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# Ground moisture evaporation in crawl spaces

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**Abstract**

Air change rate, humidity and temperature were monitored in a naturally and a mechanically ventilated crawl space of the test building, in order to determine the ground moisture evaporation rate and the mass transfer coefficient. The average value of the moisture evaporation with uncovered ground was 3.6–5.7 g/h m$^2$, corresponding to the mass transfer coefficient 0.0012–0.0018 m/s. The mass transfer coefficient determined from evaporation showed sufficient agreement with the coefficient calculated from temperature differences. Normally it would have been sufficient to consider natural convection but with high air change, forced convection also had to be taken into account. The higher air change rates increased moisture evaporation, but still brought about lower relative humidity. The lowest relative humidity, 74.5% in summer, achieved with covered ground and air change of 3 ach, indicates that the control of moisture evaporation and thermal behaviour in summer are key elements in the moisture balance. © 2000 Elsevier Science Ltd. All rights reserved.

*Keywords:* Crawl space; Moisture evaporation; Mass transfer coefficient; Air change; Humidity; Ground covers

## 1. Introduction

### 1.1. The crawl space foundation

The crawl space foundation is a commonly used ground construction in Finland. Over the last years mould and moisture problems, appearing usually as mould smell in apartments, have been considered typical. The main reason for this is the moist or wet ground surface, i.e. uncontrolled ground moisture evaporation, and a lack of air change. To solve the moisture problems not only should air change and ground cover be considered, but also rain-, surface- and ground water drainage should be made to function satisfactorily, because in modern buildings the floor level in the crawl space is usually lower than the outside ground level (Fig. 1). The building technique using a lower ground floor level was not known in the older building tradition, and has mainly come about through construction cost-effectiveness. This is then one explanation for the high incidence of moisture problems.

It is known that the behaviour of crawl spaces is problematic in the summer, when in the daytime outdoor air is usually warmer and with higher moisture content than the crawl space. This means that outdoor air can transport the moisture into the crawl space and the relative humidity will rise. Samuelson [1] reports a relative humidity of 85–95% during summer, and 100% under extreme conditions over a period of several weeks. This problem can be solved with an unventilated crawl space with perfect moisture insulation [2]: if there is no moisture source there is no need for ventilation. In practice, this is very difficult because any leakage in the moisture insulation can bring about high relative humidity. Another application, a crawl space heated with exhaust air, is discussed in [3]. Here, also, heat insulation levels should be relatively high to avoid condensation during the heating season. As both aforementioned applications are quite expensive, an outdoor-air-ventilated crawl space is the one most commonly used in practice. An easily-made application

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for a wooden base floor, a radiant barrier for raising the temperature of wooden joists, is reported on in [4]. In building codes it is usually considered that acceptable conditions in the crawl space can be provided by controlled ground moisture evaporation (ground covers) and by an appropriate air change rate.

### 1.2. Moisture balance in crawl space

The moisture behaviour of crawl spaces was analysed by Elmroth in 1975 [5]. Recommendations for calculating the ground moisture evaporation with constant moisture transfer coefficients, given by Elmroth, are also used by many authors today. Ground evaporation was measured in laboratory tests by Rantamäki [6] and in situ by Trethowen [7]. These results are not free of uncertainties; controlling the conditions on the surface of sample in laboratory tests and handling the latent heat in field measurements were problematic.

In the crawl space, it is usually considered that a relative humidity over 80–85% [1,8], during a period of several weeks or months, can cause mould growth. (Temperature is high enough for mould growth because it is usually over +5°C in crawl spaces.)

Relative humidity in the crawl space is the result of ground moisture evaporation, air change rate and thermal behaviour that are all strongly linked. The potential for ground moisture evaporation is the difference in moisture content between the ground surface and the crawl space air. The moisture content in the crawl space air is affected by air change; both air temperature and relative humidity will change correspondingly. It is worth mentioning that the temperature difference between air and ground surface can cause significant changes in the evaporation potential, even the direction of the moisture flow can be changed if the air is notably warmer than the ground surface. The latter can be the result of thermal inertia, i.e. the high heat capacity of the ground and foundation constructions causing a continuously unsteady state in the crawl space.

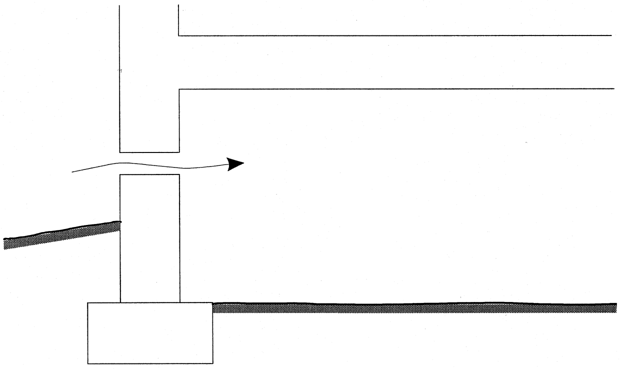


Fig. 1. An outdoor-air-ventilated crawl space foundation.

The moisture and thermal behaviour of the crawl space is affected by air change in opposing ways. In the heating season, the crawl space is warmer than outdoor air, and outdoor air with its low moisture content effectively removes the moisture from the crawl space. At the same time ventilation decreases the temperature of the crawl space, and if air change is too high this will increase relative humidity. In the summer, outdoor air is periodically warmer than the crawl space air and ventilation works inefficiently. Outdoor air with a high moisture content even transports some moisture into the crawl space on certain days in the summer. At the same time, ventilation warms up the crawl space and this decreases the relative humidity.

The ground moisture evaporation and moisture flows carried by air change are the only moisture flows in the crawl space if moisture storage and flows in constructions are not considered, and rain and surface water are not present in the crawl space as should be provided by correct design. Therefore, the moisture balance can be written in steady state

$$v_{\text{out}} \cdot q_v + g = v_{\text{air}} \cdot q_v \tag{1}$$

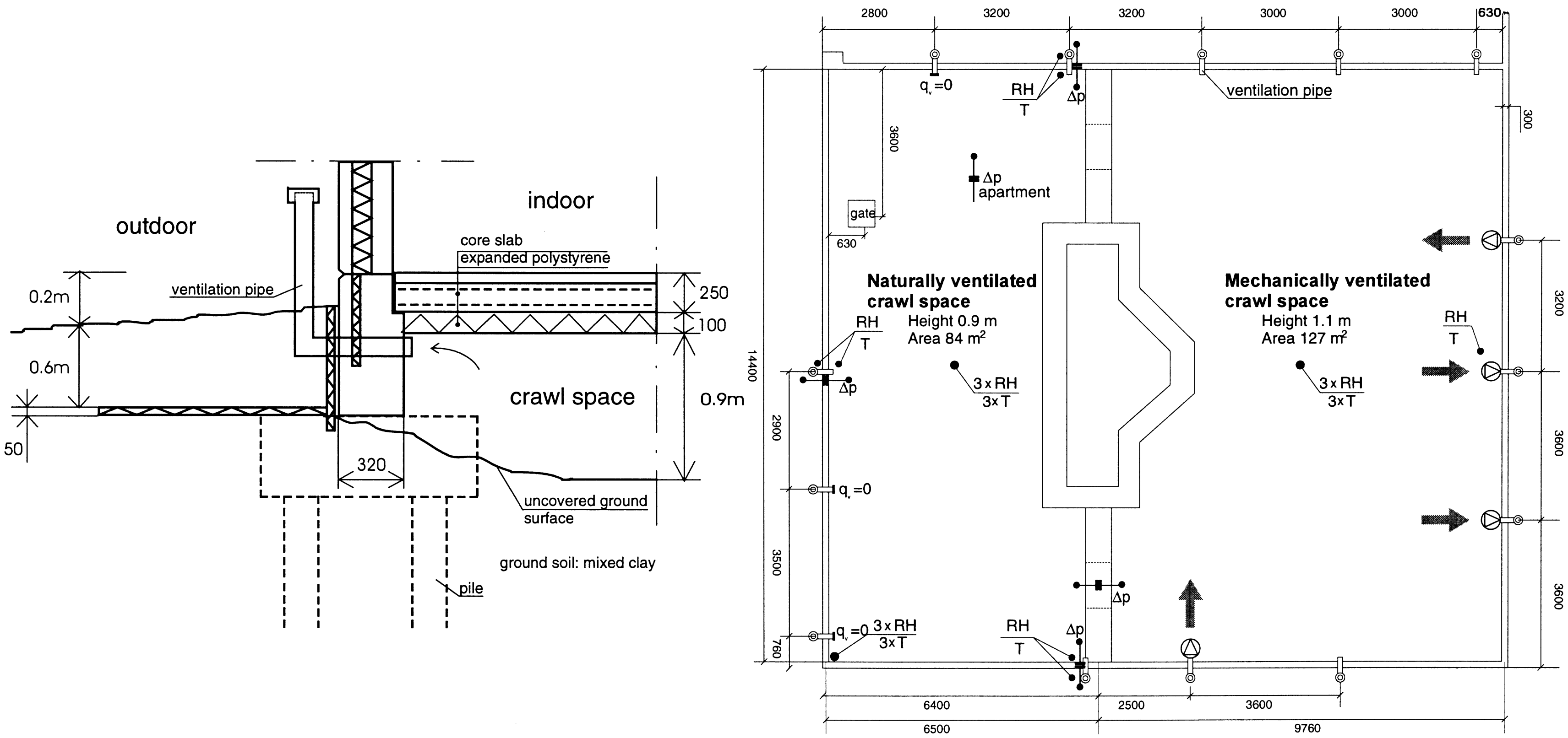
where $v_{\text{out}}$ is humidity by volume in supply, i.e. outdoor air [g/m$^3$], $q_{\text{v}}$ is the air change in the crawl space [m$^3$/s], $g$ is ground moisture evaporation [g/s] and $v_{\text{air}}$ is humidity by volume in extract air; with complete mixing it is the same everywhere in the crawl space air [g/m$^3$]. Ground moisture evaporation based on mass transfer coefficient and potential is

$$g = \beta(v_{\text{ground}} - v_{\text{air}})A \tag{2}$$

where $\beta$ is mass transfer coefficient [m/s], $v_{\text{ground}}$ is the humidity by volume on the ground surface [g/m$^3$] and $A$ is the area of the evaporation surface [m$^2$]. If the ground soil or ground cover is relatively dry, Eq. (2) overestimates the evaporation rate. In this case, the upper limit of evaporation is determined by moisture transfer in the ground soil. This can be taken into account with certain accuracy by using a constant reduction factor [5], or alternatively Fick's law can be used for moisture transfer inside the ground soil

$$g'' = -\delta_w \nabla w \tag{3}$$

where $\delta_{\text{w}}$ is the moisture transport coefficient [m$^2$/s] and $w$ is the water content of the ground soil [g/m$^3$] (when $g''$ is expressed in [g/s m$^2$]). In the case of a moist ground surface more moisture can be transferred to the surface than can be evaporated by convection and only the surface model [Eq. (2)] can be used successfully. For determining the mass transfer coefficient



3× – locations at three heights, from ground surface, middle and top

$q_v$=0 – ventilation pipe closed

Fig. 2. Section and plan of the foundations of the test building. The measurement points of RH, $T$ and $\Delta P$, ventilation pipe and fan locations.

the convective heat transfer coefficient is usually used in engineering applications [9]

$$\beta = \frac{\alpha}{\rho \cdot c_p} \frac{\rho}{\rho_{BM}} Le^{1-n} \cong \frac{\alpha}{\rho \cdot c_p} \quad (4)$$

where $\alpha$ is the convective heat transfer coefficient [W/m$^2$ K], $\rho$ is the density of air [kg/m$^3$] and $c_p$ is the specific heat capacity of air [J/kg K], $\rho/\rho_{BM}$ is the logarithmic density term and *Le* is the Lewis number.

The middle part of Eq. (4) is valid with the assumption of a laminar boundary layer, and theoretically it cannot be transformed into turbulent flow [9]. The right part of Eq. (4) is the most common expression for mass transfer coefficient. The author calculated the Lewis number and logarithmic density term within the temperature and humidity range present in the crawl space and got $Le^{1-0.33} = 1.12$ at 20°C and 1.14 at 0°C, and $\rho/\rho_{BM} \simeq 1.01$ within the complete range. Therefore, if the middle part of Eq. (4) is valid then the right part is valid, with very high accuracy for the temperature and humidity range present in the crawl space. How the assumption of laminar boundary layer functions in crawl spaces can only be tested by measurement.

## 2. Methods

Field measurements to determine air change, humidity and temperature in a crawl space were carried out in one middle block of a four-storey apartment building. A section and plan of the foundations of the block investigated are shown in Fig. 2. The height of the crawl space is 0.9 m and the bottom of the crawl space is roughly 1 m below the outside ground level. The foundation and base floor are typical for clay ground soil. The building foundations rest on piles and the base floor hollow-core slabs are borne by base rockers (all of concrete). Thermal insulation of 50 and 100 mm EPS (expanded polystyrene) will be seen from the section. The crawl space is naturally ventilated with outdoor air flowing through L-pipes of 125-mm diameter.

The crawl space of the selected block was divided into two rectangular sectors with an area of 84 and 127 m$^2$, as shown in Fig. 2. In practice, this division by base rocker existed already; only openings for passage were closed and made air-tight. According to this choice, the geometry, the ground soil and climate conditions are possibly similar in both crawl spaces, as these are in the middle of the building and within the same block. Natural ventilation was maintained without any change in the left part and mechanical ventilation was installed in the right one. For mechanical ventilation the duct fans (125-mm size) were connected directly to L-pipes inside the crawl space. The directions of fans were changed to establish extract and supply ventilation.

Measurements were carried out between April 1997 and October 1998. The following quantities were monitored continuously: air velocity and pressure drop in ventilation pipes (natural ventilation), relative humidity in crawl space and outdoors, temperature in crawl space and outdoors, pressure variation between crawl space and a selected apartment, pressure variation between the crawl spaces and between crawl space and outdoor air, wind velocity and direction provided by a weather station on the roof of the building.

The locations of the measurement points are shown in Fig. 2. Humidity and temperature are taken at several heights and locations. The moisture content of the soil was tracked by taking samples once a month. The pressure variation between the crawl space and outdoor air was measured by readings taken over three walls of the naturally ventilated crawl space. These values indicate pressure drops in the ventilation pipes too and were used to determine airflow in the pipes. Relative humidity and temperature were measured with “Vaisala HMP44L” transmitters, and the pressure difference was measured with pressure transducers “Furness FCO 44” with the range ±50 and ±20 Pa.

In the naturally ventilated crawl space, the determination of the air change rate was based on measuring the pressure difference across the ventilation pipes. Airflow characteristics for the L-type ventilation pipe, having been measured in the laboratory, were used to determine the airflow in the ventilation pipes. The measured results were compared with another method, based on measuring the velocity inside a 40-cm long duct component added to the ventilation pipe. The results were also compared to a number of instant active tracer gas measurements. Both methods, based on pressure difference and velocity, showed sufficient accuracy with short 5 or 10 min recording intervals and averaging mode of loggers with a 30-s sampling interval. The 10 min recording interval was chosen for the measurements to avoid excessive amounts of measured data. In the mechanically ventilated crawl space, air change rate was determined by airflow from the fans. Tracer gas was used once to confirm the accuracy of the method.

## 3. Results

### 3.1. Moisture conditions in crawl spaces

The relative humidity variation in the crawl spaces during the entire research period is shown in Fig. 3. The values are weekly moving average values measured at a middle height in the crawl spaces. Im-

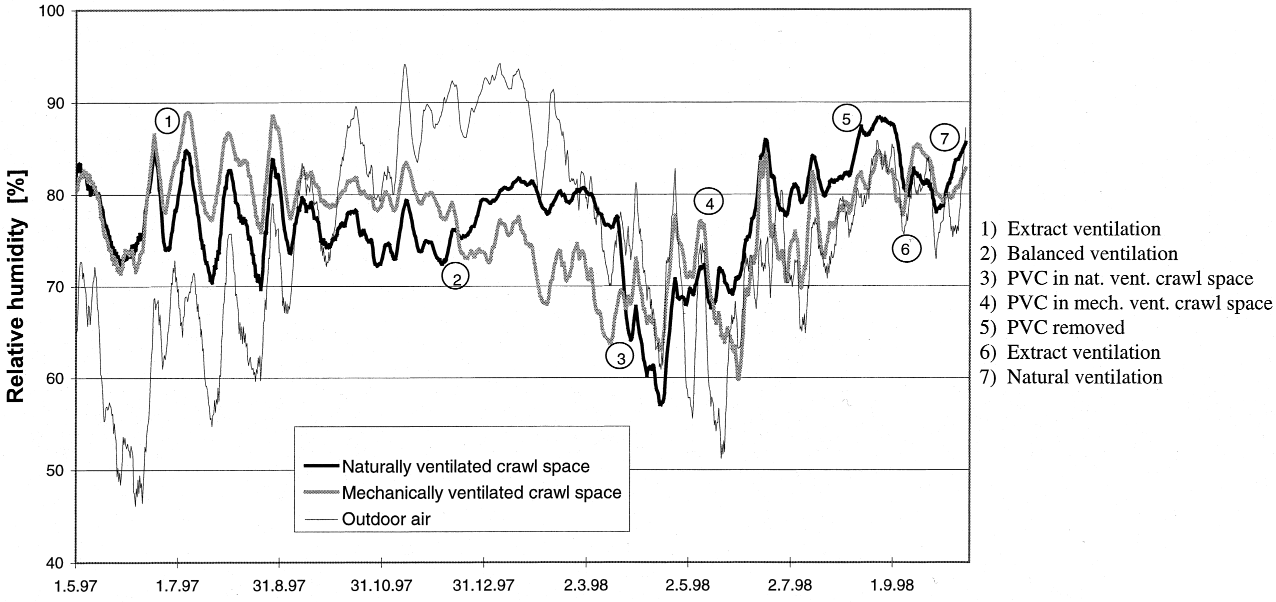


Fig. 3. Weekly moving average values of relative humidity over the entire research period.

portant phases during the research are numbered in Fig. 3. These indicate the changes made in the mechanically ventilated crawl space. At the beginning, natural ventilation was operating in both crawl spaces. At (1) extract ventilation (3.3–2.3 ach) was switched on in the mechanically ventilated crawl space. After that a higher relative humidity in the mechanically ventilated crawl space can be observed. At (2) extract ventilation was changed over to balanced ventilation (2.8–3.3 ach) and this led to lower humidity in a mechanically ventilated crawl space. Later, balanced ventilation was changed over to supply ventilation without any notable alterations in behaviour. At (3) a plastic sheet cover was laid on the ground in the naturally ventilated crawl space, and at (4) this was also done in the mechanically ventilated crawl space. It can be seen that relative humidity is mostly below 80% with the plastic cover, even during the summer in the mechanically ventilated crawl space. Plastic sheet covers were removed at (5). The extract ventilation period (6) (4.4 ach) and the natural ventilation period (7) concluded the research. (The air change rates and periods of the research are listed in detail in Tables 1 and 2.)

At the beginning of the research, conditions in the naturally ventilated crawl space were unusual. The wall dividing the crawl spaces was leaky, and when extract ventilation was switched on at (1) (Fig. 3) the air change rate was increased in the naturally ventilated crawl space from about 1 to 2.5 ach. After sealing the wall and eliminating the pressure difference between crawl spaces [first one of three extract fans was changed to a supply fan and at (2) ventilation was balanced by installing a second supply fan], the average value of the air change rate in the naturally ventilated crawl space was 1.7 ach during 1997. Since the air change was now caused mostly by under-pressure on the ground floor, i.e. a portion of intake air of the exhaust ventilation in the building was sucked from

Table 1
Calculated moisture evaporation rate and measured relative humidity and air change rate during each period in the mechanically ventilated crawl space

| Period, extract/supply fans, duration | Air change rate [l/h] | Evaporation rate [g/h m$^2$] | Relative humidity [%] |
|---|---|---|---|
| (1) Extract ventilation, 3/-, 9.9.97–24.10.97 | 3.3 | 12.4 | 80.4 |
| Extract ventilation, 2/1, 24.10.97–9.12.97 | 2.3 | 7.6 | 79.7 |
| (2) Balanced ventilation, 2/2, 9.12.97–13.5.98 | 2.8 | 5.7 | 71.6 |
| Supply ventilation, before PVC[a], 1/3, 13.5.98–25.5.98 | 3.3 | 5.9 | 65.7 |
| (4) PVC[a], supply ventilation, 1/3, 25.5.98–6.8.98 | 3.3 | 1.9 | 74.5 |
| (5) Supply ventilation, after PVC[a], 1/3, 6.8.98–3.9.98 | 3.3 | 4.4 | 81.9 |
| (6) Extract ventilation, 4/-, 3.9.98–1.10.98 | 4.4 | 10.8 | 82.2 |
| (7) Natural ventilation, -/-, 1.10-14.10.98 | | | 81.6 |

[a] Plastic sheet on ground.

Table 2
Calculated moisture evaporation rate and measured relative humidity and air change rate in naturally ventilated crawl space

| Period | Air change rate [l/h] | Evaporation rate [g/h m$^2$] | Relative humidity [%] |
|---|---|---|---|
| Before reducing ventilation, 19.9.97–22.12.97 | 1.7 | 4.1 | 75.5 |
| After reducing ventilation, 22.12.97–20.3.98 | 0.9 | 3.1 | 79.5 |
| (3) Plastic sheet on ground, 20.3.98–25.5.98 | 0.8 | 1.4 | 66.5 |
| (4) Plastic sheet on ground, 25.5.98–6.8.98 | 0.4 | 0.5 | 79.9 |
| After plastic sheet on ground, 6.8.98–14.10.98 | 1.0 | 2.2 | 83.9 |

crawl space, the number of ventilation pipes were reduced in the naturally ventilated crawl space. This was done in order to achieve a greater difference between ventilation rates in naturally and mechanically ventilated crawl spaces. After reducing the number of ventilation pipes in December by half, the average air change was 0.9 ach and during the plastic sheet period it was 0.6 ach.

The moisture balance in the crawl space depends on ground moisture evaporation and the moisture flows carried by air change. Air change can remove moisture only if the outdoor air is drier than the crawl space air. The difference in humidity between the crawl space and outdoors is shown in Fig. 4. This shows the amount of moisture that can be removed by air change. It can be seen that it was almost the same in both crawl spaces during the extract ventilation periods at the beginning of the study. In the summer of 1997, and also in 1998, there are some negative peaks indicating a higher humidity in outdoor air than in the crawl space. These negative differences appear in hot weather, when the outdoor temperature and humidity are above the corresponding values in the crawl space, and when ventilation carries moisture into the crawl space, leading to a rise in humidity. A period of balanced ventilation differs exceptionally from previous extract ventilation, as the humidity difference in the mechanically ventilated crawl space is notably lower than in the naturally ventilated crawl space. Another period showing low humidity difference is the plastic sheet period when, especially in the mechanically ventilated crawl space, the air was only very slightly more humid than the outdoor air.

### 3.2. Moisture evaporation from the ground surface

When calculating evaporation from the ground surface the common assumption is that the ground surface is in a saturated state, i.e. relative humidity is 100%. Measured results in Fig. 5 show a variation between 85 and 100%. Humidity on the ground surface was measured with sensors with a 10-mm diameter; by careful installation the results were measured a few millimetres above the ground surface, from the boundary layer. Another thing to consider is the 96–97% upper limit of the measurement range of the ca-

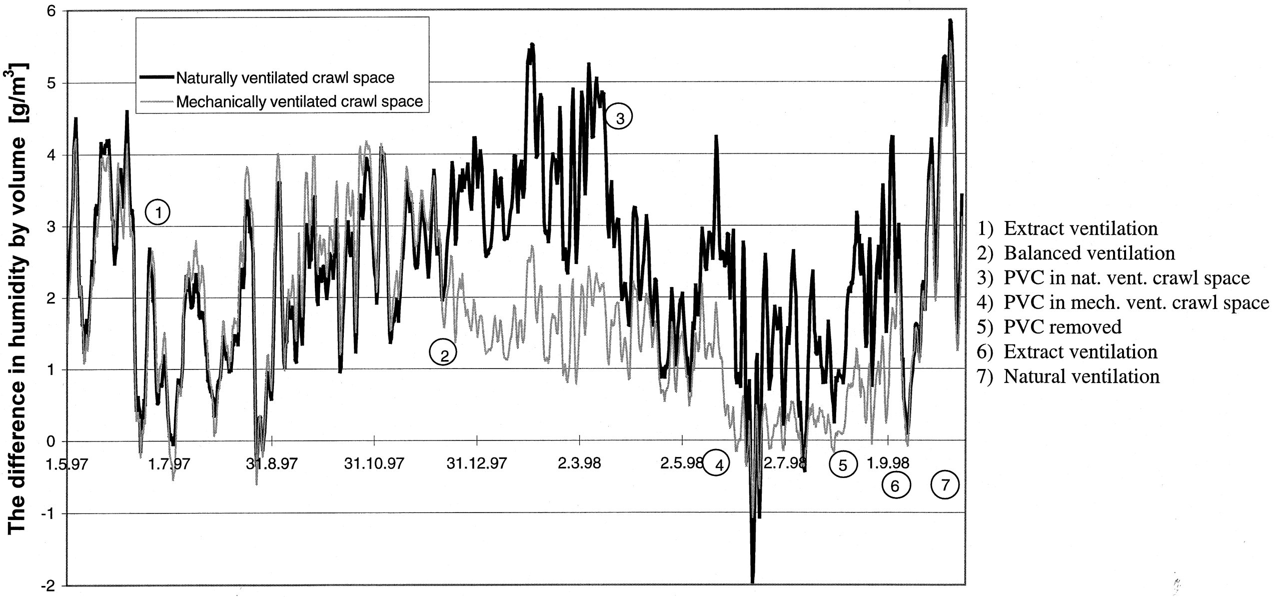


Fig. 4. The difference in humidity by volume between the crawl space air and outdoors (48-h moving averages).

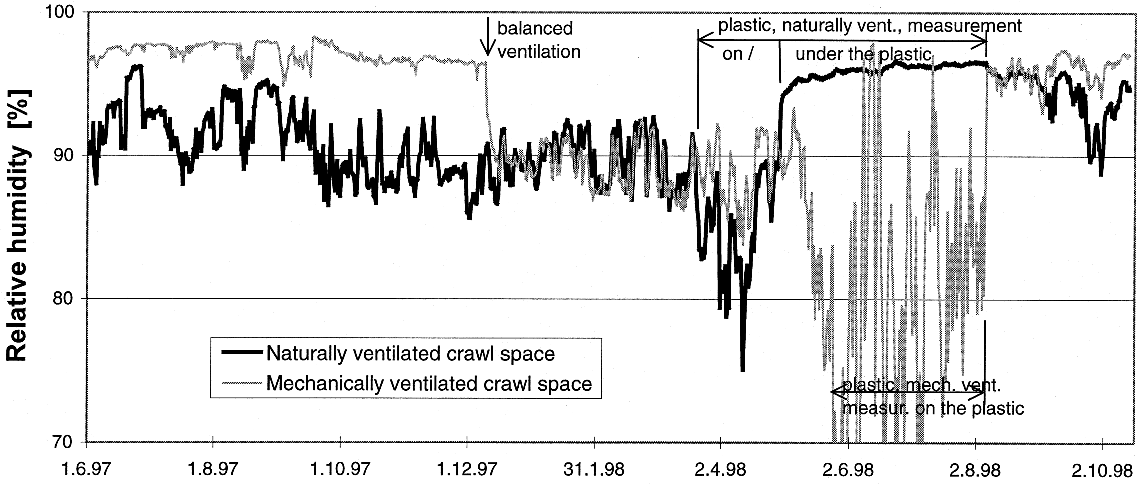
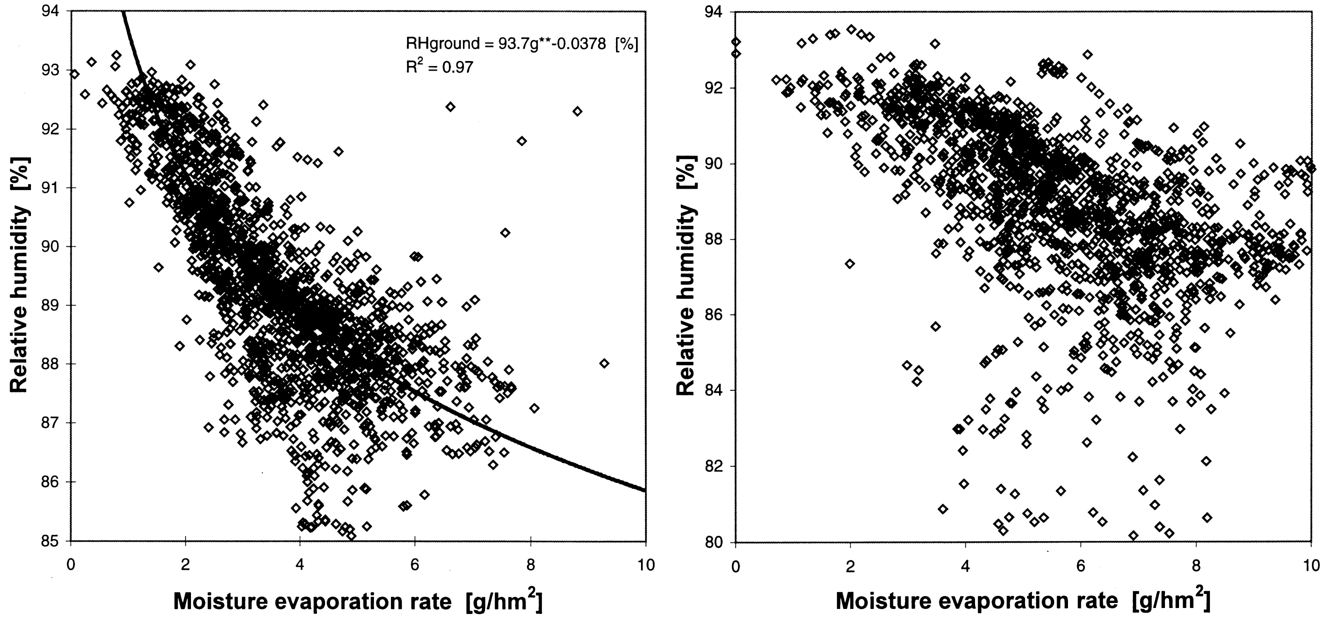


Fig. 5. Relative humidity on the ground surface (24-h moving averages).

pacitive sensors used. Therefore, about 97% in Fig. 5 could actually indicate a fully saturated state with approximately 100% RH. It can be seen that in the mechanically ventilated crawl space the humidity was slightly higher, but after changing over to balanced ventilation the humidity decreased to the same level as in the naturally ventilated crawl space, probably brought about by increased air movement.

A clear positive correlation between measured relative humidity on the ground surface and calculated moisture evaporation rate was found in the naturally ventilated crawl space, as shown in Fig. 6. This was drawn for the period between the sealing of the leaky wall dividing the crawl spaces and the laying of the plastic sheet (19 September 1997–20 March 1998) in the naturally ventilated crawl space. A similar, but not so clear correlation, was in the mechanically ventilated crawl space, when the periods with extract ventilation and plastic sheet cover are not considered (drawn for the balanced and supply ventilation period 9 December 1997–25 May 1998). The correlation in the naturally ventilated crawl space proved to be useful when com-



a) b)

Fig. 6. The correlation between measured relative humidity on ground and calculated moisture evaporation in: (a) the naturally ventilated crawl space; and (b) in the mechanically ventilated crawl space (2.5-h averages).

puter simulations were successfully carried out with a surface model of the ground in [10], not discussed in this paper. However, these correlations are highly specific and can be applied only for the ground soil of the test building.

Quite stable relative humidity on the ground surface does not mean that the moisture transfer potential is constant as well. This is determined by the difference in humidity between the ground surface and crawl space air [Eq. (2)]. This difference shows as well the direction of the moisture flow, and is shown in Fig. 7. Mainly in the hot summer of 1997, negative values appear for short periods and the variations are remarkable. When measured under the plastic sheet higher positive values are obtained. Measurement above the plastic sheet shows almost a nonexistent potential.

The ground moisture evaporation rate calculated with Eq. (1) by using measured values of humidity and air change is shown in Fig. 8. It can be seen that moisture evaporation is very high during extract ventilation periods. Some negative values in summer show moisture storage in crawl space.

From the results of the measurement of relative humidity, air change rate and computed moisture evaporation, in principle it can be seen that higher ventilation rates have led not only to a slightly lower relative humidity, but also to higher moisture evaporation. This can be seen more clearly from the correlation shown in Fig. 9. The correlation between the moisture evaporation rate and air change, and between relative humidity and air change, are drawn for the period before the plastic sheet was laid in the naturally ventilated crawl space. The $R^2$ value is about 0.4 in the whole range for both correlations.

In the mechanically ventilated crawl space a corresponding correlation cannot be drawn, because the air change rate was constant. The moisture balance can be studied by using average values for each period, shown in Table 1 for the mechanically ventilated crawl space and in Table 2 for the naturally ventilated crawl space.

The effect of the pressure conditions and plastic sheet on the moisture evaporation rate can be seen from Tables 1 and 2. It should be noted that high values of moisture evaporation during the extract ventilation periods include convection flow through drainage gravel and possible leakage. The average value of moisture evaporation was 3.6 g/h m$^2$ (19 September 1997–20 March 1998) in the naturally ventilated crawl space and 5.7 g/h m$^2$ (9 December 1997–25 May 1998) in the mechanically ventilated crawl space, if the periods with extract ventilation and plastic sheet cover are not considered. During the period with the plastic sheet cover, the average value of moisture evaporation in the naturally ventilated crawl space was 0.9 g/h m$^2$, and 1.9 g/h m$^2$ in the mechanically ventilated crawl space. Thus, plastic sheet cover reduced the ground moisture evaporation by 70%.

### 3.3. Mass transfer coefficients

The values of the ground moisture evaporation are specific because they are related to the current test building and depend on many parameters such as, for

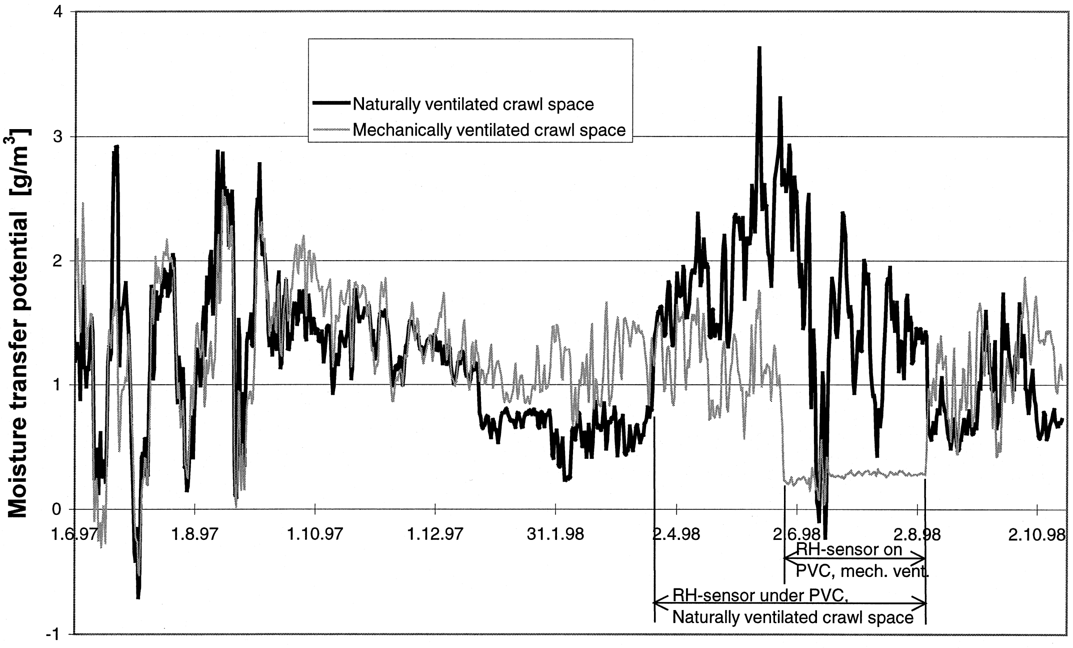


Fig. 7. The difference in humidity by volume between the ground surface and crawl space air (24-h moving averages).

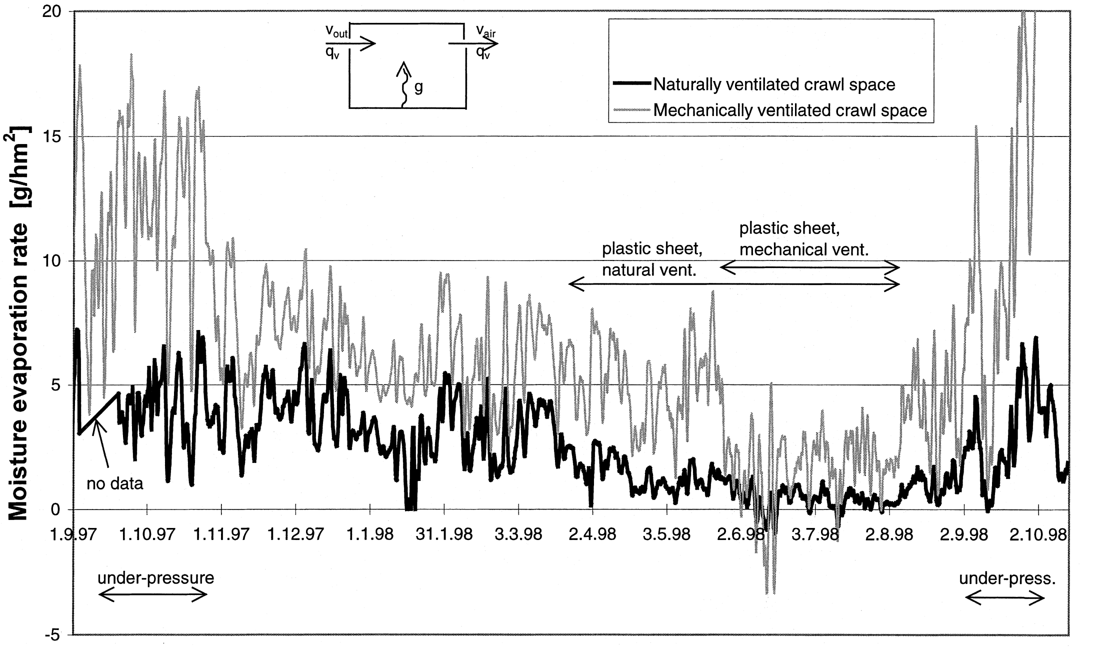
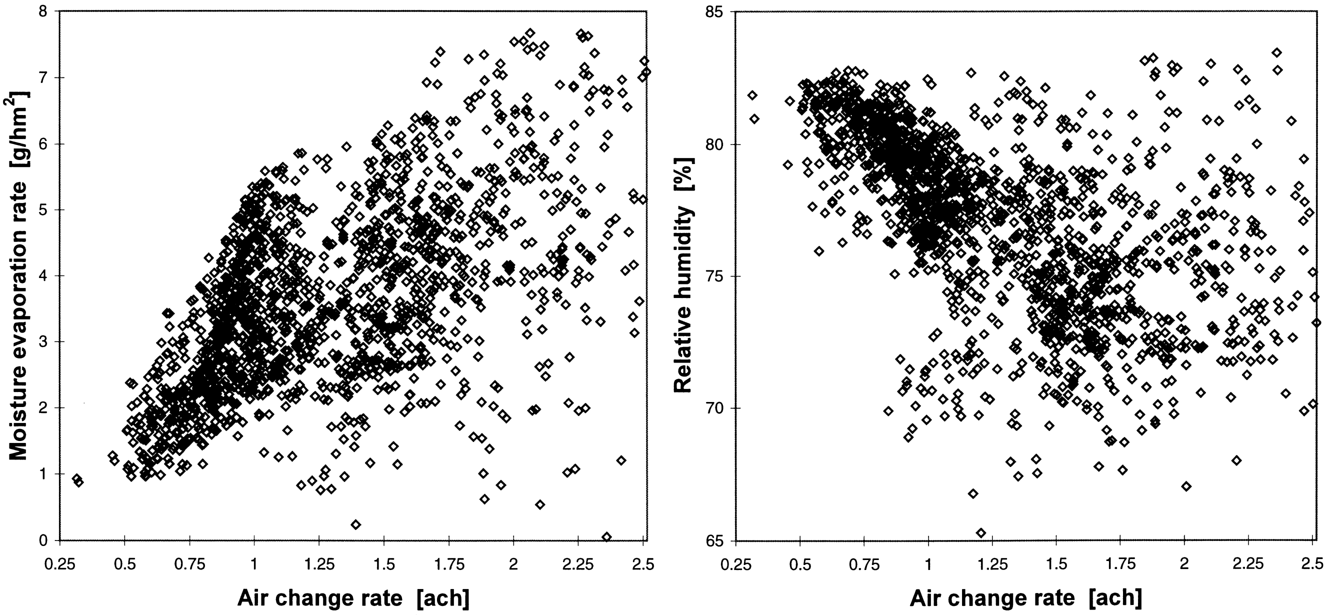


Fig. 8. Calculated ground moisture evaporation rate. (Based on the difference in humidity between supply and extract air and the air change; 24-h moving averages.)

example, air change rate. A more general and comparable way of presenting results is to present these in the form of the mass transfer coefficient. Since ground moisture evaporation was calculated from the moisture balance Eq. (1), the mass transfer coefficient can be determined from Eq. (2). To operate with more convenient values, the convective heat transfer coefficient can be calculated directly while taking into account Eq. (4), i.e. $\alpha = \beta \rho c_{\mathrm{p}}$

$$\alpha = \frac{g \cdot \rho \cdot c_{\mathrm{p}}}{(v_{\mathrm{ground}} - v_{\mathrm{air}})A} \tag{5}$$



a)

b)

Fig. 9. The correlation between calculated moisture evaporation rate and air change (a) and between measured relative humidity and air change (b), in the naturally ventilated crawl space during the period 19 September 1997–20 March 1998 (2.5-hour averages).

where the area of the evaporation surface $A$ is equal to the crawl space area when the ground surface is uncovered, and is about 10% of that area in the case of the plastic sheet cover. The value of $\rho c_p$ is about 1250 J/m$^3$ K at 10°C. Now the convective heat transfer coefficient, calculated from moisture evaporation with Eq. (5), can be compared to the coefficient based on the temperature difference, i.e. calculated in the traditional way [11]

$$\alpha = 2.2\Delta T^{1/3} \tag{6}$$

where $\Delta T$ is the temperature difference [K] between the ground surface and air. This has been computed in Fig. 10 for the naturally ventilated crawl space. It should be noted that in Eq. (5) $\alpha$ is not defined when $(v_{\text{ground}} - v_{\text{air}})$ approaches zero, and this can be seen in sharp fluctuation from time to time in Fig. 10. It is significant that there is good agreement without using any reduction factor for ground moisture evaporation, as recommended, for example, in [5]. The plastic sheet period gives here a very low value of $\alpha$ that is not correct because $(v_{\text{ground}} - v_{\text{air}})$ is measured under the plastic and the entire crawl space area is used. Values of $\alpha$ can be shifted onto the same level when compared to values calculated from temperature difference by using the correct evaporation area, that is 1/10 of the area of the crawl space. Still there is no physical significance, because the humidity on the ground is measured from the wrong place (under the plastic sheet). It is also notable that after removing the plastic sheet it took some time before $\alpha$ reached the previous level.

For the mechanically ventilated crawl space, Eq. (6) underestimates the mass transfer coefficient, because the air change rate is high (2.3–4.4 ach) and the air movement on the ground is significant. By adding the velocity term to Eq. (6), known from equations of forced convection, the results are closer to the coefficient calculated from moisture evaporation:

$$\alpha = 2.2\Delta T^{1/3} + 4v \tag{7}$$

where $v$ is velocity [m/s]. Estimating the value for air velocity on the ground surface was made very approximately, by applying jet equations. Roughly the same result was obtained when the method based on the momentum of jet [12] or, alternatively, the method for determining air velocity in the occupational zone [13] was used. For the jet with an initial velocity of 3.5 m/s and the section with 3.6 by 1 m, the velocity 0.17 m/s (on the ground) was obtained. This assumption was written as a function of air change: $4v = 5.4q_v$, where velocity is in [m/s] and airflow in [m$^3$/s]. The results are shown in Fig. 11. In addition, some field measurements were made that in general supported current assumption and gave results between 0.0–0.25 m/s with an average value 0.1 m/s when the outdoor temperature was 20°C and the crawl space temperature

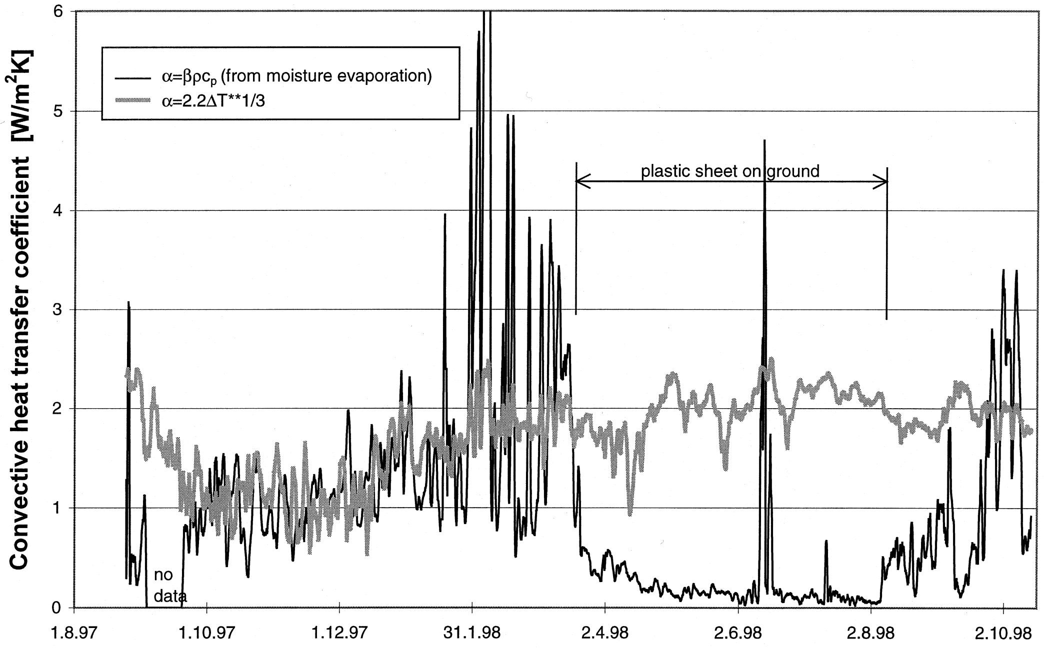


Fig. 10. The mass transfer coefficient in the **naturally ventilated** crawl space calculated from the moisture evaporation and multiplied by $\rho c_p$ (i.e. expressed as convective heat transfer coefficient $\alpha = \beta\rho c_p$), and the corresponding coefficient calculated from the temperature difference (24-h moving averages).

14°C. When the temperature conditions are vice versa, such as in the heating season, the velocities on the ground will probably be somewhat higher.

During the plastic sheet period the results are not defined because humidity $v_{\text{ground}}$ was measured above the plastic sheet. The high values of mass transfer coefficients during extract ventilation periods are caused by moisture convection flows that are included in moisture evaporation. Such moisture convection flows through permeable soil and drainage gravel, and possible direct leakages from adjacent sections of the crawl space are caused by an under-pressure in the crawl space and could not be quantified from the measured results. This means that the moisture balance, Eq. (1), is incorrect during extract ventilation periods, because there is no convection term that must be kept separate from evaporation. Therefore, the mass transfer coefficient calculated with Eq. (5) is overestimated during extract ventilation periods, because evaporation $g$ includes moisture convection flows.

In the naturally ventilated crawl space, the average value of the convective heat transfer coefficient during the period 19 September 1997–20 March 1998 was 1.5 W/m$^2$ K [Eq. (5)], and the corresponding value calculated from the temperature difference [Eq. (6)] was 1.4 W/m$^2$ K. When considering the $\rho c_p = 1250$ J/m$^3$ K, one obtains for mass transfer coefficients 0.0012 m/s. In the mechanically ventilated crawl space, the average value of the convective heat transfer coefficient during the period 9 December 1997–25 May 1998 was 2.2 W/m$^2$ K, and the value calculated from the temperature difference [Eq. (7)] was 2.3 W/m$^2$ K. These correspond to the mass transfer coefficient 0.0018 m/s. Eq. (6) gives 1.7 W/m$^2$ K corresponding to 0.0013 m/s.

## 4. Discussion

Moisture evaporation from an uncovered ground surface was found to depend on air change rate and under-pressure in the crawl space. The higher the air change rate the higher the moisture evaporation was valid in the naturally ventilated crawl space. This might also be valid in the mechanically ventilated crawl space, but was overrun by the effect of the pressure conditions. Extract ventilation periods of about 4 Pa under-pressure during period (1), and of about 6–7 Pa during (6), roughly doubled the evaporation rate. At these periods the relative humidity was even higher than in naturally ventilated crawl space. To what extent the phenomenon was caused by air flows through ground soil, drainage gravel etc., and to what extent by direct leakage from the adjacent sections, did not become completely clear because only pressure difference and air tightness measurements were carried out, and the relevant tracer gas measurements were not. Still, the effect of higher humidity was also noted during the period with one supply and two extract fans when the under-pressure was only about 0.5 Pa. Only when the under-pressure was completely removed

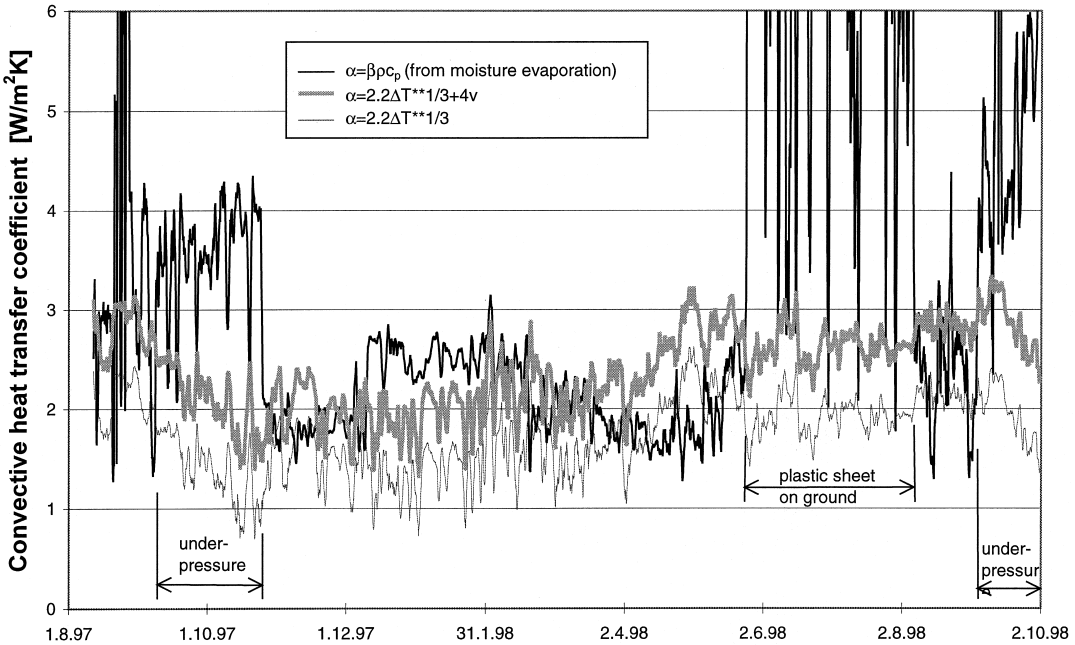


Fig. 11. The mass transfer coefficient in the **mechanically ventilated** crawl space calculated from the moisture evaporation and multiplied by $\rho c_p$ (i.e. expressed as convective heat transfer coefficient $\alpha = \beta \rho c_p$), and the corresponding coefficient calculated from the temperature difference (24-h moving averages).

by balanced ventilation was the mechanically ventilated crawl space notably drier for the first time. This change remained constant and remained valid as well with the supply ventilation.

A negative correlation between moisture evaporation and relative humidity on the ground was found. When the evaporation rate was low the ground surface became almost saturated and at high evaporation rates the relative humidity dropped to 85%. This demonstrated that the moisture transfer process in the soil plays a definite role and the assumption of 100% relative humidity on ground is not always correct. This will be very important in the case of ground covers with low capillary rise such as crushed stone, gravel or granulated (expanded) clay.

It was demonstrated that higher air change rate brings about lower relative humidity, despite the rise in moisture evaporation. There was a clear correlation in the naturally ventilated crawl space, and relative humidity was also lower in the mechanically ventilated crawl space with a high air change rate of about 3 ach, when extract ventilation periods are not considered. In the naturally ventilated crawl space, the negative correlation between the air change rate and the relative humidity was clear up to 1 ach. One can draw the conclusion that this is the lower limit for optimum ventilation. How these results can be generalised on is an open question. They are related to the moisture properties and conditions of the ground soil. In the test building the ground surface was rather moist as relative humidity on the surface was mostly 90% or more. With a completely saturated surface the results might still be different.

Moisture behaviour in summer is a key issue in crawl spaces. Outside air carried moisture into the crawl space over a period of several days, but at the same time it warmed up the crawl space. The results show that higher air change reduced humidity in the summer. In the summer of 1997 average relative humidity was 78.3% in the naturally ventilated crawl space, with an air change of 2.5 ach. (Its extract air was removed through the mechanically ventilated crawl space.) The best result, 74.5% relative humidity, was achieved in 1998 with a plastic sheet cover and an air change rate of 3.3 ach in the mechanically ventilated crawl space. During this period the relative humidity was mostly below 80%. It can be generalised that increasing the air change rate from a certain level can reduce humidity if ventilation removes relatively more moisture than is added by increased ground moisture evaporation. This includes also the effects of temperature: in the summer the crawl space is warmed up (decreasing RH) and in the heating season very high air change rates cool the crawl space down (increasing RH). On the other hand, ventilation is always required if any moisture evaporation occurs in the crawl space. Otherwise, everywhere in the crawl space will be in the same, almost saturated, condition. This is a risk in the unventilated crawl space application; the crawl space can be left unventilated only when moisture evaporation is prevented completely.

Determined average moisture evaporation rates 3.6–5.7 g/h m$^2$ from the uncovered ground, and 0.9–1.9 g/h m$^2$ with the plastic sheet cover, indicate that the plastic sheet cover reduced the evaporation by about 70%. This is very similar to at least 70% and possibly as much as 95%, reported by Trethowen [7]. Rose concludes in [14] that ground covers are undoubtedly effective, and it seems to be a general agreement in previous literature as well. This can be recognized, as laboratory measurements, made by Kettunen [10], showed clearly the effect of ground covers on the clay. He reports evaporation rates (with 0.03–0.1 m/s velocity) of 2.1 g/h m$^2$ for gravel, 1.3 g/h m$^2$ for granulated clay and 0.3 g/h m$^2$ for plastic and expanded polystyrene.

When comparing the moisture evaporation rates from the uncovered ground, as reported in several studies, quite high values can be remarked on. Trethowen [7], who used free-water lysimetry, gives a measured average rate of about 17 g/h m$^2$ (0.082 lb/ft$^2$ day). Kettunen [10] has arrived at exactly the same result — 17 g/h m$^2$ in laboratory tests for the clay sample taken from the test building of the present study (with 0.03–0.04 m/s velocity on the surface of the sample, 2°C temperature difference between the surface of the sample and ambient air and about 80% relative humidity for the ambient air). With 0.1–0.3 m/s velocity on the surface, 25–31 g/h m$^2$ was measured for clay and the highest value was 75 g/h m$^2$ with 2 m/s velocity. Also, 6 g/h m$^2$ was measured for sand and 7–17 g/h m$^2$ for gravel [10] (both with water surface in the capillary rise area and 0.03–0.1 m/s velocity). Such variations are natural because evaporation rates depend not only on properties and moisture content of the soil, but, also, on the mass transfer coefficient and evaporation potential. Still, rates over 6 g/h m$^2$ were not being measured in the test building with the moist ground surface and high 3 ach air change, and seem a bit unrealistic in practice. (However, it is generally known that evaporation from clay, silt and colloids can be as high as from a free water surface or even higher due to the large surface area of these materials.) Trethowen [7] points out that more than 10 ach would be needed for removing an evaporation rate of 17 g/h m$^2$ without exceeding 100% relative humidity. A later survey by Trethowen showed that the likely air change rates are much lower than 10 ach. A possible cause might be latent heat, i.e. when measured in situ from a small area the evaporation heat can be enhanced by heat conduction from nearby ground soil, probably with a considerably lower evaporation rate.

Mass transfer coefficients, derived from ground moisture evaporation and calculated directly from the temperature difference, showed very satisfactory agreement in the naturally ventilated crawl space. It is remarkable that there is no need at all to use any reduction factor for moisture evaporation, as, for example, the reduction factor 0.1 and the heat transfer coefficient 7 W/m$^2$ K as recommended by Elmroth [5]. This shows that the ground has been saturated, and if any drying has occurred, it has been only in the very surface layer of the ground. In addition, drying has not turned out to be very important because measured relative humidity has always remained over 85%. One could argue about the measuring by the probe with the diameter of 10 mm that was pushed by half into the soil to get readings on the surface but at least in the naturally ventilated crawl space, where there was no big air movement, it seems to be good enough. In the mechanically ventilated crawl space, where conditions were much more varied and where the boundary layer is certainly thinner, this might cause some uncertainty. Still, this was not apparent from the results of the mass transfer coefficient. Firstly, the coefficient was higher (average 2.2 W/m$^2$ K in the mechanical and 1.5 W/m$^2$ K in the natural ventilation), and calculations from temperature difference gave a slightly lower result — 1.7 W/m$^2$ K. Secondly, it seems that velocity on the ground plays a significant role. From Fig. 11, a sharp rise can be noticed when one extract fan was changed over to a supply fan on 9 December 1997. After this, there was probably a notable velocity on the ground surface, as a cold supply (outdoor) air descends in winter, and the coefficient becomes quite high — about 2.5 W/m$^2$ K. In spring, the value of the coefficient drops, and the reason might be that supply air is warmer and velocity is lower on the ground surface. Such a variation is not taken into account in the velocity term applied in Eq. (7), and it might explain the slight disagreement in the coefficient calculated with Eq. (7). (However, the average value 2.3 W/m$^2$ K is almost the same.) It should also be noted that such high air change rates as 3–4 ach in mechanically ventilated crawl space are somewhat extraordinary and, therefore, the traditional equation (6) can be used with sufficient accuracy in practice.

Determined mass transfer coefficients can be compared to the moisture transport coefficients reported in previous studies. These are shown in Table 3 as convective heat transfer coefficients, i.e. multiplied by $\rho c_p = 1250$ J/m$^3$ K. Elmroth [5] gives the convective heat transfer coefficient of 7 W/m$^2$ K and the reduction factor of 0.1 for moist ground soil and of 0.02 with the plastic sheet cover. Rantamäki [6] and Kettunen [10] gave merely the resulting moisture transfer coefficient. The last-mentioned reports that this is calculated from the measured evaporation rate with Eq. (2), when 100% relative humidity is assumed on the surface of the sample, ambient humidity is measured (about 80%) and temperature difference is measured (about 2°C). This means that the value for ground covers includes a reduction factor describing the moisture transfer process in the sample (i.e. there are resistances caused by capillary movement and diffusion and by the mass transfer coefficient). Such values represent directly the reduction factor if one considers the coefficient 1 W/m$^2$ K, and the reduction factor is twice as small if one considers the coefficient 2 W/m$^2$ K.

The values given by Kettunen [10], for the uncovered ground surface with an average value of about 3 W/m$^2$ K, are notably higher than the average values 1.5 and 2.2 W/m$^2$ K in the naturally and mechanically ventilated crawl spaces of the test building. This can be explained by the remarkably lower temperature difference in the test building. Kettunen used 2°C, but in the naturally ventilated crawl space we found an average value of only 0.4°C, and in the mechanically ventilated crawl space 0.5°C. This causes differences of 1.8 and 1.6 times respectively, i.e. 3 W/m$^2$ K becomes 1.7 W/m$^2$ K for the naturally ventilated and 1.9 W/m$^2$ K for the mechanically ventilated crawl spaces, which shows much satisfactory agreement.

## 5. Conclusions

1. Ground moisture evaporation is a key element in moisture balance in crawl spaces. If any moisture

Table 3
Moisture transport coefficients reported in previous studies, expressed as convective heat transfer coefficients [W/m$^2$ K], i.e. multiplied by $\rho c_p = 1250$ J/m$^3$ K

| Author | Clay | Gravel | Sand | Crushed stone | Crushed stone on clay | Granulated clay on clay | EPS[a] on clay | Plastic on clay |
|---|---|---|---|---|---|---|---|---|
| Kettunen [10][b] | 2.5–4.8 | 3.1 | 2.9 | 0.6 | 0.15 | 0.11 | 0.03 | 0.01 |
| Rantamäki [6] | 1.7 | 1.3–1.5 | | | 0.11 | 0.15 | 0.06 | 0.04 |
| Elmroth [5] | 0.7 | 0.7 | 0.7 | | | | | 0.14 |

[a] Expanded polystyrene.

[b] Average values within the velocity range 0.03–0.1 m/s.

evaporation occurs, ventilation will always be required to remove this moisture. Otherwise, all the crawl space will reach an equilibrium, almost saturated, condition. This is a risk in the unventilated crawl space application; the crawl space can be left unventilated only when moisture evaporation is completely prevented.

2. Increasing the air change rate from a certain level can reduce humidity only if ventilation removes relatively more moisture than is added by an increased ground moisture evaporation. This also includes important temperature effects: in the summer the crawl space is warmed up (decreasing RH) and in the heating season the very high air change rates cool down the crawl space (increasing RH). When mechanical ventilation is used, supply or balanced ventilation is recommended because extract ventilation doubled moisture evaporation due to ground flows, and brought about even higher relative humidity than did natural ventilation.
3. Thermal behaviour in summer is another key element in moisture balance. Outside air transported moisture into the crawl space over periods of several days, but at the same time it warmed up the crawl space. The results show that the higher air change rates, such as 1–3 ach, increased moisture evaporation when the ground was moist and uncovered, but still brought about lower relative humidity. This was, in general, valid all the year round and with ground cover as well. The lowest relative humidity in summer, 74.5% average value, was achieved with the ground cover and air change rate of 3.3 ach. During this period, the relative humidity was mostly below 80%. The corresponding average value with the uncovered ground and air change rate of 2.5 ach was 78.3%.
4. Ground covers reduce moisture evaporation very effectively, during the heating season, when the mass transfer potential from moist uncovered surface is high. In summer, ground covers are needed as well, but the effect is reduced because the mass transfer potential is lower and thermal behaviour will determine the resulting relative humidity in crawl space.
5. The average value of moisture evaporation with the uncovered ground was 3.6 g/h $m^2$ in the naturally ventilated and 5.7 g/h $m^2$ in the mechanically ventilated crawl space, when the periods with extract ventilation are not considered. From previous studies, much higher values can also be found. During the period with the plastic sheet cover, the average value was 0.9 g/h $m^2$ in the naturally ventilated and 1.9 g/h $m^2$ in the mechanically ventilated crawl space. The plastic sheet cover reduced moisture evaporation by 70%, and relative humidity was reduced roughly by 10% on average, but the reduction was higher in the heating season and lower in summer.
6. The mass transfer coefficient can be calculated from the convective heat transfer coefficient with sufficient accuracy. Determined mass transfer coefficients also showed reasonable agreement with the results from laboratory measurements carried out in previous studies. The coefficients determined from ground moisture evaporation and calculated directly from temperature difference (natural convection) showed satisfactory agreement in naturally ventilated crawl space. The average values, expressed as convective heat transfer coefficients, were 1.5 W/$m^2$ K (0.0012 m/s) and 1.4 W/$m^2$ K, respectively. In the mechanically ventilated crawl space, 2.2 W/$m^2$ K (0.0018 m/s) was determined from moisture evaporation and 1.7 W/$m^2$ K from the temperature difference. When the forced convection (velocity on the ground surface) was taken into account very approximately, the latter value was increased to 2.3 W/$m^2$ K, yet a certain disagreement in instant values was maintained, caused probably by the temperature-dependent behaviour of air movement. In practice, the mass transfer coefficient can be calculated merely from temperature differences with sufficient accuracy, because such high air change rates as 3.3 ach used in the mechanically ventilated crawl space will usually not be used.

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