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Moisture conditions in highly insulated outdoor ventilated crawl spaces in cold climates

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Abstract

This study simulated the effects of thermal insulations on the ground, in the foundations and in the base floor in order to achieve as dry conditions as possible in outdoor air ventilated crawl spaces in a cold climate. The objectives of the study were to find out how the thermal capacity and resistance and the placement of insulation layers affect relative humidity (RH) in the crawl space. The possibilities to reduce the air change rate to very low levels corresponding to natural ventilation, and to control RH by minimising the thermal capacity present in the crawl space were simulated. Mold growth analyses were used as performance criteria to predict the acceptability of the hygrothermal conditions in the studied crawl spaces. Most of the simulations were carried out with a low U-value for the base floor which normally results in a low temperature and high RH in the crawl space during the summer. The results show that there are two alternative ways to use ground covers in combination with air change in order to achieve acceptable conditions in crawl spaces. First, a traditional thin layer of lightweight expanded clay aggregate (LWA) or expanded polystyrene (EPS) may be used, but in this case, the air change rate has to be increased in the summer at least to 1 ach. An alternative solution is to use thicker ground covers, such as at least 30 cm lightweight aggregate or 10 cm polystyrene, and a low air change rate of approximately 0.5 ach all the year round. This solution provides even lower RH values and mold growth index values because the thick ground covers effectively insulate the massive ground whereby the crawl space warms up quickly when the warm season starts.

Keywords: Crawl space; Moisture; Ground covers; Dynamic simulation

1. Introduction

In recent years, a significant amount of crawl spaces have been repaired in Finland. Mold and moisture problems, usually noticed by the smell of mold in apartments, have been typical. It seems that changes in building tradition, particularly highly insulated base floors and crawl space floor levels lower than the surrounding ground level, have made crawl spaces more problematic.

Moisture problems have brought on a need for the better control of the moisture conditions in crawl spaces. It is well known that in an outdoor ventilated crawl space, especially in the summer, the moisture conditions become problematic because the crawl space remains cold and outdoor air is usually warmer and has a higher moisture content than the air in the crawl space. Thus, outdoor air can transport net moisture into the crawl space. This can be prevented by reducing the time lag between the time it takes for the temperatures of outdoor air and the crawl space to become equal. The time lag is caused by the high heat capacity of the ground soil and foundations. In principle, the time lag can be decreased by increasing the air change rate or decreasing the heat capacity.

The objective of this study is to find out how moisture conditions in a crawl space can be controlled by means of thermal and moisture insulation. Especially, the study focuses on whether the high air change rates, which are normally needed to warm up the crawl space in the summer, can be compensated with a thicker thermal insulation, i.e. by reducing the time lag, which may possibly provide a similar effect as a higher air change rate.

The most important factors causing mold growth in a crawl space are relative humidity (RH), temperature, nutrition and pH. In practice, RH is the most significant factor causing mold growth in the crawl spaces. The limit value for RH in crawl spaces is usually considered to be from 75 to 80% [1–5]. RH and temperature are strongly linked together. The thermal mass of the structures and ground soil affects the temperature behaviour of the crawl space. When the ground is not insulated, the crawl space remains cold during the summer due to the time lag caused by the thermal mass

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of the massive ground. An earlier study [1] recommends the use of a thermal insulation on the ground surface. In addition, the ground soil is a moisture source, which makes it important to use a ground cover to reduce moisture evaporation by means of ground cover.

In principle, RH and temperature in a crawl space can be very close to outdoor humidity and temperature if the air change rate is very high and all thermal mass present in the crawl space is highly insulated. The question is: how should the insulation be placed and what air change rates are needed to achieve acceptable conditions in respect of mold growth? These aspects were studied by parametric simulations which were carried out for a relatively cold crawl space. The crawl space was denominated cold as the heat losses through the base floor were small (base floor U-value 0.2 W/m^2 K), and there were no other heat sources in the crawl space such as district heating pipes. A relatively warm crawl space was left out of consideration due to earlier studies [6] which show that the conditions are acceptable with all ground covers. In this study the heat capacity of the base floor and foundations were varied. Various air change rates and ground covers were studied. The possibility to reduce the air change rate to a minimum when using a highly insulating ground cover was simulated. Mold growth analyses were used as performance criteria to predict the acceptability of the hygrothermal conditions in the studied crawl spaces.

2. Methods

2.1. The model

The simulation was carried out in an IDA simulation environment, where an RC network model of a crawl space was used [7]. IDA is a modular simulation environment which consists of an NMF translator, solver and modeller. The solver and the modules are separate, which makes it possible to change the mathematical formula of any component without changing the model description file. Via the translator, the modules can be used in several modular simulation environments. The used computer language for the models is neutral model format (NMF) which serves as a readable document of the code, as well [8,9].

The heat and moisture transfer equations are the same as reported in [10,6]. Heat transfer is modelled in structures and the ground (conduction, convection, and radiation only between ground and base floor). The model includes also the heat and moisture flows carried by ventilation. The conduction in the ground soil is modelled by means of semicircular heat flow patterns ‘‘Ground 1’’, ‘‘Ground 2’’, and ‘‘Wall 1’’, as shown in Fig. 1. The floor area of the crawl space is divided into two parts: the first meter along the external walls (Ground 1) and the remainder (Ground 2; Fig. 1). The heat flow along circular arcs that is known from heat conduction theory (reported for example in heat loss calculation methods by Vuorelainen [11] and Hagentoft [12]) is here applied for a dynamic simulation of heat transfer. The floor area is divided into two parts: into the first meter along the external walls and the remainder. Thus, the ground surface is subjected to two temperatures, and the external walls and base floor to one single temperature. The outdoor side of the ‘‘Ground 1’’ and ‘‘Ground 2’’ is connected to the climate data which includes solar radiation, temperature, wind velocity and its direction, and absolute humidity. When the model was being worked out, three heat flow patterns in the ground were tested, but this provided almost the same results as the traditional division into two flow patterns. The modelling of the inner floor area as a 10 m thick layer of soil having a constant annual average temperature at its bottom was tested as well. The results were the

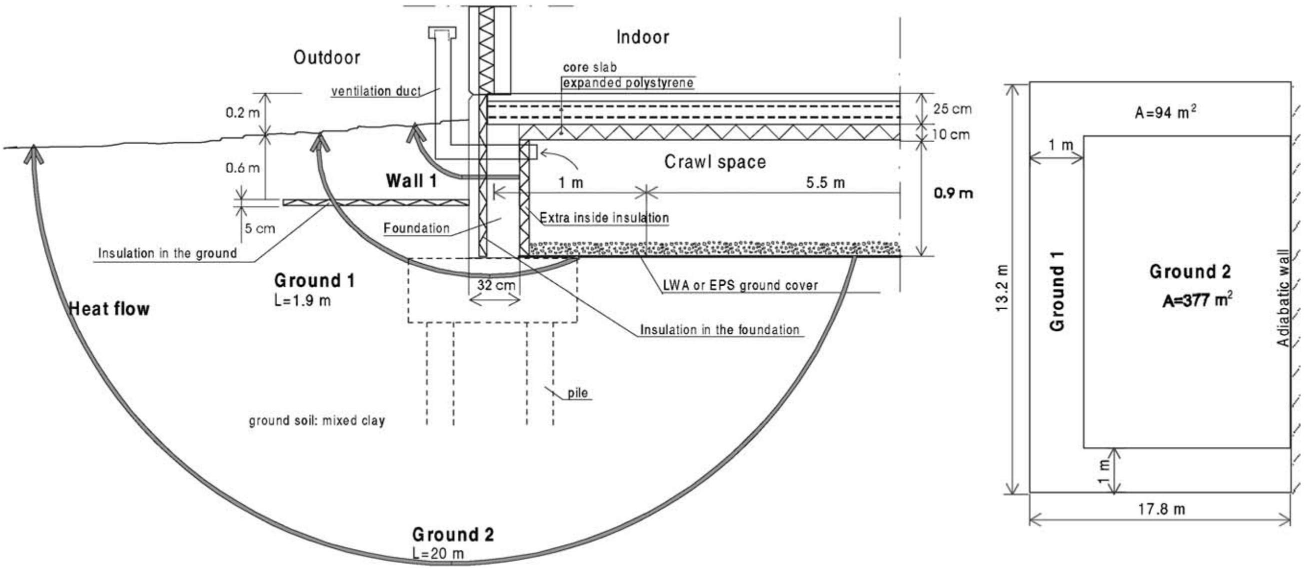

Fig. 1. A section with heat flow patterns and a plan of the modelled crawl space.

same as with semicircular "Ground 2". The freezing of the ground soil surface outside the crawl space was not considered. Facilities for calculating phase change in the ground soil were not developed as the effect of freezing is not significant due to thin frozen layer on the ground surface. The ground surface in the modelled building was either covered by a PVC sheet, lightweight expanded clay aggregate (LWA) or EPS.

In the following simulation cases for the indoor conditions, a constant surface temperature of 19 °C of the floor was considered. Moisture flow inside the base floor was calculated up to the upper surface of the floor, where as a boundary condition moisture flow was assumed to be zero, which corresponds to vapour tight plastic carpet.

2.2. Apartment building

Simulations to study the effects of various insulations in the foundations and base floor were carried out in the apartment building. According to Finnish building standards, the base floor *U*-value should be 0.22 $W/m^2 K$, however, in old buildings the *U*-value is usually around 0.4 $W/m^2 K$. In the simulations the *U*-value of base floor was either 0.2 or 0.4 $W/m^2 K$. With the smaller *U*-value, a case with insulation on the warm side of the base floor (on the slab) was simulated as well. First, the simulations were carried out when the ground was covered with a PVC sheet (no moisture evaporation from the ground) and secondly when the ground was covered with a 15 cm LWA insulation. In all simulation cases the ground was insulated against frost (Fig. 1). The foundation was insulated in two ways: (1) a 5 cm insulation in the foundation, (2) a 5 cm insulation in the foundation with an extra 10 cm insulation on the crawl space side of the foundation. The effect of the crawl space area compared to the area of foundations was studied with floor areas of 470 and 100 m^2. The air change rate in the simulations was 1 ach.

2.3. Wooden building

The building with a wooden base floor (Fig. 2) was chosen for more detailed study due to its higher sensitivity for mold growth. As reported earlier [6], a cold crawl space needs a ground cover which insulates the heat capacity of the ground and, on the other hand, decreases the moisture flow from the ground. In the wooden building, the aim of the simulations was to control RH using various kinds ground covers. The ground covers used were LWA and EPS. The ground soil was mixed clay. Material properties used in the calculations are shown in Table 1. The study focused especially on whether the high air change rates, which are needed to warm up the crawl space in the summer, can be compensated with thicker thermal insulation.

2.4. Validation of the model

The used model calculated the temperature and moisture behaviour of the measured crawl space with sufficient accuracy (Fig. 3). A more detailed description of the model is given in [10,13,14], and the validation of the model is reported in [6]. For the validation, the temperature and RH in the crawl space were measured in three different heights in the air and in three different depths in the ground cover. As the crawl space had natural ventilation an average air change rate, based on pressure difference measurements across each ventilation pipe, of a 3 months measurement period was used. The measured outdoor temperature and RH were used as boundary conditions for the model. As the weather data used significantly affects the climate in the crawl space the weather data of a typical year has to be used. In [6], the data

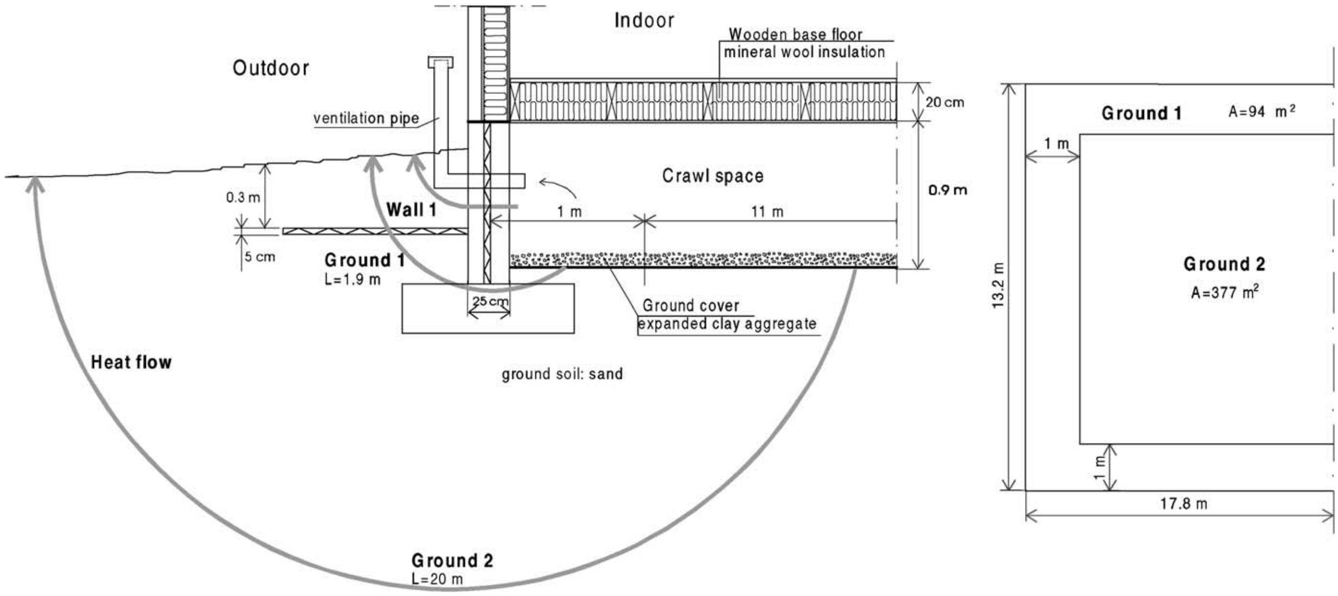

Fig. 2. A section and plan of the simulated wooden building.

Table 1
Material properties of ground covers and ground soil used in the calculations

	Ground soil (mixed clay)	EPS	LWA
Thermal conductivity (W/m K)	1.6	0.04	0.12
Specific heat capacity (J/kg K)	1800	900	950
Volume weight (kg/m^3)	1600	20	250
Moisture permeability (m^2/s)		1.0E−6	1.7E−5
Sorption isotherm given by (0; 0), first and second point			
First point (w_1 (kg/m^3); RH$_1$ (%))	–	(0.2; 85)	(1.0; 94)
Second point (w_2 (kg/m^3); RH$_2$ (100%))	–	0.6	2.0

of 1998 (Helsinki, Finland) was chosen as the weather of this year was considered to be a typical year in Finland. In this study, all the results are calculated by using weather data of 1998. The material properties shown in Table 1 were used for ground covers, whereas for foundations and other materials the properties were the same as used in validation in [6].

2.5. *Prediction of mold growth*

In order to predict mold growth, the equations for wood (pine and birch) given by Viitanen were used. Predictions based on both stable conditions [15], and for dynamic conditions [16] were carried out. The equation for stable conditions gives the time needed to start mold growth in wood [15]:

$$t_m = \exp(-0.68 \ln T - 13.9 \ln \mathrm{RH} + 0.14W - 0.33\mathrm{SQ} + 66.02) \quad (1)$$

where t_m is the time for mold growth to reach the microscopic stage (weeks), T the temperature (0.1–40 °C), RH the relative humidity (%), W the wood species (pine $= 0$, spruce $= 1$) and SQ is the factor describing the nutrients on the wooden surface (a resawed surface after drying $= 0$, a kiln-dried surface $= 1$). The higher the RH, the shorter the time needed to start mold growth. In the worst case (RH $\cong 95\%$, $T = 20$ °C), it takes only 2 weeks for mold growth to start in pine.

The criterion is that t_m must be shorter than the time of wetness (TOW), i.e. there is no risk of mold growth if TOW $\ll t_m$. TOW is defined here as the cumulative time period when RH is higher than 75%. This means that the counting of TOW starts when RH exceeds 75%. The periods when RH $< 75\%$ are not taken into account. The calculation ends when the duration of the dry period (RH $< 75\%$) is longer than 2 months—this is the time needed to reset the contamination. The temperature and RH used for the calculation of TOW are average values of 2 weeks period. This period was chosen since it is the shortest possible time needed for mold growth to start [15], and long enough to perform manual calculations of TOW. In Eq. (1), average

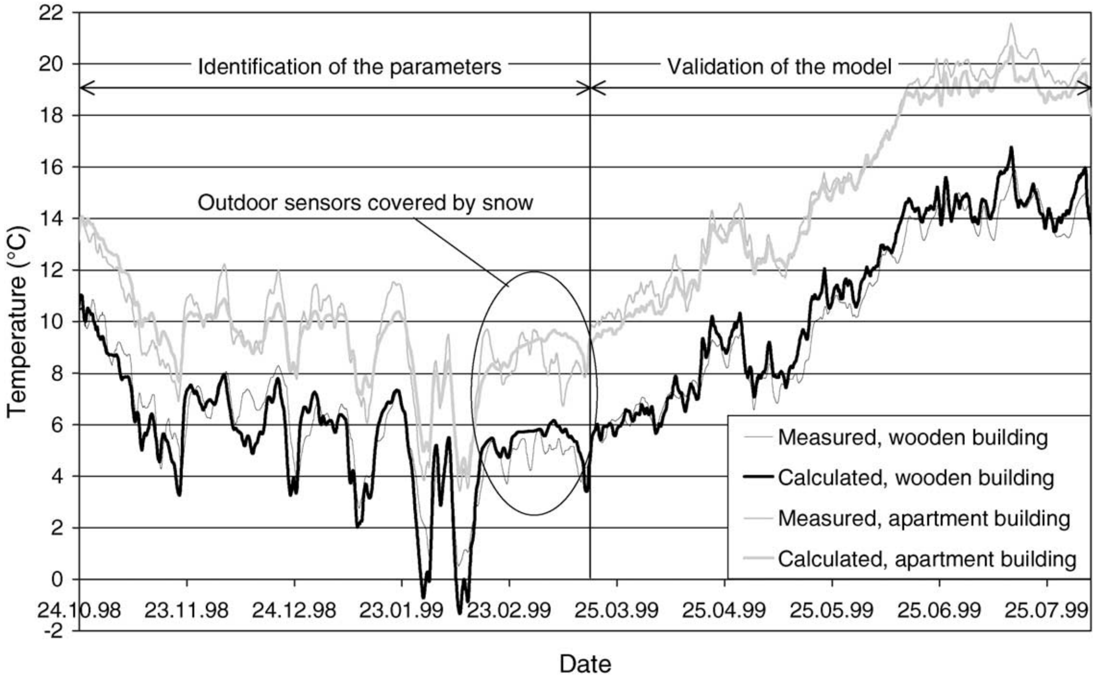

Fig. 3. Measured and calculated temperatures in the simulated crawl space [6].

values of temperature and RH of the cumulative TOW period are used. It is assumed that the wood is pine and the surface has not been sawed after drying ($W = 0$, $\mathrm{SQ} = 1$).

For varying temperature and humidity conditions, Viitanen interprets Eq. (1) as a differential equation [17]:

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \frac{1}{7\exp(-0.68\ln T - 13.9\ln \mathrm{RH} + 0.14W - 0.33\mathrm{SQ} + 66.02)} \tag{2}$$

where M is the mold growth index and t is the time calculated in days. The mold growth index illustrates the growth rate. The scale for M is: $M = 0$ no growth, $M = 1$ some growth is detected only with microscope, $M = 3$ some growth is detected visually and $M = 6$ very heavy and dense mold growth covers nearly 100% of the surface. When conditions become unfavourable, the mold growth will slow down and the index M will decrease. The delay of the mold growth when RH drops below the critical RH value is given by using the time (days) passed from the beginning of the dry period $t - t_1$:

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \begin{cases} -0.032, & \text{when} \quad t - t_1 \le 6\,\mathrm{h} \\ 0, & \text{when} \quad 6\,\mathrm{h} < t - t_1 \le 24\,\mathrm{h} \\ -0.016, & \text{when} \quad t - t_1 > 24\,\mathrm{h} \end{cases} \tag{3}$$

In [18], the critical value for RH is 80%, thus, Eq. (3) should be used when RH < 80%.

3. Results

3.1. Insulation of base floor and foundations

To find out how the heat resistance affects RH, the simulations for the crawl space of the apartment building were carried out with two base floor U-values (0.2 and 0.4 W/m^2 K). A base floor U-value of 0.2 W/m^2 K is achieved with for example with a 20 cm layer of mineral wool. The foundation beam was insulated in two different ways (Fig. 1). The crawl space ground was covered with a PVC sheet in the first simulations and with a 15 cm LWA cover in the rest of the simulations. When the 15 cm LWA cover was used, the effect of the crawl space area, which was either 470 or 100 m^2, was also calculated. The air change rate used in the calculations was 1.0 ach.

In the case of the PVC cover, the thermal resistance of the base floor significantly affects the crawl space temperature, which can be seen from the duration curve of the temperature (Fig. 4, left). If the base floor U-value is reduced by half ($U = 0.4 \rightarrow 0.2$ W/m^2 K), the temperature in the crawl space is on average 2 °C lower, and the RH nearly 10% higher (Fig. 4, right). RH and temperature reach their maximum values in the summer. When the crawl space ground is covered with a PVC sheet, there are only minute differences in temperatures and RH in the cases with different insulation of foundations and frost insulation in the ground. Both the insulation in the soil only, and the 5 cm EPS insulation inside the foundation beam and a 10 cm EPS insulation on the inner surface of the foundation beam gave almost the same results.

The thermal capacity of the ground soil seems to have such a dominant effect on the temperature that the extra insulation has only a very small effect on the temperature. In this case, the surface area of the foundation beam is also relatively small (87 m^2) compared to the base floor surface area (470 m^2).

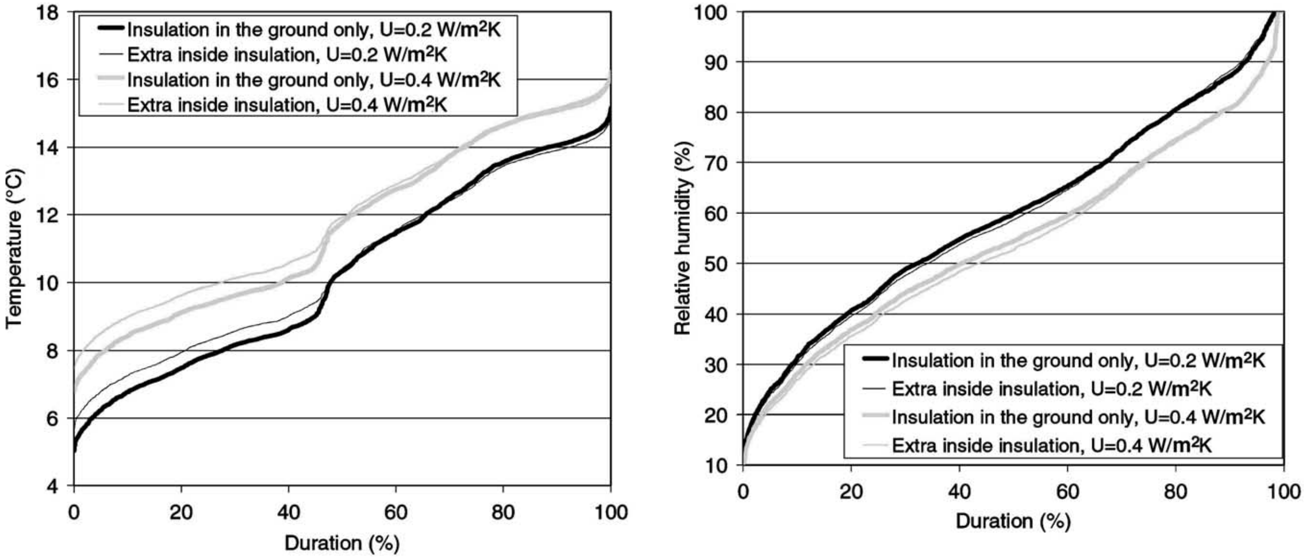

Fig. 4. The duration curve of the temperature (left) and RH (right) over 1 year in the crawl space when the insulation of the foundations is varied. The U-value of the base floor is either 0.2 or 0.4 W/m^2 K.

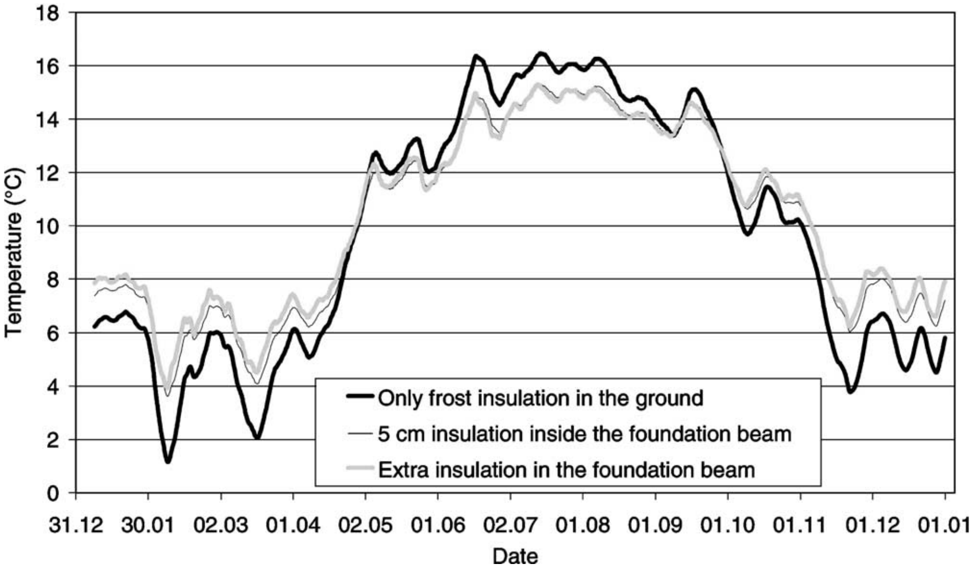

Fig. 5. Temperature (weekly moving average) in the crawl space with 15 cm LWA ground cover when the insulation of the foundations is varied. The *U*-value of the base floor is 0.2 W/m^2 K, and the air change rate is 1.0 ach.

Usually, the insulation of the base floor is installed on the crawl space side. When the insulation was placed on the warm side of the base floor (on the slab), the effect was negligible, not shown in Fig. 4. As Fig. 4 (right) shows, the RH values are high.

In order to reduce RH, an insulation layer of 15 cm LWA on the ground is used in the following simulations. The *U*-value of the base floor is in the following simulations 0.2 W/m^2 K. As the LWA layer is an effective insulation between the ground soil and the crawl space air, the temperature is higher in the summer and also the insulation of the foundations has some effect on crawl space behaviour. If there is insulation only in the ground, the crawl space is distinctly the coldest in the winter, and RH is at its highest (Figs. 5 and 6). However, in the summer, this case is distinctly the warmest (>1 °C), and RH in the crawl space is 5% lower than in the other cases. A 5 cm insulation inside the foundation beam seems to be enough to insulate the heat flow between the crawl space and outdoor, and therefore, the extra insulation inside the foundation does not affect conditions.

When the size of the crawl space is reduced from 470 to 100 m^2, the effect of the foundation is emphasised as the area of the foundation beam (98 m^2) is as big as the area of the base floor. The changes in temperature and RH are now much more extreme (Fig. 7). RH in the crawl space is

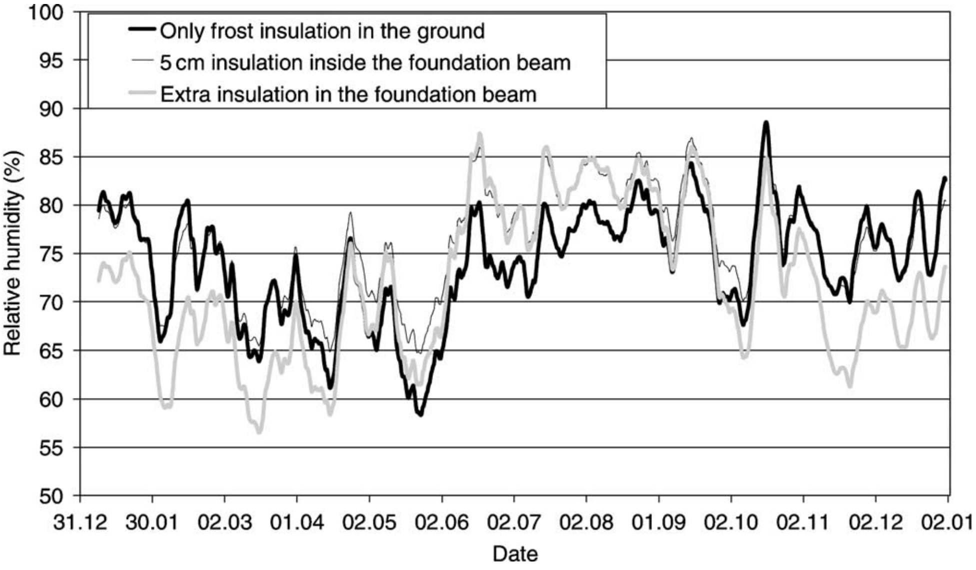

Fig. 6. RH (weekly moving average) for the case shown in Fig. 5.

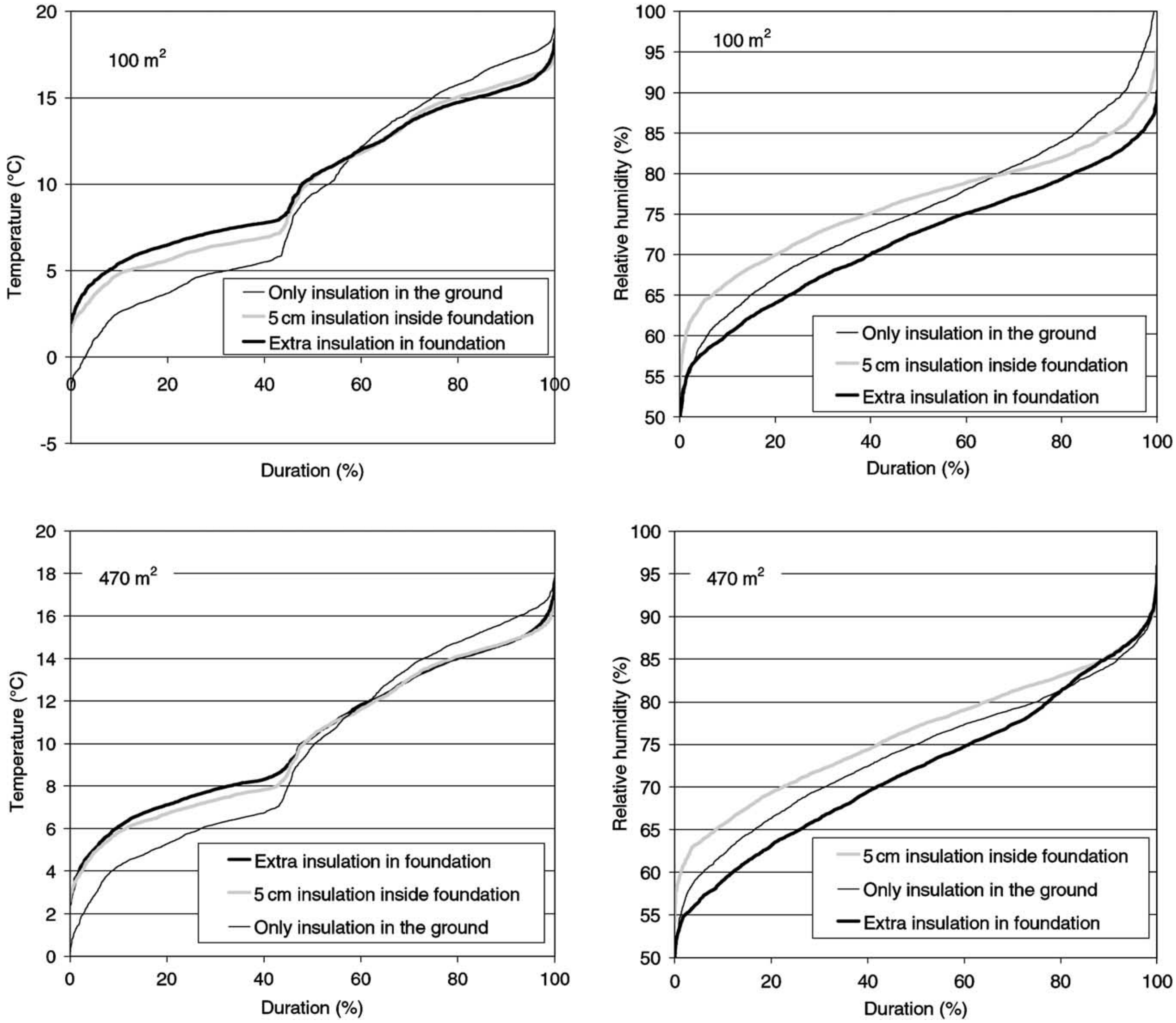

Fig. 7. The duration curve of the temperature (left) and RH (right) over 1 year in the crawl space when the area of the crawl space is 100 or 470 m^2, and the insulation of the foundations is varied. The U-value of the base floor is 0.2 W/m^2 K, the ground is covered with a 15 cm LWA layer and the air change rate is 1.0 ach.

approximately 5% lower in the summer, but in the winter, RH is higher. However, this cannot be seen in the duration curves because the difference between the seasons compensates the phenomenon. In the case of insulation in the ground only, the heat flow through the foundation beam warms the crawl space in the summer and RH is lower, compared to the case with insulation inside the foundation beam. In the summer, the results are almost the same in the cases with insulation inside the foundation and with an extra insulation in the foundation. In the winter, the case with extra insulation shows distinctly the lowest RH.

3.2. Thickness of ground covers

The building with the wooden base floor (Fig. 2, the U-value of the base floor 0.2 W/m^2 K) was chosen for more detailed study due to its higher sensitivity for mold growth. The aim was to determine the optimal combination of ground cover and air change. The simulations were carried out for four insulation layer thicknesses, both for EPS and LWA ground covers. The air change rate was varied from 0.5 to 5 ach. During the heating season (1st October–30th April) a low air change rate of 0.5 ach was used as recommended in an earlier study [6].

3.2.1. LWA ground cover

The simulations were carried out for LWA layer thicknesses of 10, 20 and 30 cm, and in addition, for an extra thick LWA layer of 50 cm. Compared to the EPS layer, LWA has a much higher thermal capacity, and a nearly three times higher thermal conductivity. The RH levels vary the most when the thinnest LWA cover (10 cm) is used. In this case,

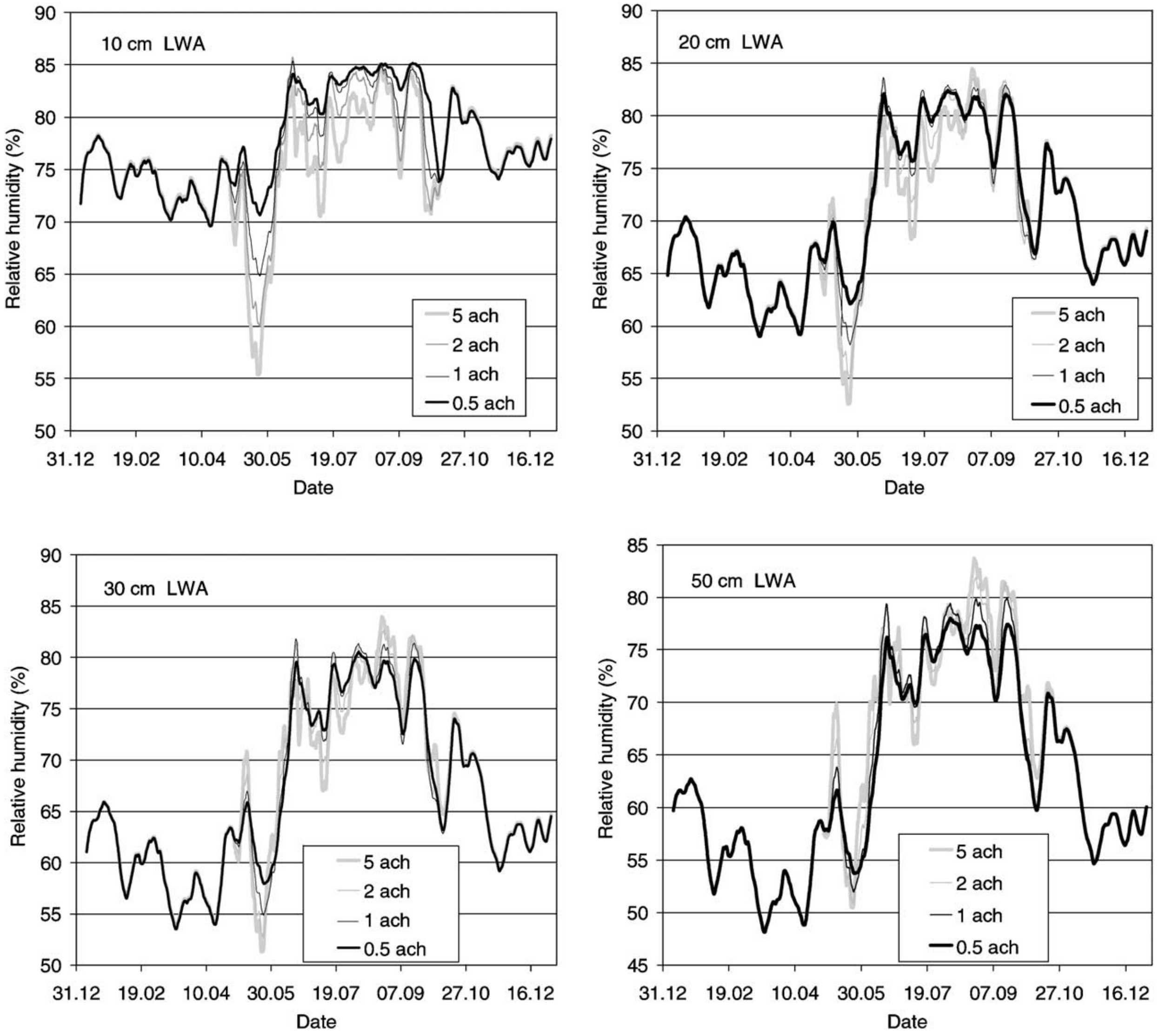

Fig. 8. RH in the crawl space at various air change rates, when 10, 20, 30 and 50 cm LWA ground covers were used.

the highest air change rate (5 ach) provides the driest conditions in the crawl space (Fig. 8). The effect of air change rate is much smaller with 20 cm LWA cover, which gives the driest conditions during most of the summer at 5 ach, but in August the differences are minute, and at some peaks 5 ach even gives the highest RH. With the 30 cm LWA layer, all air change rates give nearly the same RH in the summer. The behaviour is similar with the 50 cm LWA layer, but now 0.5 ach gives slightly lower RH than the other air change rates.

3.2.2. EPS ground cover

When a 5 cm EPS insulation layer was used on the ground surface, the RH level depends strongly on the air change rate in the summer (Fig. 9). The highest air change rate, 5 ach, usually gives the driest conditions in the crawl space. But in the late summer and early autumn the higher air change carries moist air into the crawl space and the RH level rises. The situation is nearly the same when the used layer thickness is 10 cm (Fig. 9). Thicker insulation layers (20–40 cm EPS) give significantly lower RH values at all air change rates in the summer. The lowest air change rate, 0.5 ach, gives the lowest RH. Especially in August and September, the higher air change rates give higher RH values. Thus, when the thermal mass of the ground is effectively insulated, a higher air change rate does not provide any benefit, as the crawl space has already warmed up in the spring.

Ground moisture evaporation having higher values in the winter than in the summer is shown in Fig. 10. In the summer, the moisture flow is during some periods from air to ground (negative values). The moisture flow is clearly higher with LWA than with EPS as LWA has higher moisture permeability. At higher air change rates the fluctuation of moisture flow increases. With a thinner ground cover the moisture flow is nearly all summer from air to ground.

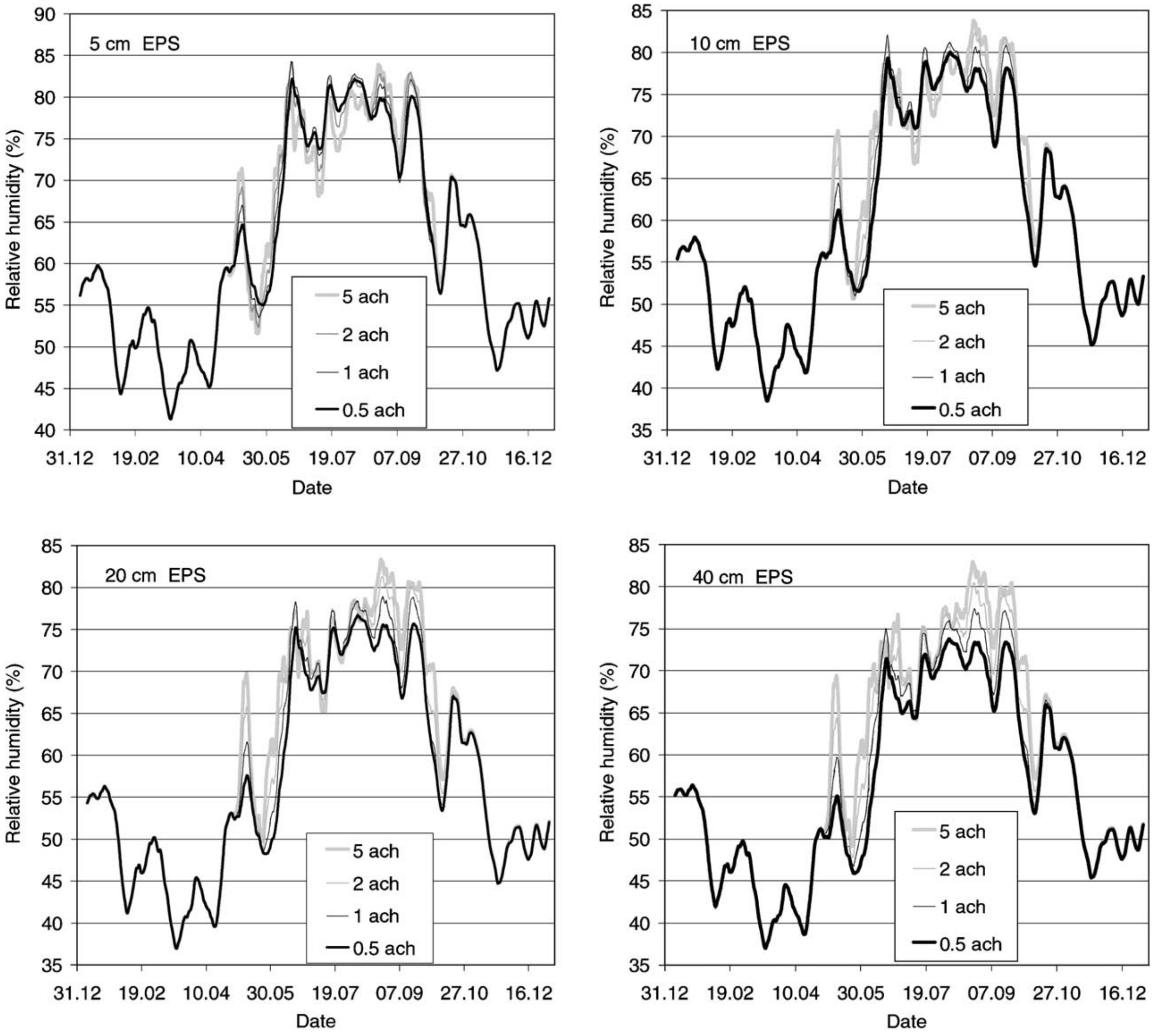

Fig. 9. RH in the crawl space at various air change rates, when 5, 10, 20 and 40 cm EPS ground covers were used.

3.3. Humidity conditions during the critical period

In cold climates, the critical months in respect of mold growth are usually July and August, when the temperature and absolute humidity of the outdoor air are the highest. In the following, the calculated cases are compared using the monthly average value of RH which is plotted as a function of the thermal resistance of the ground cover. The results for July are shown in Fig. 11 for LWA and in Fig. 12 for EPS. In July, the higher the thermal resistance of the ground cover, the less important is the value of the air change rate. When the thermal resistance of a LWA cover is ≥ 4 m^2 K/W, RH is 74% with an air change rate of 0.5 ach and 73% with an air change rate of 5 ach (Fig. 11). If the heat resistance is less than 1 m^2 K/W, the difference in RH is nearly 6% between the air change rates of 0.5–5 ach.

In August, the situation is not the same due to different temperature behaviour. As August is already slightly cooler than July, higher air change rates cool the crawl space down. At lower air change rates, the crawl space remains warmer and RH is also lower. Thus, the smallest air change rate (0.5 ach) gives the lowest RH (Fig. 11). Only in the case of the thinnest LWA RH is lower at high air change rates. When the thickness is increased, the behaviour is again the same—the lowest air change gives the lowest RH (Fig. 11, right).

The EPS ground cover shows basically the same performance as the LWA cover (Fig. 12). When comparing RH in July with the same thermal resistance and air change rate, RH is approximately 2% lower with an EPS cover. At low air change rates EPS shows better performance than LWA.

3.4. Prediction of mold growth

Mold growth was predicted with the equation for stable conditions (Eq. (1)) and with the equation for varying

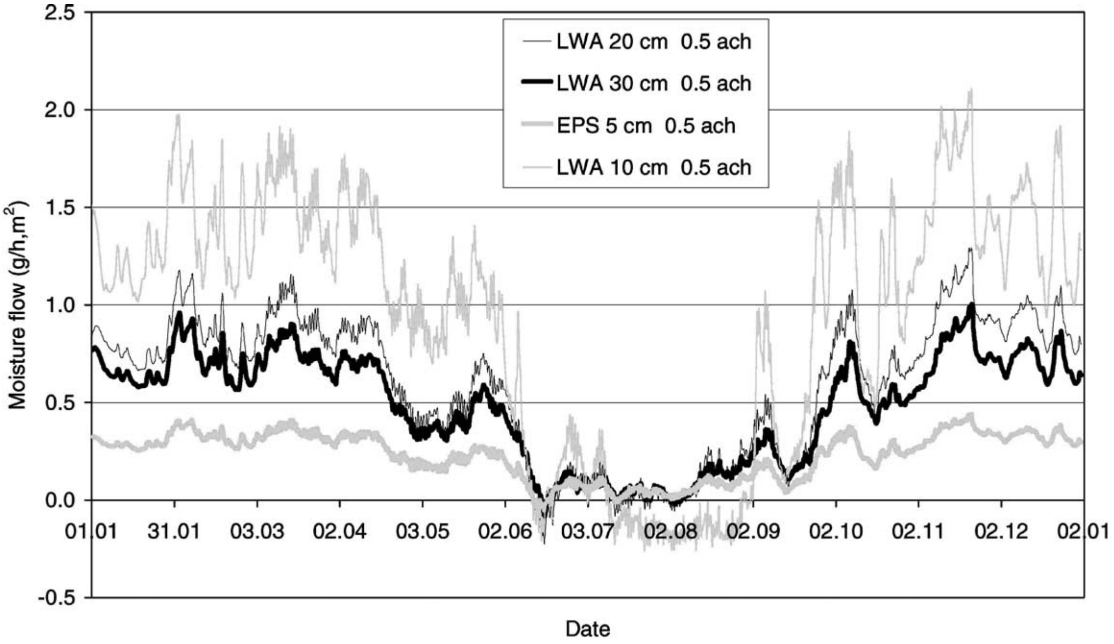

Fig. 10. Moisture flow from the ground. Positive values indicate evaporation and negative values moisture flow from air to ground.

conditions (Eqs. (2) and (3)). The calculations were performed for a critical period, starting from 1st June, when RH first reaches the 75% level, and lasting until 1st November. The TOW, which has to be shorter than the time needed to start mold growth t_m to show no risk of mold growth, is here defined as the time when RH is higher than 75%. When the values of 80 and 85% were used, the TOW was much shorter than t_m, and these results are not shown. Parameter t_m is calculated using the same 2 weeks periods as for TOW and using average temperature and RH values. If the TOW is clearly shorter than t_m, there is no risk of mold growth.

With an LWA cover there is an obvious risk of mold growth when the heat resistance is low (<1 m^2 K/W). However, when the heat resistance is higher than 2 m^2 K/W, there is no risk. In the case of EPS there is no risk even at the smallest heat resistance studied (1.8 m^2 W/K; Fig. 13).

The results of the dynamic predictions are similar to the previous results. The dynamic prediction was based on the calculation of the mold growth index M. In Eq. (3), 75% was chosen as the critical RH value since it is the lowest RH at which mold growth is possible in crawl space conditions [2,19]. The value of M equal to 1, which is the limit value of

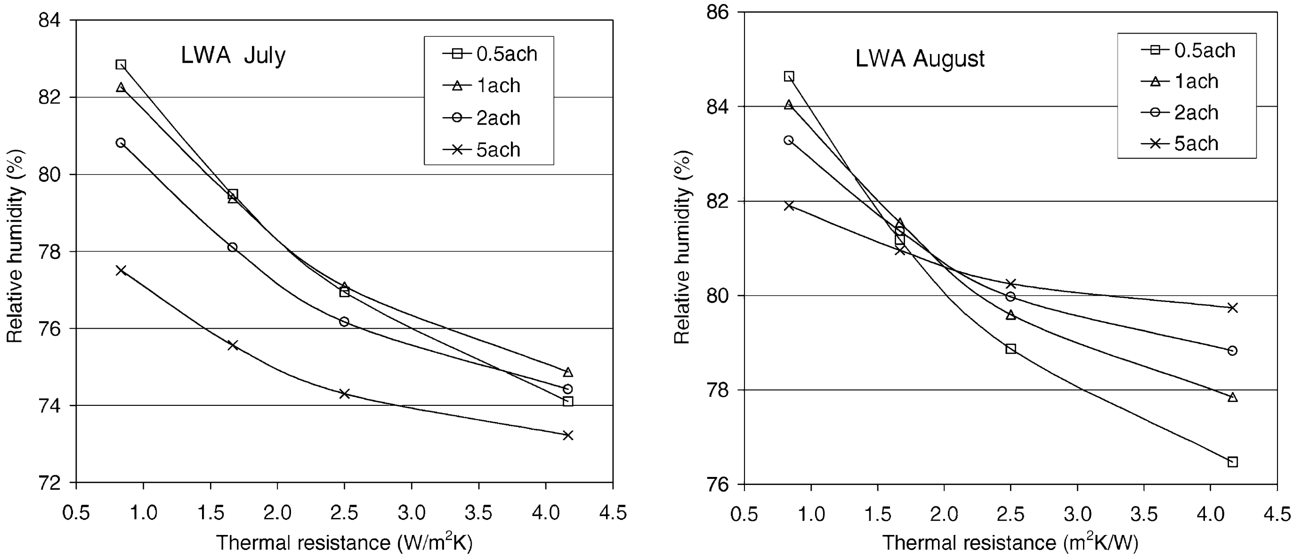

Fig. 11. Monthly average value of RH in the crawl space in July (left) and in August (right) as a function of the thermal resistance of the LWA ground cover and air change rate.

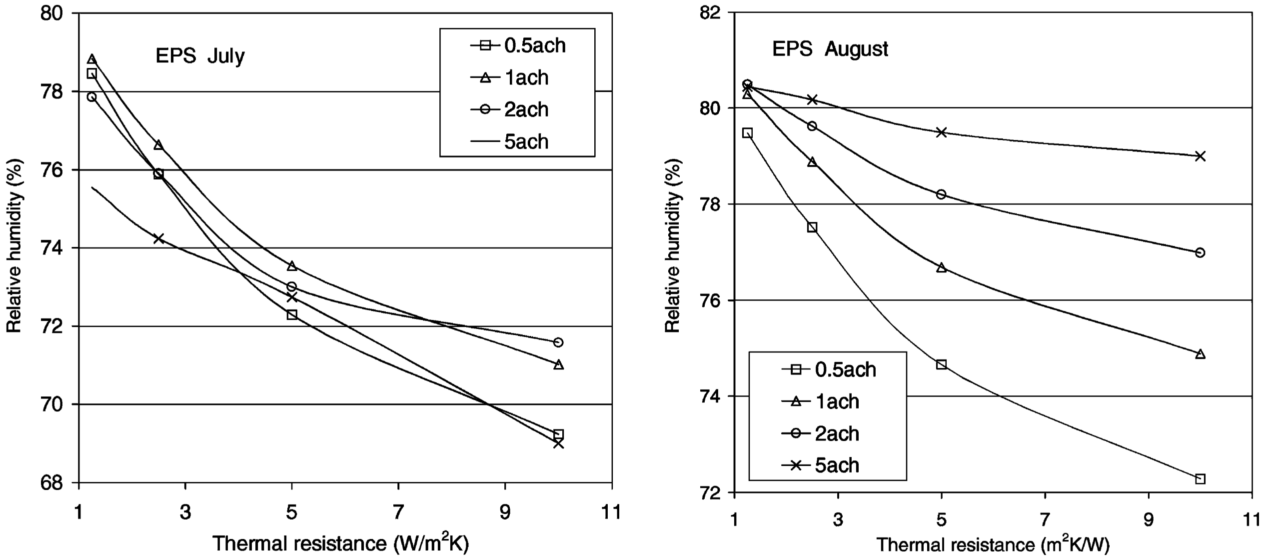

Fig. 12. The monthly average value of RH in the crawl space in July (left) and in August (right) as a function of the thermal resistance of the EPS ground cover and air change rate.

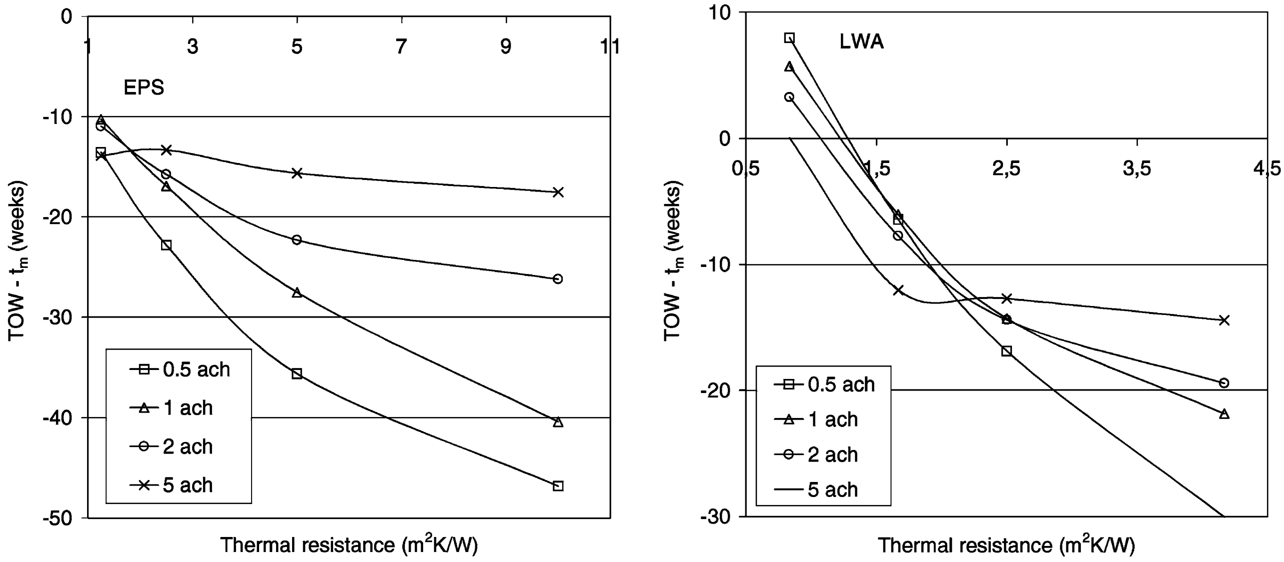

Fig. 13. Time difference between TOW and t_m in weeks when RH $>$ 75%. Negative values indicate no risk of mold growth as the time needed to start mold growth t_m is longer than the TOW, EPS cover (left), LWA cover (right).

mold growth at a microscopic discerning stage, was used as a criterion. With the EPS ground cover there is no risk of mold growth (Fig. 14) as the index does not exceed 0.5 even when the ground cover is only 5 cm thick. With the thinnest LWA cover there is a definite risk of mold growth because the index exceeds 1. To achieve acceptable conditions, a heat resistance higher than 1.5 m^2 K/W has to be used.

4. Discussion

An earlier study [6] recommends the use of ground covers (15–30 cm LWA or 5–10 cm EPS) and the sufficient ventilation of the crawl space to control RH. During the heating season an air change rate of 0.5–1.0 ach provided the driest conditions, but in the summer, it was necessary to use an air change rate of 2.0–5.0 ach to warm up the crawl space and to achieve acceptable conditions [6]. This study shows that highly insulated crawl spaces behave differently: a low air change rate gives the driest conditions in the summer.

The study concerning the effect of insulating foundations showed rather surprising results. It seems that a heat flow through the foundation warms the crawl space in the summer, thus, the crawl space was at its warmest and RH was at its lowest when there was no insulation in the foundations. In the further calculations concerning the effect of ground

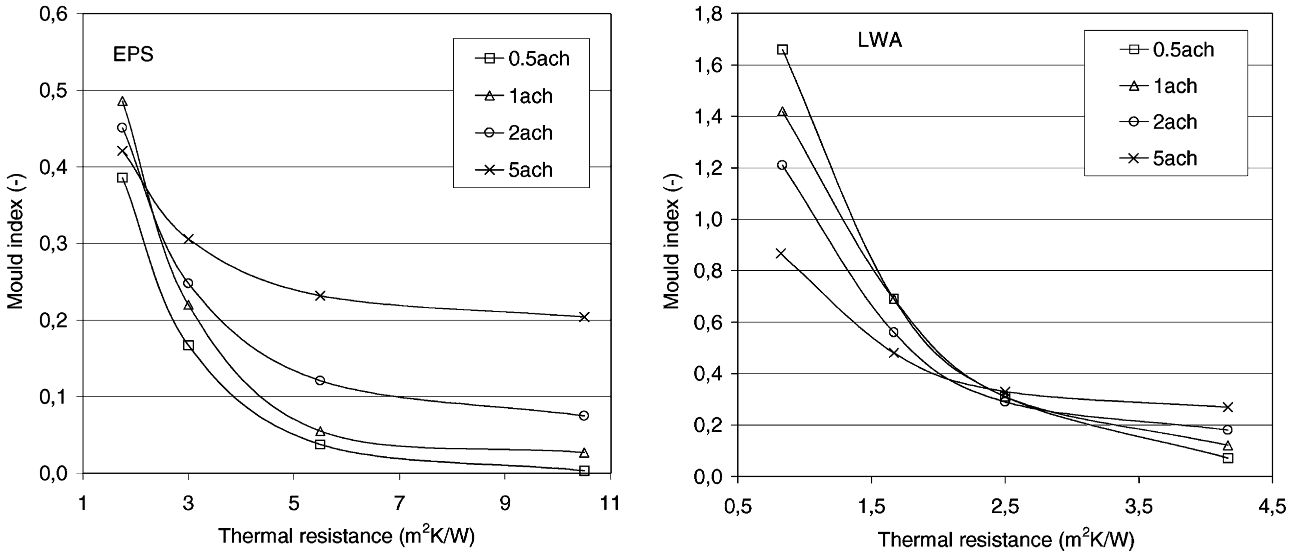

Fig. 14. The mold growth index as a function of the thermal resistance of the ground cover: EPS (left), and LWA (right).

covers and air change, an insulation inside the foundation was used to eliminate a possible source of inaccuracy. Because the heat flow is modelled as the average heat flow through the whole of the foundation, it may cause some inaccuracy to the results. Another significant result was that the location of the insulation on the base floor construction seems to have no effect on crawl space conditions. The results were the same regardless of whether the insulation was on or under the slab.

There is a considerable amount of data existing on the growth characteristics of molds on various types of surfaces under different steady state conditions. However, the literature gives many results only for single species in a limited range of conditions. Here the limit value for RH in respect of mold growth is chosen to be 75% since it is the lowest RH value in crawl space conditions where highly xerophilic (viable in dry conditions) species of mold can grow [19]. Two methods, based on stable and varying conditions, were used to predict mold growth. Both methods provide very similar results. This demonstrates that there are probably no significant differences in the results regardless of whether the mold growth in the crawl space is calculated with the averaging technique or with dynamic prediction. An important result is that the mold growth index can be kept at a very low level ($M < 0.5$) when thick ground covers are used.

Weather conditions have a significant effect on the moisture conditions in an outdoor air ventilated crawl space. If the weather conditions are moist and warm, even outdoor conditions are favourable for the mold growth. This makes it impossible to completely avoid some mold growth in outdoor air ventilated crawl spaces. However, in cold climates there are only a few critical periods in the summer, and during ordinary years it is possible to ventilate the crawl space with outdoor air without a risk of mold growth. The simulations carried out in this study using the typical weather data of 1998 show that very dry conditions can be achieved in highly insulated crawl spaces. Thus, these crawl spaces are also less sensitive to mold growth during extraordinarily humid outdoor conditions compared to common outdoor air ventilated crawl spaces.

5. Conclusion

This study shows that the safest way to control moisture conditions in outdoor air ventilated crawl spaces is to use highly insulating ground covers and a low air change rate. The massive ground soil has a major role in controlling crawl space heat and moisture behaviour. When the thermal resistance of the ground cover is high, a low air change rate of 0.5 ach is sufficient during the whole year to keep the crawl space dry. Actually, in highly insulated crawl spaces a high air change rate can even raise RH, especially in the autumn. Thus, by using highly insulating ground covers, the energy consumption of mechanical ventilation system of the crawl space can also be saved.

The insulation of the foundations and the location of the base floor insulation had relatively small effects on crawl space conditions. The temperature and RH were nearly the same regardless of whether the insulation was on or under the slab. The insulation of the foundations had the most significant effect on the temperature and RH when ground was covered with LWA and the crawl space was small, i.e. the crawl space area was the same as the foundations' area. In the case with no insulation in the foundations, the heat flow from outside warmed the crawl space up by 1 °C in the summer, and RH was 5% lower compared to the case with insulation.

Mold growth prediction carried out by methods based on stable and varying conditions showed very similar results. It was possible to achieve very safe conditions, described by the mold growth index as less than 0.5, in highly insulated crawl spaces.

There are two alternative ways to use ground covers in combination with air change in order to achieve acceptable conditions in crawl spaces. First, a traditional thin layer of LWA or EPS may be used. In this case, the air change rate has to be increased in the summer. For example, 20 cm LWA needs an air change rate of at least 1 ach in the summer. An alternative solution is to use thicker ground covers, such as at least 30 cm LWA or 10 cm EPS, and a low air change rate of 0.5 ach all the year round. This solution provides even lower RH values and mold growth index values as thick ground covers effectively insulate the massive ground whereby the crawl space warms up quickly when the warm season starts.

In practice, a crawl space is sufficiently highly insulated when a 30 cm LWA or a 10 cm EPS ground cover is used. Since a highly insulated crawl space is not sensitive to the air change rate, it can be naturally ventilated.

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