MICROBIAL CONTAMINATION OF INDOOR AIR DUE TO LEAKAGES FROM CRAWL SPACE – A FIELD STUDY

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ABSTRACT
Mechanical exhaust ventilation system is typical in apartment buildings in Finland. In most buildings the base floor between the first floor apartments and crawl space is not air tight. As the apartments have lower pressure than the crawl space due to ventilation, contaminated air may flow from the crawl space to the apartments. The object of this study was to find out whether a potential air flow from crawl space has an influence on the indoor air quality. The results show that in most cases the concentration of fungal spores was clearly higher in the crawl space than inside the building. The size distribution of fungal spores depended on the fungal species. Correlation between the fungal spores in the crawl space and indoors varied with microbial species. Some species have sources inside the building, which confounds the possible relation between crawl pace and indoor concentrations. Some species, such as *Acremonium,* do not normally have a source indoors, but its concentration in the crawl space was elevated; our measurements showed also elevated concentrations of *Acremonium* in the air of the apartments. This consistent finding shows a clear linkage between fungal spores in the indoor air and crawl space. We conclude that a building with a crawl space and pressure difference over the base floor could be a potential risk for indoor air quality in the first floor apartments.

PRACTICAL IMPLICATIONS
Mechanical exhaust ventilation causes an under pressure to the apartment and, thus, air flow from crawl space to indoors may occur. Very often some contamination in a crawl space exists and according to these measurements fungal spores are transported indoors. It seems that a ventilation system causing an under-pressure inside apartment might be a potential health risk, thus, a balanced ventilation system is recommended.

KEYWORDS
Microbes, Transport to Indoors, Crawl Space, Pressure difference, Leakage

INTRODUCTION
Crawl space foundation is one of the most commonly used ground constructions in Finland, and they are also typical in other countries, e.g. in Sweden and the USA. Ventilation in the crawl space is mostly carried out by outdoor air and it is usually natural, but mechanical exhaust ventilation is also used in some scale. In subartic climates the behaviour of a crawl space becomes problematic in the summer when in the daytime outdoor air is usually warmer and has a higher moisture content than the air in the crawl space. Thus, outdoor air can transport moisture into the crawl space and consequently the relative humidity raises. Relative humidity is reported to be high (85 – 95%) during the summer and even conditions to allow condensation of water had prevailed for several weeks (Samuelsson 1994). In an other report (Kurnitski 2000) relative humidity in the crawl space varied between 70 – 90% during the summertime. The limit value for relative humidity in respect of mould growth in crawl spaces is usually considered to be from 75% up to 80%. (Nevander and Elmasson 1991, Pasanen A-L 1992, Pasanen et al. 1992, Viitanen and Ritschkoff 1991)

In cold climates a typical cause for indoor air quality problems is insufficient amount of fresh air valves when a mechanical exhaust ventilation is used. In mechanical exhaust ventilation system the exhaust air is removed mechanically but the supply air comes through fresh air valves in the building envelope, and, hence, the supply air is not mechanically controlled and is affected e.g. by wind pressure. If the

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supply air does not have appropriate routes indoors it will find its way through leakages. In buildings with a crawl space, the main leakage air often comes through the cracks in the base floor allowing transport of contaminants indoors. The surfaces in the crawl space are favourable environment for microbes to grow, as there are nearly always enough nutrients. The relative humidity and temperature are usually high enough to support at least slow fungal growth in the crawl spaces. (Pasanen et.al. 2001).

According to earlier studies (Pellikka et. al. 1984, 1985, Pasanen et. al. 1990) in summer the concentration of the viable spores in outdoor air is in the range of 10 to 1.000 colony-forming units per cubic meter of air. When the ground is frozen or covered with snow, the concentration is usually less than a hundred colony-forming units per cubic meter of air.

The microbial contamination is typically much higher in the crawl space than inside the building. The level of fungal spores is about ten times higher in the crawl space than indoors. In crawl spaces, the spore concentrations in a range of 10^3-10^5 colony-forming units per gram (cfu/g) of material are common. The levels have usually been highest on wood-based boards and on timber (Kurnitski and Pasanen 2000). Under heavy fungal colonization, airborne spore concentrations up to 10^3-10^4 cfu/m^3 have been detected (Kurnitski and Pasanen 2000).

In Finland, dwellings have commonly mechanical exhaust ventilation, Figure 1. Mechanical exhaust ventilation creates under-pressure into the apartment. Very often the base floor has some leakages, and pressure measurements have shown that air flows through the leaks in the base floor to the apartment. The change of ventilation in the dwelling affects the air change in the crawl space. The pressure difference between indoor and outdoor or between indoor and crawl space is often in a range of 5 – 10 Pa. (Säteri et. al. 1999)

In buildings with balanced mechanical supply and exhaust ventilation, the pressure differences between indoor and outdoor as well as between indoor and crawl space are typically only a few Pascals (0-2 Pa). (Kokotti et. al. 1994)

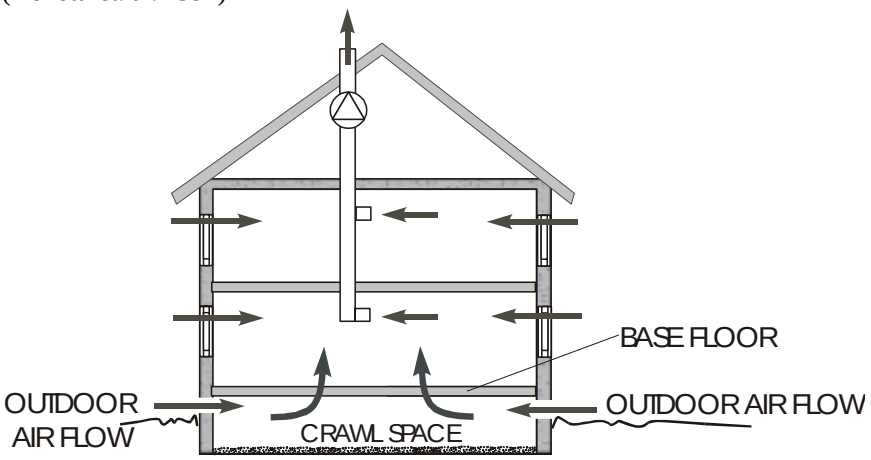

Figure 1 A principle of a mechanical exhaust ventilation in an apartment building with a crawl space.

In a study of Thatcher and Layton (1995) the penetration factor of particles through a building envelope was near one for all studied particle sizes between 1-25 µm. On the other hand in a study of Liu and Nazaroff (2001) the penetration was found to have highest values for particles between 0.1-1.0 µm. According to recent studies (Mosley et al. 2001, Vette et al. 2001) it seems, that particles in a size range of 1.0-2.5 µm are penetrating easily through cracks. This is an interesting result, since usually the median of the aerodynamic diameter of fungal spore is typically 2.0-3.0 µm in indoor air (Reponen 1995, Macher et al. 1991), being very suitable for penetration.

The objective of this study was to find out whether there is a relation between indoor and crawl space concentration of fungal spores, and whether microbes are transported from crawl space to indoors. The data of eight buildings with a crawl space were used to find out the possible relations.

METHODS

The concentrations of airborne fungal spores and bacteria were measured indoors, in the crawl space and outdoors in eight buildings in Southern Finland (Helsinki region, Table 1). The buildings were chosen to represent typical buildings with crawl space foundations. Some of the crawl spaces were suspected to cause indoor air quality problems. Three of the buildings were primary schools, two day-care centres and three dwellings. Half of the buildings had a wooden base floor. The dwellings had mechanical exhaust ventilation. Both of the day-care centres had mechanical exhaust ventilation in the crawl space, but all the other crawl spaces had natural ventilation except for two crawl spaces without any ventilation. The buildings 2 and 6 were divided into two parts a and b as the crawl spaces of the buildings were two separate sections. The area of the base floor varied between 80 – 800 m^2.

Table 1 The properties of studied buildings

	Building type	**Base floor**	**Base floor area (m^2)**	**Ventilation system in the building**	**Ventilation system in the crawl space**
Building 1	Apartment building	Wooden		Mechanical exhaust	Natural ventilation
Building 2a	Apartment building	Concrete slab	82	Mechanical exhaust	Mechanical exhaust
Building 2b	Apartment building	Concrete slab	127	Mechanical exhaust	Natural ventilation
Building 3	Apartment building	Wooden	200	Mechanical exhaust	Natural ventilation
Building 4	Primary school	Concrete slab	650	Mechanical supply and exhaust	Natural ventilation
Building 5	Primary school	Concrete slab	350	Mechanical supply and exhaust	No ventilation
Building 6a	Day-care centre	Wooden	210	Mechanical supply and exhaust	Mechanical exhaust
Building 6b	Day-care centre	Wooden	285	Mechanical supply and exhaust	Mechanical exhaust
Building 7	Day-care centre	Wooden	820	Mechanical supply and exhaust	Mechanical exhaust
Building 8	Primary school	Concrete slab	550	Mechanical supply and exhaust	No ventilation

Pressure and air change measurements in the crawl space

Building 2 represents a typical apartment building with a mechanical exhaust ventilation system, thus the pressure conditions were detected detailed. The air change rate of naturally ventilated crawl space was measured from every ventilation pipe, which was based on the measurement of the pressure drop in the ventilation pipes. The changes in pressure differences between 1) the crawl space and outdoor, 2) crawl space and apartment, and 3) apartment and outdoor were monitored continuously. The pressure variation between the crawl space and outdoor were measured across three walls of the crawl space with natural ventilation. A two-speed fan was used in the mechanical exhaust ventilation system of the apartments inside building 2. A detailed description of the measurements is reported in (Kurnitski 2000).

Sampling and analysis of fungal spores

Airborne fungal spores were sampled using six-stage cascade Andersen impactors (Andersen Samplers, Inc. 1979). Samples were taken from indoor, outdoor and crawl space air. Sets of samples were taken in the winter (January 25-27, 1999 and February 9-11, 1999) and others in late spring (May 17-25, 1999). The fungal spores were collected on 2% malt extract agar (MEA). To avoid contamination due to spore transportation with the clothes, the indoor samples (2 samples) were taken first. Two successive samples were also taken from the crawl space, but if the crawl space had clearly different sections such as different ground cover materials, two samples were taken from each section. According to previous studies e.g. (Reponen 1994), fungal spore concentrations are low during winter. During the winter sampling, the temperature was below 0°C, and, therefore, outdoor samples were not

taken. In the summer, one sample from outdoor air was taken on each study site. The sampling time was 10 min indoors and outdoors and 5 min in the crawl space, thus, the computational limit of identification was 7 CFU/$m^3$and 3.5 CFU/m^3. The incubation time of the samples was seven days (14 days for the actinomycetes) at 25°C.

The number of colonies were counted and the results were calculated from each stage of the Andersen impactor, and the size distribution of the spores were analyzed from each environment separately. The species were identified to genus level.

When counting the number of total fungal spores and species the results of the studied buildings were kept separate. However, when the size distribution of different species was counted the average of all the studied buildings was used.

RESULTS

Pressure difference between indoor and crawl space

Inside building 2, due to a mechanical exhaust ventilation, the pressure is lower than in the crawl space, thus, air is flowing through leaks in the base floor to the dwelling. There was a significant leakage between the crawl space and apartments that can be seen from the air change measurements. The fan for the mechanical exhaust ventilation of the building was a two-speed fan. The full speed increased under-pressure in the apartments and the pressure difference compared to the crawl space increased as well. This change can be clearly seen on the outdoor air flow through ventilation pipes to the crawl space, Figure 2. Zero value of extract flow through ventilation pipes indicates that almost all of the extract air of the crawl space flows through the base floor to apartments (there were only occasional peaks of extract flow through ventilation pipes on windy weather). Thus, it was not necessary to take the leakage into account since the flow direction was constantly from crawl space to apartments, and the measured outdoor air flow through ventilation pipes indicates the whole air change in the crawl space.

Most of the time, the pressure difference between the crawl space and dwelling is about 6 Pa, Figure 2. However, there were three periods each day when the ventilation was operated at higher speed and the pressure difference rose up to 16 Pa. The pressure difference between outdoor and apartment was around 9 Pa, indicating that the apartment had a lower pressure. The crawl space had 2 Pa lower pressure than outdoor.

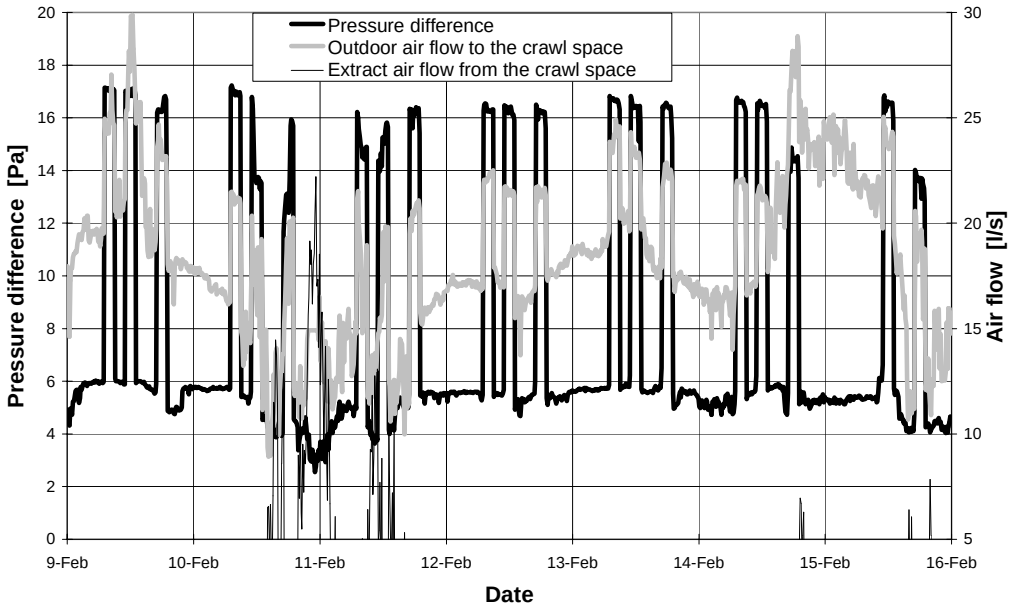

Figure 2 The pressure difference between crawl space and indoor, and outdoor air flow to the crawl space of building 2. Apartment has under-pressure and crawl space over-pressure. Outdoor air flow of 20 l/s corresponds to air change rate of 1 ach in the crawl space.

Concentration of fungal spores in the indoor, outdoor and crawl space air

In most cases the concentration of microbes was clearly higher in the crawl space than indoors or outdoors, Table 2. Typically the mean concentrations of fungal spores varied between 1.000 – 3.000 CFU/m^3, but concentrations of tens of thousands were measured. The most common species were *Penicillium*, *Acremonium* and *Cladosporium* in all the environments of the measured buildings.

Table 2 Concentration of different fungal species (CFU/m^3), their average, median, minimum, maximum values and standard deviation.

	Spores (CFU/m^3)	Average	Median	Min	Max	Std	n
Penicillium	Indoor	290	90	5	1620	460	20
	Crawl Space	4020	2760	60	17150	4190	20
	Outdoor	20	20	5	30	10	10
Acremonium	Indoor	160	40	2	730	240	15
	Crawl Space	2240	1870	0	8970	2600	15
	Outdoor	15	10	7	30	10	4
Cladosporium	Indoor	30	15	5	150	40	15
	Crawl Space	100	30	8	500	140	20
	Outdoor	110	90	6	240	100	6
Aspergillus	Indoor	70	70	15	130	80	2
	Crawl Space	110	50	2	270	140	3
	Outdoor			0	0		0
Yeasts	Indoor	10	8	3	40	10	10
	Crawl Space	15	15	3	20	8	10
	Outdoor	15	20	3	30	8	6
Sterile	Indoor	50	20	4	250	70	10
	Crawl Space	20	10	3	80	30	10
	Outdoor	220	80	30	1000	380	6

Std Geometric standard deviation

n prevalence of fungal species in the samples, number of total samples was 47.

In the summer the concentration of fungal spores indoors was lower or at the same magnitude as outdoors, Table 3. In the winter the concentration of fungal spores outdoors were not measured as the soil was frozen and covered by snow. In the crawl space the concentration of fungal spores was lower in the winter than in summer. The exceptions were in buildings 2 and 6, whose concentrations of fungal spores in the crawl space were higher in the winter.

Both indoors and in the crawl space the number of species was clearly higher in the summer than in the winter, especially later in the sampling week (Buildings 4, 5 and 1), Table 3. In most cases, the species found in the crawl space air were also found in indoor air. *Penicillium* was the dominant species both in indoor air and in the crawl space air in buildings 7, 3, 6 and 4 in the summer. In buildings 3 and 6, the concentration of fungal spores (dominant species *Penicillium* and *Cladosporium*) in the crawl space was roughly of the same magnitude in the summer, but inside the building the concentration was lower in building 6 with a mechanical exhaust ventilation in the crawl space. The concentration of *Penicillium* in the crawl space was highest in building 7. However, the concentration indoors was even lower than in building 3. As in building 6, also in building 7 the crawl space has mechanical exhaust ventilation and the building has mechanical supply and exhaust ventilation.

Table 3 The concentration of fungal spores in measured buildings in the winter and summer. *I* denotes indoor air, *CS* crawl space air and *O* outdoor air.

WINTER	**Building 7**			**Building 2a and b**				**Building 6a and b**				**Building 4**			**Building 8**			**Building 3**		
Species	January 25.-27. 1999			January 25.-27. 1999				January 25.-27. 1999				February 9.-11., 2000			February 9.-11., 2000			February 9.-11., 2000		
MEA	**I**	**CS**	**O**	**I**	**CS a**	**CS b**	**O**	**I**	**CS a**	**CS b**	**O**	**I**	**CS**	**O**	**I**	**CS**	**O**	**I**	**CS**	**O**
Penicillium	370	570		140	6000	3300		430	6400	2400		6	2500		110	5100		53	1200	
Aspergillus										20										
Cladosporium	7				10	830		7	44	10		5	31			8		5	450	
Acremonium	256	2800		140	810	450			260	120			3			3				
Rhizopus				7									5							
Mucor													3		3					
Yeasts				4	3					37		6						10	22	
Steriles				4		7			6			34	6		22	8		12	13	
Total concentration	**630**	**3400**		**300**	**6800**	**4600**		**440**	**6700**	**2600**		**51**	**2548**		**130**	**5120**		**70**	**1700**	

SUMMER	**Building 7**			**Building 2a and b**				**Building 3**			**Building 6a and b**				**Building 4**			**Building 5**			**Building 1**		
Species	May, 17.-19. 1999			May, 17.-19. 1999				May, 17.-19. 1999			May, 17.-19. 1999				May 23.-25. 2000			May 23.-25. 2000			May 23.-25. 2000		
MEA	**I**	**CS**	**O**	**I**	**CS a**	**CS b**	**O**	**I**	**CS**	**O**	**I**	**CS a**	**CS b**	**O**	**I**	**CS**	**O**	**I**	**CS**	**O**	**I**	**CS**	**O**
Penicillium	56	12900	32	12	1200	3500	7	106	2100	29	5	4200	1500	16	7	3100	4	9	60	18	76	2800	18
Cladosporium	23	47		20	18	21	29	18	300	100	8	91	48	6	87	86	220	150	170	240	70	91	72
Acremonium				2	930	76		26	2	26	16				42	130	14	4		7	2	39	7
Alternaria/Ulocladium															13						4		
Aspergillus															15	270			48		130	2	
Aureobasidium	3	2	3		2				1						9		4	2	0		5	4	
Botrytis																						16	
Exophiala															4	4		4			4		
Gliocladium																	4						
Monilia				5																			
Oidiodentron															7				14				
Paecilomyces																7		11	4		10		
Phialophora																5							
Sphaeropsidales				2												64	22		9	4		2	
Yeasts	2			23	21	3	3	7	3	19	8			19	4	16	14	20	16	16	18	21	29
Steriles	55	5	110	44	11		98	12	14	26	12			99	250	52	120	40	78	43	110	66	1000
Unknown															4			11		4	4		
Total concentration	**140**	**13000**	**150**	**110**	**2200**	**3600**	**140**	**170**	**2400**	**200**	**49**	**4300**	**1600**	**140**	**440**	**3734**	**402**	**251**	**399**	**332**	**433**	**3041**	**1126**

Indoor/Outdoor –ratio and Indoor/Crawl space –ratio of fungal spores

The indoor/outdoor –ratio in the summer was between 0.4 and 0.8 in most of the buildings, Figure 3. The outdoor concentrations were not measured in the winter as the ground soil was covered with snow. The indoor/crawl space –ratio was of the same magnitude or higher in the winter than in the summer. The only exception in the summer is building 5, in which the concentration of fungal spores in the crawl space was very low and therefore the indoor/crawl space –ratio was high. As the concentrations in the crawl space varied a lot depending on the crawl space, the concentrations of the same crawl space measured in the winter and in the summer should be compared. In this study, the indoor/outdoor –ratio did not differ much between the buildings with mechanical exhaust ventilation and mechanical supply and exhaust ventilation, Figure 3.

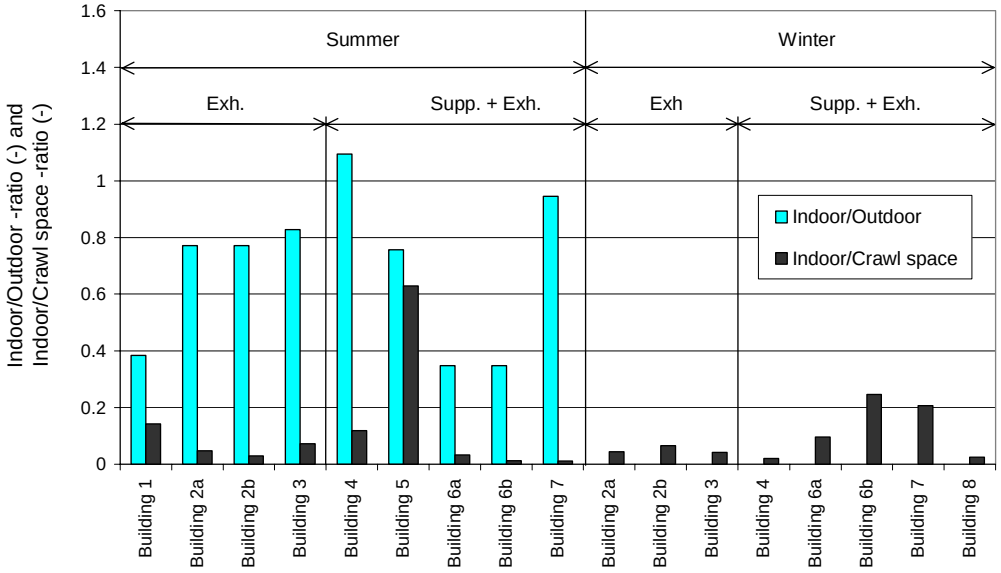

Figure 3 Indoor/Outdooor –ratio (grey bars) and Indoor/Crawl space –ratio (black bars) in the summer and winter in the studied buildings. Exh. denotes Mechanical Exhaust ventilation in the building, Supp.+Exh. denotes mechanical supply and exhaust ventilation in the building.

Correlation between indoor and crawl space microbes

The correlation between indoor and crawl space concentration of microbes was tested with Pearson correlation coefficient. The concentrations of *Penicillium* indoors and in the crawl space did not correlate (Pearson coefficient 0.11) although it was the dominant species both indoors and in the crawl space. The concentration of *Acremonium* in the indoor air and crawl space air had a relationship (Pearson coefficient 0.89), indicating presence of high counts in crawl spaces reflecting as high counts in indoor air, Figure 4.

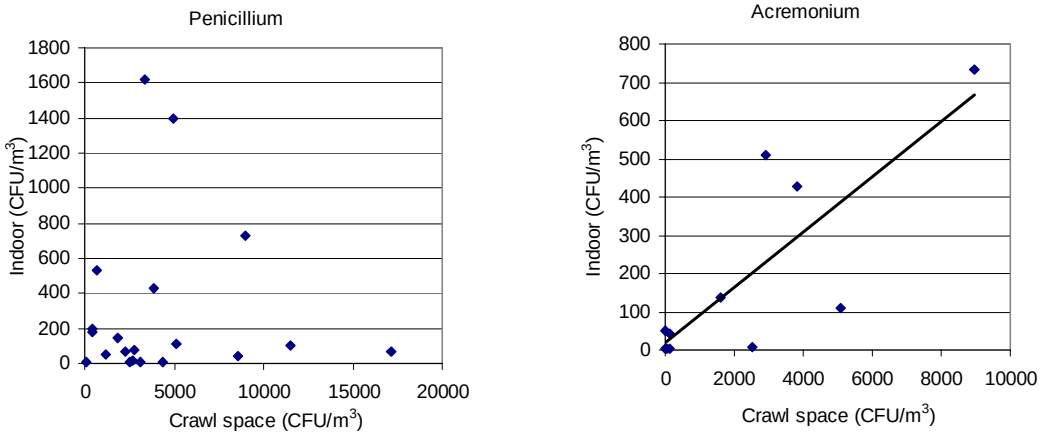

Figure 4 Correlation between indoor and crawl space fungal spores.

The total concentration of fungal spores between indoor air and crawl space air did not correlate. However, from Figure 5 it can be seen that the elevated levels of fungal spores in the crawl space can be seen as elevated levels of fungal spores in indoor air.

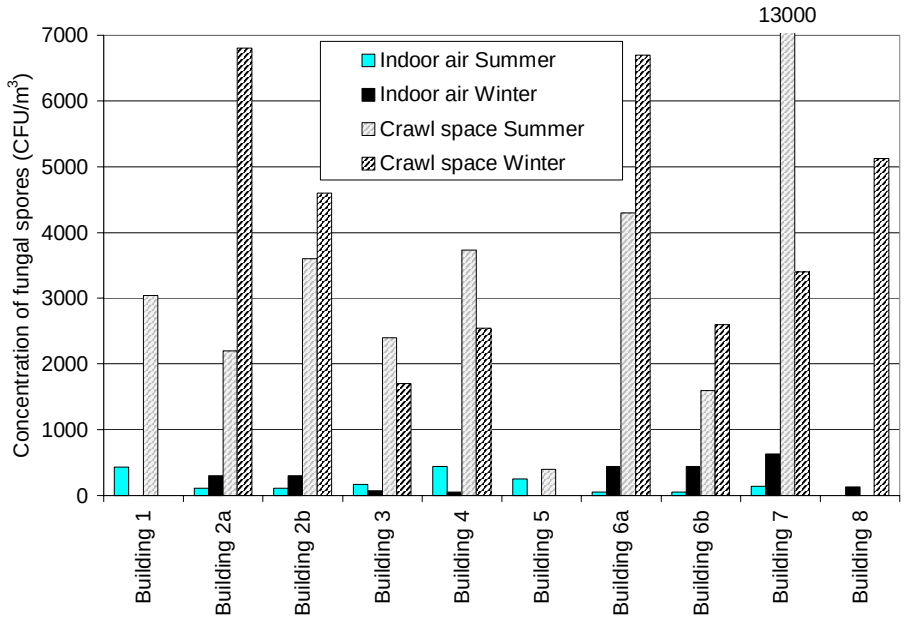

Figure 5 The total concentration of fungal spores in the crawl space and indoors.

The size distribution of fungal spores

The size of a particle has an important role in respect of penetration of a crack in a building envelope, thus, it is important to study the size distribution of fungal spores to estimate their penetration indoors. The size distribution varied depending on microbial species. The size distribution of *Penicillium* in the crawl space and indoor air were similar in shape, and most microbes were impacted in a stage whose average aerodynamic diameter was 1.4 µm, Figure 6. Outdoors the highest *Penicillium* counts were received for the smallest sizes. The size distribution of *Cladosporium* were equal in shape in indoor air, in crawl space and in outdoor air, Figure 6. Most of the fungal spores of *Cladosporium* were impacted in a stage whose average aerodynamic diameter was 2.6 µm. Compared to *Penicillium* the size distribution of *Cladosporium* is clearly skewed towards bigger particles, indicating that *Cladosporium* spores are bigger and uniform in their shape.

Size distributions of *Acremonium* having its peak at 1.4 µm were similar in all the measured environments. The fungus is not a typical genus indoors, which indicates a presence of leakage from the crawl space to indoors, Figure 6. Yeasts have equal size distributions in the crawl space and outdoors, and the most of the yeasts were impacted on the lowest stages. Yeast indoors were clearly bigger in size, most microbes were impacted in a stage whose average aerodynamic diameter was 4.2 µm, Figure 6. Yeasts may have sources indoors, which seem to produce yeast particles in bigger size fractions. Also, the species of yeast might be different in indoors and in the crawl space. There were only a few non-sporulating microbes, and their size distributions differed in the different environments. This may indicate different species growing on the plates. The data presented are based on the counts and identification of the fungi growing on the M2 agar.

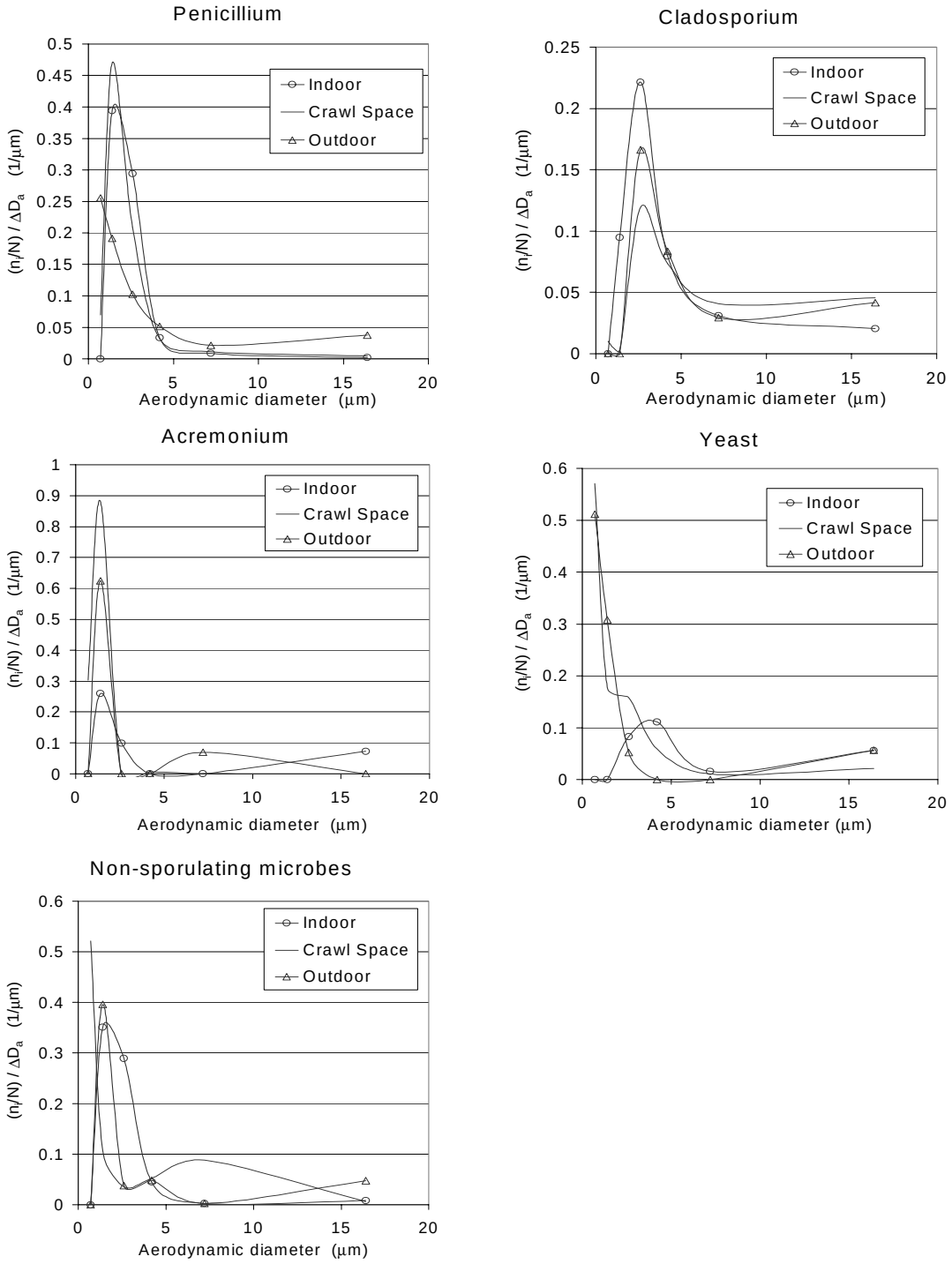

Figure 6 The count size distribution of fungal spores indoors, outdoors and in the crawl space of different microbes. The explanations of abbreviations in the figure: n_i number of spores in size interval *I*, *N* total number of spores, ΔD_A width of a size interval.

There are many factors affecting the size of fungal spores such as age, dehydration, agglomeration and relative humidity of surrounding air. In an earlier study (Reponen 1994) it was found out that the most common fungal spores, such as *Penicillium*, *Cladosporium*, *Aspergillus* and yeasts, have their maximum concentrations in the size range 2.1 – 3.3 μm. In this study, the maximum counts were observed in smaller fungal spores, between 1.4 – 2.6 μm, indicating that the fungal spores are mainly detected as single spores and not as aggregates. This size range is interesting as the alveolar deposition of particles above 0.5 μm has a maximum at about 3 μm.

Therefore, even small changes in particle size around this maximum value effect on the deposition pattern of particles (Reponen 1994).

DISCUSSION

Mechanical exhaust ventilation in an apartment may cause high under-pressure inside the building if there are not enough supply air valves. A pressure difference between crawl space and indoors up to 17 Pa was measured. The pressure difference causes air flow through small cracks inside the building. Often the base floor has some leakages and the air and its contaminants from the crawl space flow to the apartment causing potential health risks. The pressure difference caused by mechanical ventilation might be so high that even a mechanical exhaust ventilation in the crawl space cannot compensate the pressure difference (Kurnitski 2000).

As many studies have proved, the concentration of microbes outdoors is clearly higher in summer than in winter. However, there is only a very limited number of reports on concentrations in the crawl spaces. In this study, the concentration of fungal spores in the crawl space was lower in the winter than in the summer. This may indicate that the conditions for the microbes in the surfaces of the crawl space are more favourable for fungal growth in spring and summer when the weather outdoor is warm. All the measured crawl spaces were outdoor air ventilated. The outdoor air was not filtered and, thus, the spores in the outdoor air may also be driven into the crawl space. It is well known that in summer the crawl space remains cold. The outdoor air is usually warmer and has a higher moisture content, which is transported via ventilation to the crawl space. The extra moisture condensates to the surfaces in the crawl space giving better conditions for microbes in the surfaces.

The concentrations of viable fungal spores in the crawl spaces were a few thousand cfu/m^3. There are no guidelines or sufficient reference data in Finland for the concentration of fungal spores in crawl spaces. The high concentrations of fungal spores in the air under the floor may exposure occupants to fungal spores or fungal metabolites if there are cracks or holes between the spaces.

In subartic climate, in summer the concentration of fungal spores indoors is usually smaller than the concentration outdoors, whereas in winter the indoor/outdoor –ratio often is over 1 in the apartments as well as in the offices (Pasanen et. al. 1990). Generally outdoor air is the main source of fungal spores and the seasonal variation is wide; three to four order of magnitude in subartic climate (Finland). In this study the indoor/outdoor –ratio in the summer was between 0.4 and 0.8 in most buildings which is of the same range as measured in earlier studies e.g. (Reponen et. al.1989).

The indoor/outdoor –ratios in this study did not differ between the buildings with mechanical exhaust ventilation and mechanical supply and exhaust ventilation. However, according to an earlier study (Reponen et. al. 1989) indoor/outdoor –ratio had been higher in buildings with mechanical exhaust ventilation than in buildings with mechanical supply and exhaust ventilation. A reason for this might be that in this study all the measured buildings with mechanical supply and exhaust ventilation were primary schools or day-care centres, and the measurements were done during the working day and the influence of outdoor air to indoor air concentrations could not be avoided. Also the clothes of the children might be a potential carrier of spores (Pasanen A-L 1992). The measurements of the fungal spores in outdoors, indoors and in crawl space were not done simultaneously, but first indoors and outdoors and then in the crawl space. This may also cause some uncertainty to the results.

The concentrations of *Penicillium* indoors and in the crawl space did not correlate (Pearson coefficient 0.11). *Penicillium* is a very typical microbe indoors and outdoors, and there are several sources of *Penicillium* indoors, which makes the correlation complicated. Also previous results show that *Aspergillus* and *Penicillium* spores are released into air more easily than *Cladosporium* spores. This is one reason why *Penicillium* spores are common in indoor air (Pasanen et. al. 1991). Compared to *Penicillium*, the size distribution of *Cladosporium* is clearly skewed towards bigger particles, indicating that *Cladosporium* spores are bigger and uniform in their shape as reported in literature (e.g. Reponen 1994). On the other hand, previous study have shown that the size of the spores increases when humidity increases (Pasanen A.-L. et. al. 1991).

The concentration of *Acremonium* indoors and in crawl space had a relationship (Pearson coefficient 0.89), indicating presence of high counts in crawl spaces to be high also in indoor air. As *Acremonium* has not typical sources indoors, it most probably originates from the contaminated crawl space via leakage through the base floor.

Transport of inert particles through cracks has been studied in many studies; Vette et al. (2001) report penetration factors 0.5-0.8 for particles in a size range of 0.5-2.5 μm. Mosley et al. (2001) have found that at a pressure of 5 Pa 40% of 2 μm particles and <1% of 5 μm particles penetrate through horizontal slits of height 0.508 mm. In a study (Liu and Nazaroff 2001) particles of 0.1-1.0 μm are predicted to have the highest penetration efficiency, nearly unity for crack heights of 0.25 mm or larger at pressure difference of ≥4 Pa. These results are important and support findings in this study; most of the fungal spores were impacted at the stage corresponding mean aerodynamic diameter of 1.4 μm being very suitable for penetration through a base floor.

CONCLUSION

In mechanical exhaust ventilation, if the base floor has some leaks, pressure measurements show that air is flowing through leaks in the base floor to the apartment. The change of ventilation rate in the dwelling reflects directly to that in the crawl space. In some worst cases, all the extract air from the crawl space flows through the base floor to the apartment.

A comparison of the fungal spore concentrations indoors, in crawl spaces and outdoors usually results in the highest concentration in the crawl spaces. The size distribution of spores of fungal species was mainly similar in the shape in the crawl space and indoors in the studied buildings. The shape of the size distribution varied between fungal species.

The concentration of fungal spores in the crawl space was highest in the summer indicating that the conditions for the microbes in the surfaces of the crawl space are better in spring and summer when the weather outdoor is warm. The outdoor air is warmer and has a higher moisture content which is transported via ventilation to the crawl space.

The indoor/crawl space –ratio was of the same magnitude or higher in the winter than in the summer. As the concentrations in the crawl space varied a lot depending on the crawl space, the concentrations of the same crawl space measured in the winter and in the summer should be compared. The concentration of fungal spores in the crawl space was lower in the winter than in summer.

Correlation between the fungal spores in the crawl space and indoors depended on the microbial species. The concentration of the most abundant species, *Penicillium*, did not correlate between crawl space and indoors. However, species like *Acremonium* do not have a natural source indoors, and, thus, the concentration of *Acremonium* correlated to the indoor concentration indicates air leakage from crawl space to indoor air.

ACKNOWLEDGEMENTS

The National Technology Agency and Ministry of The Environment in Finland are gratefully acknowledged for their financial support to this study.

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