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A Comparative Study of Indoor Radon Concentrations between Dwellings and Workplaces in the Ko Samui District, Surat Thani Province, Southern Thailand

Kanokkan Titipornpun, Tripob Bhongsuwan, Jan Gimsa

Abstract**—**The Ko Samui district of Surat Thani province is located in the high amounts of equivalent uranium in the ground surface that is the source of radon. Our research in the Ko Samui district aimed at comparing the indoor radon concentrations between dwellings and workplaces. Measurements of indoor radon concentrations were carried out in 46 dwellings and 127 workplaces, using CR-39 alpha-track detectors in closed-cup. A total of 173 detectors were distributed in 7 sub-districts. The detectors were placed in bedrooms of dwellings and workrooms of workplaces. All detectors were exposed to airborne radon for 90 days. After exposure, the alpha tracks were made visible by chemical etching before they were manually counted under an optical microscope. The track densities were assumed to be correlated with the radon concentration levels. We found that the radon concentrations could be well described by a log-normal distribution. Most concentrations (37%) were found in the range between 16 and 30 Bq.m^{-3}. The radon concentrations in dwellings and workplaces varied from a minimum of 11 Bq.m^{-3} to a maximum of 305 Bq.m^{-3}. The minimum (11 Bq.m^{-3}) and maximum (305 Bq.m^{-3}) values of indoor radon concentrations were found in a workplace and a dwelling, respectively. Only for four samples (3%), the indoor radon concentrations were found to be higher than the reference level recommended by the WHO (100 Bq.m^{-3}). The overall geometric mean in the surveyed area was 1.65±32.6 Bq.m^{-3}, which was lower than the worldwide average (39 Bq.m^{-3}). The statistic comparison of the geometric mean indoor radon concentrations between dwellings and workplaces showed that the geometric mean in dwellings (46.0±1.55 Bq.m^{-3}) was significantly higher than in workplaces (28.8±1.58 Bq.m^{-3}) at the 0.05 level. Moreover, our study found that the majority of the bedrooms in dwellings had a closed atmosphere, resulting in poorer ventilation than in most of the workplaces that had access to air flow through open doors and windows at daytime. We consider this to be the main reason for the higher geometric mean indoor radon concentration in dwellings compared to workplaces.

Keywords**—**CR-39 detector, indoor radon, radon in dwelling, radon in workplace.

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I. Introduction

RADON-222 (^{222}Rn) is a naturally occurring radioactive, colorless, odorless, and tasteless noble gas with a half-life of 3.82 days (92 hours). The ubiquitous gas is formed by the decay of Radium-226 (^{226}Ra). The latter originates from the decay of Uranium-238 (^{238}U), which is found in all soils, rock and water. Therefore, radon gas can easily diffuse through the ground to the air above and enters into buildings through the cracks, gaps and cavities in the foundation, resulting in most of the exposure of the population to radon occurs at home [1], [2]. Radon contributes more than 50% to the effective dose received from all natural radiation sources [3]. During decay, radon emits an alpha particle and its daughters (^{212}Po or ^{214}Po). Radon gas is hazardous in case the decay process occurs after inhalation. The alpha particles emitted from the short-lived decay products of radon can damage lung tissue, which is the second leading cause of lung cancer in humans after smoking [4]-[9]. An estimated 13.4% of lung cancer deaths in the U.S. are believed to be radon-related [10]. The action level of 148 Bq.m^{-3} for indoor radon concentration at home was recommended by the Environmental Protection Agency (U.S. EPA) [11]. To minimize the health risks from radon exposure, the World Health Organization (WHO) recommended the reference level of 100 Bq.m^{-3} [1]. However, there is no known threshold concentration below which no risk exists. Worldwide, an arithmetic mean of 39 Bq.m^{-3} was found for the indoor radon concentrations in dwellings [1]. The variations of the indoor radon concentrations in between countries and within country were found to be large [12].

Measurements of indoor radon concentrations in dwellings and workplaces were conducted in many countries. A recent focus was the variations in the indoor radon concentrations, which depend on various factors, such as the geological area and the soil properties [13]-[16], as well as the seasonal variations [17]-[19]. Some reports were focusing on the characteristics of the buildings, such as room types, floor levels, ventilation systems, building materials, type of foundation, type of windows, type of plastering, building age, etc. [20]-[27]. Because of the many factors influencing the indoor radon concentrations, only measurements of the radon concentrations may predict the radon hazard and provide a correct risk assessment. For risk prediction, geological maps, soil gas [14] and airborne equivalent uranium have been studied [28].

In this work, CR-39 alpha track detectors were used to measure the indoor radon concentrations in dwellings and workplaces of the Ko Samui district, Surat Thani province, Southern Thailand. In addition, the variations of indoor radon concentrations for different building materials, building age and ventilation systems were investigated.

II. Materials and Methods

A. Location of the Surveyed Areas

Ko Samui district is one of 19 districts of Surat Thani province located at the Gulf of Thailand (9° N, 100° E). After Phuket and Ko Chang, Ko Samui is the third largest island of Thailand. The district is divided into seven sub-districts: Ang Thong, Mae Nam, Bo Phud, Ma Ret, Lipa Noi, Taling Ngam and Na Muang. Ko Samui district also covers the Ang Thong archipelago and some small islands nearby. However, we selected the main seven sub-districts as our survey areas because they exhibited high ground surface concentrations of uranium, according to airborne radiometric surveys that were carried out by the Department of Mineral Resources of Thailand. The uranium concentration is given in parts per million of equivalent uranium (ppm eU) referred to the isotope equilibrium of ^{238}U series. Fig. 1 shows the map of equivalent uranium concentrations in the ground surface of the Ko Samui district that was completed using ArcGis 10.2 and ArcView 3.1 programs by the Geographic Informatics Research Center for Natural Resource and Environment, Prince of Songkla University, Thailand.

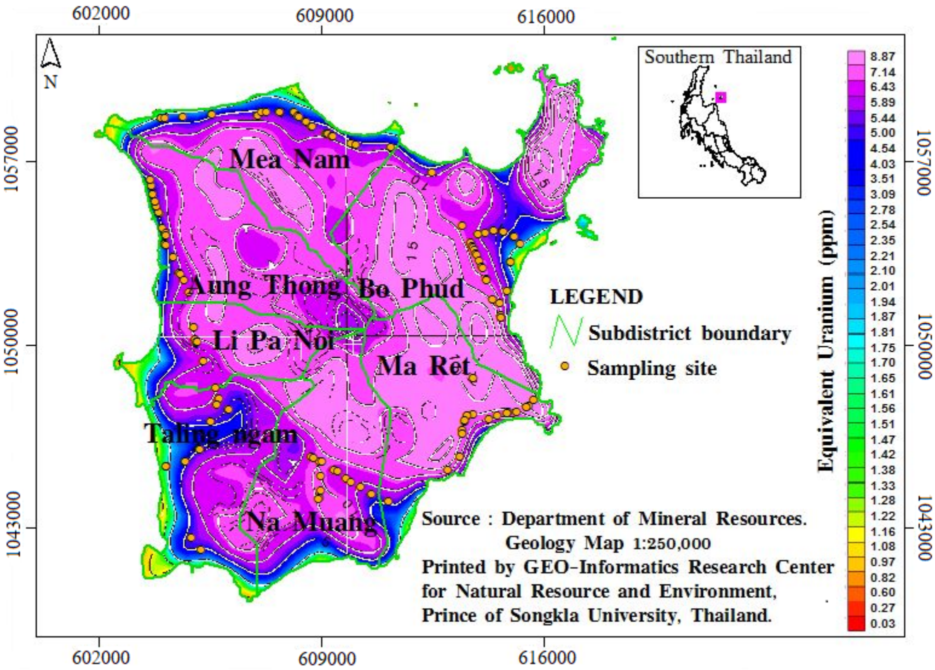

Fig. 1 Map of equivalent uranium concentrations in the ground surface of the Ko Samui district, Surat Thani province, Southern Thailand showing sampling site (circle symbol) selected for indoor radon measurements

The ground surface equivalent uranium levels of the Ko Samui district are exceeding 6 ppm eU in most areas. Concentrations higher than 3 ppm eU have been identified as causing a high risk for excessive indoor radon concentrations [29]. It must therefore be assumed that the population in the Ko Samui district is at high risk of adverse indoor radon exposure.

B. Measurement of Indoor Radon Concentrations

Radon measurements were carried out using CR-39 (Allyl diglycol carbonate) alpha track detectors (commercial name “TASTRAK”; Track Analysis Systems Ltd, UK). The CR-39 chip for indoor radon measurement is square-shaped with 1.5 cm x 1.5 cm and 1 mm thick. The CR-39 chips were numbered at one corner for identification. For measurements, each CR-39 chip was fixed by a small piece of adhesive tape to the bottom center of 300-ml round plastic cups. The cups had an 8.5 cm diameter orifice, a 5 cm diameter base and a depth of 9.5 cm. The orifice of each cup was closed with cling film to allow only ^{222}Rn gas to pass through the filter and to exclude the nongaseous radon daughters from entering the dosimeter [22], [30]-[31]. The survey measurements of indoor radon concentrations were carried out in 46 dwellings and 127 workplaces. A total of 173 CR-39 detectors were distributed in seven sub-districts (Fig. 1). The detectors were placed in the bedrooms of dwellings and working rooms of workplaces at the ground floor, where the indoor radon concentrations are higher than at the upper floors [8], [21]-[22], [25]-[26]. Inside the rooms, the detectors were located distant from the windows and doors at a representative breathing height of approx. 1.5 m above the floor. All detectors were installed in the buildings for an exposure time of 90 days. After this period, all detectors were chemically etched in a 6.25 M NaOH solution at 85 °C for 100 minutes. Each detector was thoroughly rinsed with distilled water before drying. The alpha track density in each detector was counted manually under an optical microscope (Fig. 2).

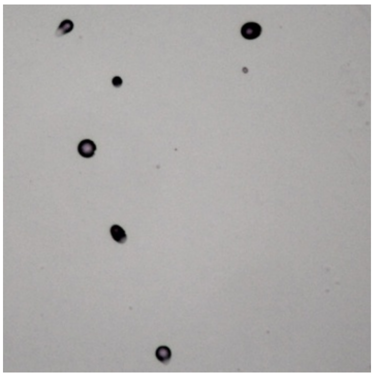

Fig. 2 Alpha tracks in a CR-39 detector viewed under a Nikon E200 optical microscope with a 100x magnification

The counted track density of each CR-39 detector was converted into radon concentration using a calibration factor, as in [22]:

$$C_{Rn} = D / kt \tag{1}$$

where C_{Rn} is the radon activity concentration (in Bq.m^{-3}), D is the track density in tracks per cm^2 corrected for background, t is the exposure time (90 d), and k is the calibration factor (0.075 tracks per cm^2 d per Bq.m^{-3}).

III. Results and Discussion

A. Characteristics of the Buildings

TABLE I
CHARACTERISTICS OF THE BUILDINGS

Characteristics of the buildings		Number of samples		Sum	%
		Dwellings	Workplaces		
Building materials	Concrete	42	115	157	90.8
	Concrete and wood	4	12	16	9.2
Building age	<10 years	13	41	54	31.2
	11-20 years	23	64	87	50.3
	21-30 years	6	11	17	9.8
	>30 years	4	11	15	8.7
Ventilation	Closed	46	18	64	37.0
	Natural	-	109	109	63.0

In this study, 173 buildings were surveyed for their radon concentrations. The buildings were classified into two groups: 46 dwellings and 127 workplaces with different characteristics. Most buildings (90.8%) were built from concrete and full brick, while some buildings (9.2%) were built from concrete with wooden walls. The buildings were classified into 4 age groups: younger than 10 years (31.2%), in between 11 and 20 years (50.3%), in between 21 and 30 years (9.8%), and more than 30 years old (8.7%). Rooms in closed systems with poor ventilation were found only in 37% of all buildings, while the natural ventilations by open doors and windows throughout the day was found in most buildings (63%) (Table I).

B. Distributions of Indoor Radon Concentrations in Dwellings and Workplaces

The histograms of the number of buildings as a function of indoor radon concentrations in dwellings (Fig. 3 (a)) and workplaces (Fig. 3 (b)) in the Ko Samui district were found to be skewed to the right (Kolmogorov-Smirnov normality test, $p < 0.05$). Comparison of the distributions of the indoor radon concentrations between dwellings and workplaces showed that most dwellings collected from 46 buildings (Fig. 3 (a)) had indoor radon concentrations in the range from 31 to 45 Bq.m^{-3} (20 buildings: 44%). 11 buildings (24%) were found in the range from 46 to 60 Bq.m^{-3}. However, the indoor radon concentrations were found to exceed the reference level of 100 Bq.m^{-3} recommended by the WHO only in 4% of all dwellings (2 buildings), though with the extreme values of 124 and 305 Bq.m^{-3}. In the workplaces of 127 buildings, concentrations were found in the range from 16 to 30 Bq.m^{-3} in most of the buildings (60 buildings: 47%) (Fig. 3 (b)). Some buildings (35 buildings: 28%) were found in the range from 31 to 45 Bq.m^{-3}. Only in 2% of all workplaces (2 buildings) the concentrations were found to exceed 100 Bq.m^{-3}, though with extreme values of 112 and 125 Bq.m^{-3}.

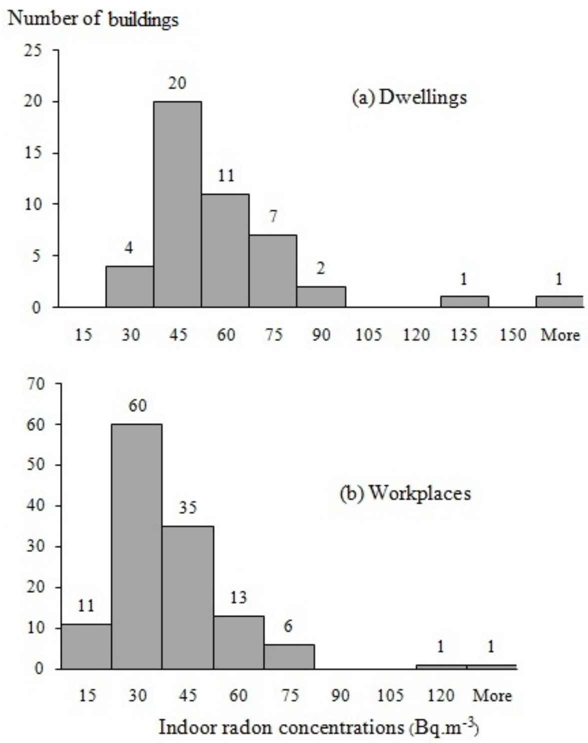

Fig. 3 Histograms of the number of buildings as a function of the indoor radon concentrations in dwellings (a) and workplaces (b) of the Ko Samui district, Surat Thani province, Southern Thailand

The data of all 173 buildings in the Ko Samui district show that the highest number of buildings had indoor radon concentrations in the range from 16 to 30 Bq.m^{-3} (37%, 64 buildings). The second and third highest numbers of buildings were in the ranges from 31 to 35 Bq.m^{-3} (55 buildings: 32%) and from 46 to 60 Bq.m^{-3} (24 buildings: 14%), respectively. Only 3% of the entire number of buildings (four buildings with radon levels of 112, 124, 125 and 305 Bq.m^{-3}) had indoor concentrations higher than 100 Bq.m^{-3}.

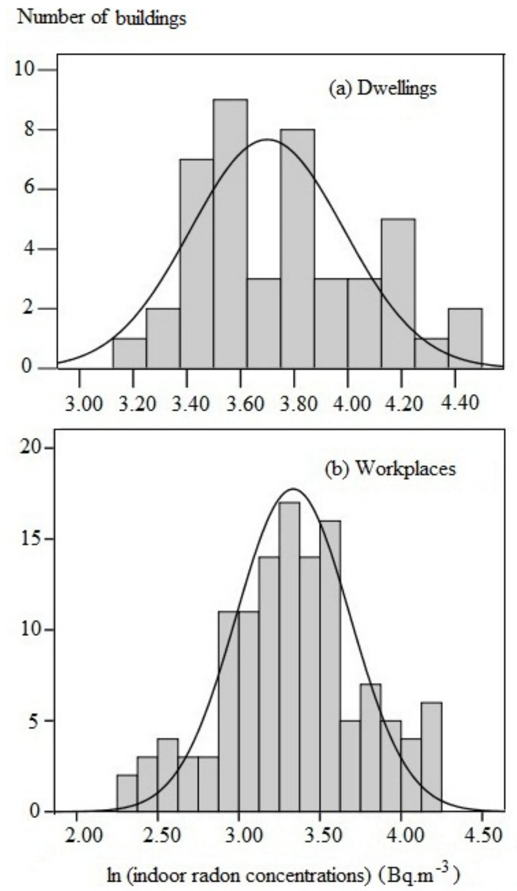

Fig. 4 Histograms of the number of samples as a function of the indoor radon concentrations under natural logarithm in dwellings (a) and workplaces (b) of the Ko Samui district

Because of the skew in the data distribution, the concentration data were transformed by applying the natural logarithm. Fig. 4 indicates that the data distributions can be well fitted by the log-normal function (Kolmogorov-Smirnov normality test, $p>0.05$). Therefore, the geometric mean (GM) and geometric standard deviation (GSD) as well as minimum (Min) and maximum (Max) values were used for the descriptive statistics and comparison of means.

C. Indoor Radon Concentrations in Surveyed Areas

A summary of the statistical analysis of the indoor radon concentrations measured in the Ko Samui district is shown in Table II. In dwellings collected from 46 buildings, the indoor radon concentrations varied from 24 to 305 Bq.m^{-3}. The minimum indoor radon concentration was found in the Ang Thong sub-district, while the maximum value was found in the Bo Phud sub-district. In workplaces collected from 127 buildings, the indoor radon concentrations varied from 11 to 125 Bq.m^{-3}. The minimum indoor radon concentration was found in the Ang Thong, Mae Nam and Taling Ngam sub-districts, while the maximum value was found in the Ma Ret sub-district. The GM of the indoor radon concentration for our entire data was 32.6±1.65 Bq.m^{-3}. A comparison with some districts of Surat Thani province showed that this value is higher than the indoor levels of the Chaiya (26±2 Bq.m^{-3}), Tha Chana (30±2 Bq.m^{-3}) [23], and Pa Nom districts (26±1 Bq.m^{-3}) [24], while it was lower than the indoor level of the Ko Pha-ngan district (51±2 Bq.m^{-3}) [24]. However, our present survey showed a GM of the radon concentration, which was lower than the worldwide average for indoor radon levels (39 Bq.m^{-3}) [1].

TABLE II
INDOOR RADON CONCENTRATIONS IN DWELLINGS AND WORKPLACES OF THE KO SAMUI DISTRICT, SURAT THANI PROVINCE, SOUTHERN THAILAND

Types of buildings	Sub-districts	n	%	Indoor radon concentrations (Bq.m^{-3})			
				Min	Max	GM	GSD
Dwellings	Ang Thong	6	13.0	24	62	34.6	1.34
	Mae Nam	9	19.6	31	71	41.9	1.26
	Bo Phud	7	15.2	29	305	49.4	2.14
	Ma Ret	6	13.0	29	83	46.1	1.42
	Lipa Noi	7	15.2	31	67	47.0	1.30
	Taling Ngam	5	10.9	39	84	54.2	1.33
	Na Muang	6	13	33	124	55.0	1.57
	Sum	**46**	**100**	**24**	**305**	**46.0**	**1.55**
Workplaces	Ang Thong	15	11.8	11	49	24.7	1.52
	Mae Nam	26	20.5	11	65	22.1	1.57
	Bo Phud	26	20.5	18	68	31.0	1.41
	Ma Ret	24	18.9	16	125	31.8	1.58
	Lipa Noi	10	7.9	27	66	39.7	1.33
	Taling Ngam	13	10.2	11	70	26.1	1.62
	Na Muang	13	10.2	22	112	35.8	1.56
	Sum	**127**	**100**	**11**	**125**	**28.8**	**1.58**
	Overall	**173**	**100**	**11**	**305**	**32.6**	**1.65**

D. Comparison of Indoor Radon Concentrations between Dwellings and Workplaces

A comparison of the GMs of the indoor radon concentrations between the dwellings and workplaces in different sub-districts showed statistically significant differences (One-way ANOVA, $p<0.05$) (Fig. 5). In dwellings and workplaces, the highest concentrations were found in the Na Muang sub-district (55.0±1.57 Bq.m^{-3}) and in the Lipa Noi sub-district (39.7±1.33 Bq.m^{-3}), respectively, while the lowest values were found in the Ang Thong sub-district (34.6±1.34 Bq.m^{-3}) and in the Mae Nam sub-district (22.1±1.57 Bq.m^{-3}), respectively. All values were significantly different (Tukey's HSD, $p<0.05$).

The highest GM of the indoor radon concentration (42.3±1.70 Bq.m^{-3}) was found in the Lipa Noi sub-district, while the lowest GM (26.0±1.65 Bq.m^{-3}) was found in the Mae Nam sub-district. The two levels are significantly different (Tukey's HSD, $p<0.05$).

Comparison of the GMs of the indoor radon concentrations between dwellings and workplaces showed that the concentration in dwellings (46.0±1.55 Bq.m^{-3}) was higher than in workplaces (28.8 ± 1.58 Bq.m^{-3}) (t-test for independent samples, $p<0.05$).

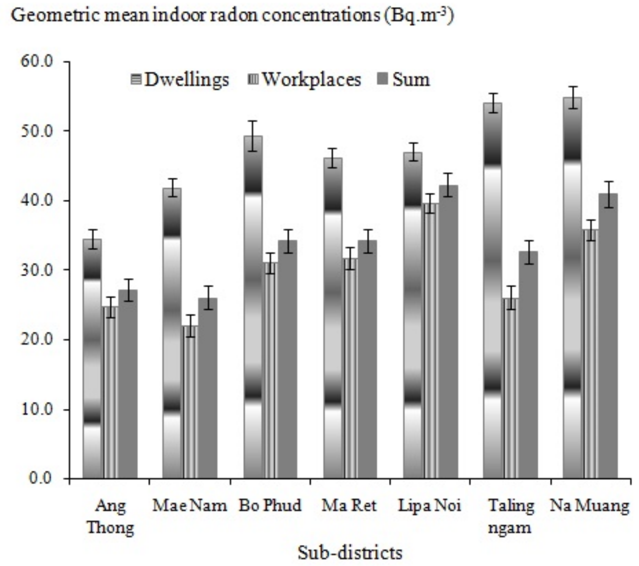

Fig. 5 Comparison of the GMs of the indoor radon concentrations between dwellings and workplaces in 7 sub-districts of the Ko Samui district

E. Indoor Radon Concentrations for Different Building Characteristics

The variations in the GMs of the indoor radon concentrations for different building characteristics are shown in Fig. 6. The GM for buildings with rarely opened windows and doors (34.8±1.51 Bq.m^{-3}), resulting in closed atmospheres, was slightly higher than for buildings with natural ventilation (32.2±1.67 Bq.m^{-3}) that permitted the air flow through opened doors and windows during daytime. The results for the influence of the buildings' age on the indoor radon concentrations showed that buildings in the <10 years and in the 11-20 years classes exhibited lower GMs of their indoor radon levels than buildings, which were older than 20 years. However, the GM indoor radon levels for the different ventilation systems and buildings age were not significantly different (independent samples t-test, $p>0.05$ and one-way ANOVA $p>0.05$), respectively. Significantly different results were found for different building materials (independent samples t-test, $p<0.05$). The maximum value (305 Bq.m^{-3}) and the minimum value (11 Bq.m^{-3}) of the indoor concentrations of all data were found in buildings, which were more than 30 years and less than 10 years old, respectively. These results corresponded to reports that describe high radon level for old buildings because of the cracks, gaps and cavities in the foundations, leading to radon diffusion into these buildings [23], [25]-[27]. Very high values were also found in buildings constructed from concrete that contained radium as a source of radon [13], [23]. Our study also showed that most rooms in dwellings have a closed atmosphere because the householders rarely open their windows and doors, neither at daytime nor nighttime. This results in the poor ventilation of dwellings compared to rooms at workplaces with free air flow through open doors and windows at daytime (Table I).

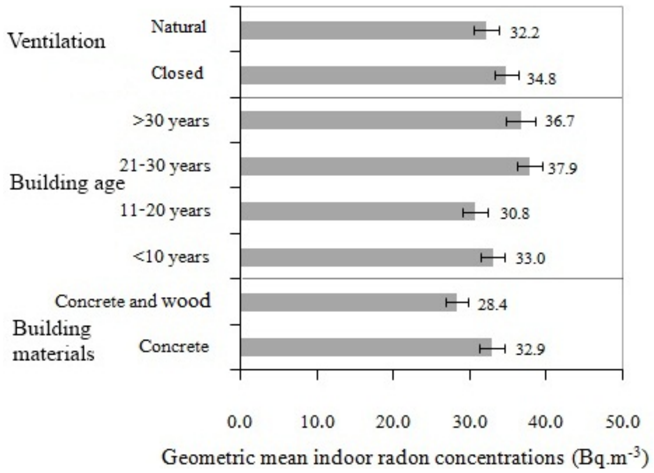

Fig. 6 Variation of the GM indoor radon concentrations for different building characteristics of the Ko Samui district

IV. Conclusion

The indoor radon concentrations in dwellings and workplaces of the Ko Samui district exhibit a log-normal distribution function. In most of the dwellings, indoor radon concentrations were detected in the range from 31 to 45 Bq.m^{-3}, while the radon concentrations in workplaces varied from 16 to 30 Bq.m^{-3}. The distribution of the indoor radon concentration of all data of the Ko Samui district showed indoor radon concentrations in the range from 16 to 30 Bq.m^{-3} in most of the rooms. Only 3% of the indoor radon concentrations were higher than the reference level of 100 Bq.m^{-3} recommended by the WHO. The highest GM of the indoor radon concentration (42.3±1.70 Bq.m^{-3}) was found in the Lipa Noi sub-district, while the lowest level (26.0±1.65 Bq.m^{-3}) was found in the Mae Nam sub-district.

The GM of all indoor radon concentrations found in the Ko Samui district was 32.6±1.65 Bq.m^{-3}, which is lower than the worldwide average of 39 Bq.m^{-3}. This probably results from the natural ventilation in the majority of the buildings (63%). Interestingly, we found that the GM indoor radon concentration in dwellings (46.0±1.55 Bq.m^{-3}) was significantly ($p<0.05$) higher than in workplaces (28.8±1.58 Bq.m^{-3}). However, the GMs of indoor radon concentrations for different building characteristics were not significantly different. In future studies, the influence of other factors on the indoor radon concentrations, such as the radon sources soil and ground water should be taken into account.

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