, B., & McColl, N. (2011). An analysis of radon remediation methods. Didcot, UK: Health Protection Agency. (HPA-CRCE-019).

Stephanie C. Long, S., Fenton, D., Scivyer, C., Monahan, E., 2016. Factors underlying persistently high radon levels in a house located in a karst limestone region of Ireland – lessons learned about remediation. NUKLEONIKA 2016;61(3):327-332