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Moisture safe and mould free crawl spaces: State-of-the-art and design of full-scale experiment

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Abstract

This paper reviews common problems and approaches in the design of modern crawl spaces. It also presents a full-scale experimental set-up and a set of laboratory experiments designed to further investigate their hygrothermal and microbiological behaviour. This work is a part of a long-term research project to determine the basic rules for designing naturally ventilated crawl spaces in the Central European climate that would be moisture-safe, mould-free and with minimum maintenance requirements.

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Keywords: crawl space; moisture; mould growth; ground cover; ventilation; full-scale experiment

1. Introduction

The crawl space is a traditional foundation construction in North America, Nordic countries, and Australia, and is becoming very popular in Central Europe too, especially for timber buildings. The investors usually appreciate lower investment cost and saving of time compared to the traditional slab-on-ground foundations. Also antipathy to artificial materials like plastic foils or concrete sometimes plays a role. The crawl space can be a relatively safe way for using natural thermal insulation (e.g. straw bales, wooden or hemp fibres) in the base floor. In some cases, it is the best or even the only suitable solution for building foundation (e.g. sloping terrain). However, many authors have reported major moisture problems in modern crawl spaces followed by mould growth and decay of building materials.

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This paper reviews the main causes of these problems as well as possible measures to ensure safe operation of modern crawl spaces. It also presents an experimental project proposed to further investigate the hygrothermal and microbiological behaviour of modern crawl spaces in the Central European climate.

1.1. Moisture and mould growth risks in crawl spaces

In general, several moisture sources may cause critical conditions in the crawl space: (1) improper drainage and grading around the house, (2) plumbing leaks, (3) ground moisture evaporation, and (4) ventilation by the outdoor air [1]. While the ingress of rain water and plumbing leaks can be avoided by a routine design and regular maintenance, dealing with the remaining two sources is a complex issue. Williamson and Delsante [2] concluded that at least six factors linked together influenced the relative humidity in the crawl space: ground moisture evaporation, air change rate, soil type, building geometry, ambient climate conditions, and thermal behaviour of the sub-floor. Matilainen and Kurnitski [3] also pointed out that the changes in building traditions, particularly a shift to highly insulated base floors ($U \approx 0.20\ W/(m^2 \cdot K)$), had made modern crawl spaces more problematic.

The most critical for modern crawl spaces is the warm period of the year, especially when they are naturally ventilated by the outdoor air. Several reports showed that the relative humidity in the crawl space could exceed the critical value for mould growth (80 % [4,5,6]) or even reach 100 % for several weeks [e.g. 7]. The reason can be found in the specific thermal regime of the ground beneath the crawl space. High thermal capacity of the soil and lack of solar radiation heat input produce a long time lag and strong damping in the ground temperature. This can result in significantly lower temperatures in the crawl space than in the exterior during the summer months [8]. In addition, the surface temperature of the well-insulated base floor can stay lower than the air temperature in the ventilated cavity because of radiation heat loss to the cold ground and limited heat input from the interior. Consequently, as the warmer and moist outdoor air enters the crawl space, it cools down, its relative humidity increases and condensation may take place on the floor surface, see Fig.1 (a). When capillary active materials are used for cladding of the base floor, they absorb the condensate and become more sensitive to mould growth and biodegradation, see Fig.1 (b). Wood and wooden based products are especially in danger here [6]. In the cold period, ventilation by the outdoor air has a drying potential. As the air passes through the warmer crawl space, it is heated up and capable of absorbing more water vapour. However, when the ground surface is left uncovered, the air can absorb enough water vapour to reach the critical relative humidity. Furthermore, condensation or frost formation can take place at the outlet, where the surfaces are colder. When appropriate measures are not adopted, both moisture sources – ventilation by the outdoor air and ground moisture evaporation – can cause unacceptable conditions in the crawl space throughout the year.

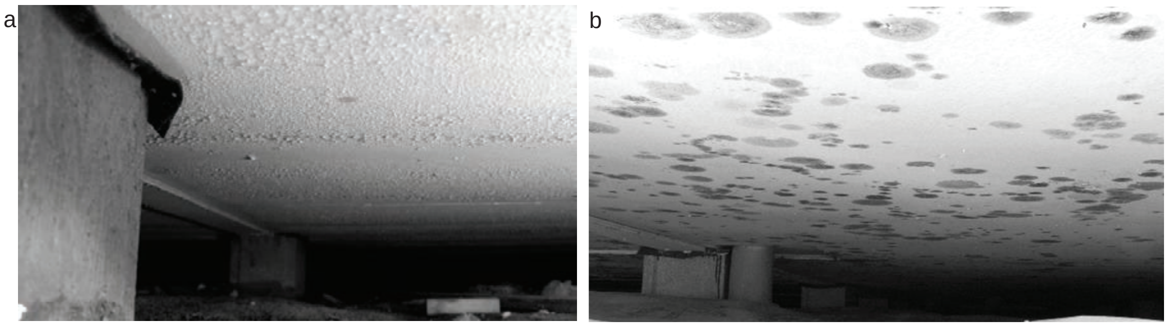

Fig. 1. (a) Surface condensation and (b) mould growth on the lower cladding of the base floor (gypsum fibreboards). [15]

1.2. Possible preventive measures

In countries with a long tradition of crawl spaces, there was a need to find preventive measures to reduce the moisture and mould growth risks. Two design rules for crawl spaces are generally accepted: (1) site drainage and terrain grading to prevent ingress of rain water and (2) a ground cover to prevent moisture evaporation from the underlying soil [1]. A well-sealed ground surface is especially needed when a capillary active fine-grained soil (clay, silt) and high ground water table are present. On the other hand, the optimum air change rate seems to be a sensitive issue and in some cases no ventilation can be the best option [12].

Kurnitski [9] showed that a plastic sheet (PVC foil) reduced the ground moisture evaporation by 70 % in average (higher reduction in the heating season, lower in summer). He also concluded that if any moisture evaporation occurred, ventilation would always be required [9,10]. Several Finnish authors recognized that the crawl space temperature in summer could be increased, in principle, by increasing the air change rate or decreasing the heat capacity by a proper ground cover [3,11]. Airaksinen et al. [11] studied the effect of various ground covers and air change rates on moisture regime of outdoor-ventilated crawl spaces. The study included a warm and a cold crawl space with the base floor U-values of 0.38 W/(m^2·K) and 0.20 W/(m^2·K), respectively. The authors concluded that the best moisture performance could be reached using a ground cover with low thermal and high moisture capacity as well as high moisture and thermal resistance. 15–30 cm of light-weight clay aggregate (LWA) or 5–10 cm of EPS were recommended for the cold crawl space together with a two-speed air change rate: 0.5–1.0 ach in the heating season and 2.0–5.0 ach in the warm season (June to October). The uncovered ground as well as PVC cover produced unacceptable conditions. In the warm crawl space any ground cover and a constant air change rate of 0.5–2.0 ach gave acceptable conditions. Further investigation of Matilainen and Kurnitski [3] showed that the cold crawl space with highly insulated ground surface (30 cm of LWA or 10 cm of EPS) was not sensitive to air change rates and could be naturally ventilated. The authors recommended a low air change rate of 0.5 ach to keep such a cold crawl space sufficiently dry during the whole year. The current practice in North America, however, often advises to encapsulate the crawl space [13], particularly for the mixed to hot and humid climates [12]. Within this approach, a plastic foil is laid on the ground and attached to the foundation structures, which are thermally insulated, see Fig. 2 (a). The crawl space is left unventilated so that the moisture cannot penetrate neither from exterior nor from the soil. The encapsulated crawl space can be also included in the heated zone. In addition, dehumidifiers can be installed to keep the encapsulated crawl space dry, see Fig. 2 (b). Carpenter [14] warned against migration of bacteria, mould spores and radon from the unventilated sub-floors into the living space, and presented a different approach. He suggested a system of adaptive mechanical ventilation controlled on the basis of water vapour concentrations – the fan is switched on when there is a potential to dehumidify the crawl space by the outdoor air. Salonvaara [8] aimed at another aspect. He recognized that radiation heat exchange had a dominant effect in the crawl space, and thus the surface temperature of the base floor could be increased by using a low emissivity foil. He concluded that the emissivity of the foil had to be lower than 0.15 in order to have a significant effect on the hygrothermal performance of the sub-floor, i.e. to decrease the relative humidity in summer below 80 %. The author however pointed out that the foil had to be kept clean and dry since the dust formation or surface condensation would rapidly increase its emissivity.

It is a question to what extent it is possible to generalize the approaches listed above (climate, building size and geometry, soil type, etc.), and if the additional costs for the suggested solutions – thermally insulating ground covers, adaptive ventilation, or even complete encapsulation of the crawl space – are acceptable for most of the investors in Central Europe, where moisture-safe slab-on-ground foundations have a long tradition.

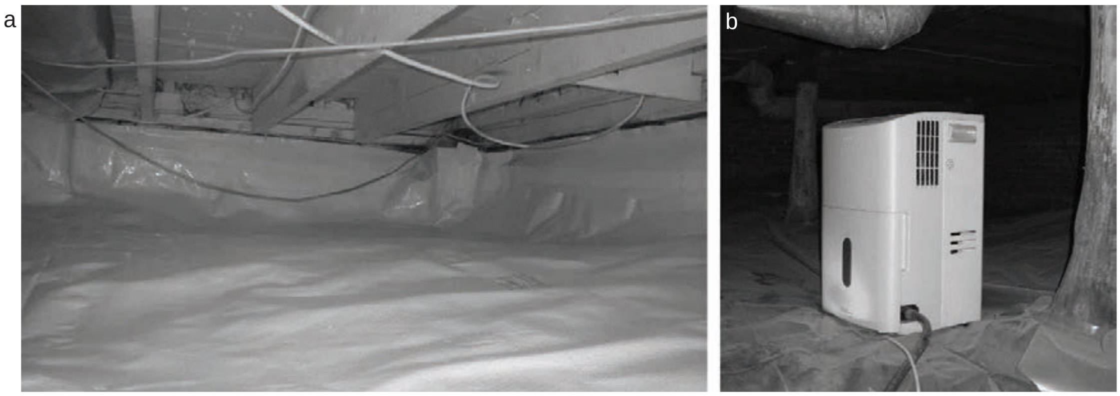

Fig. 2. (a) Encapsulated crawl space; (b) Dehumidifier in the crawl space. [12]

2. Experimental project

2.1. Full-scale experimental crawl space

A full-scale experimental crawl space has been designed and is currently under construction. It is a part of a long-term research project to determine the basic rules for designing modern crawl spaces in the Central European climate that would be moisture-safe, mould-free and with minimum maintenance requirements, but also cost effective.

The crawl space is composed of two symmetrical sub-floor spaces with west-east orientation, see Fig. 3. Each of them is 2.0 m wide, 7.5 m long and the height of the sub-floor cavity is 0.7 m. The crawl space is designed as cold, with the base floor U-value of 0.20 W/(m^2·K). Interior climate above the base floor is simulated by a 20 cm high insulated space equipped with a thermostat-controlled heating foil providing a stable temperature of 20 °C during the heating season. In the warm period the interior space is naturally ventilated by automatically operated shutters which open when the interior temperature exceeds 27 °C. The side walls as well as the wall separating the two experimental spaces are thermally insulated by XPS boards inserted 0.64 m below the ground surface in order to emphasize the 2D character of the experiment. All the structural connections are properly sealed to ensure airtightness of the experimental space. A drainage system is installed around the crawl space.

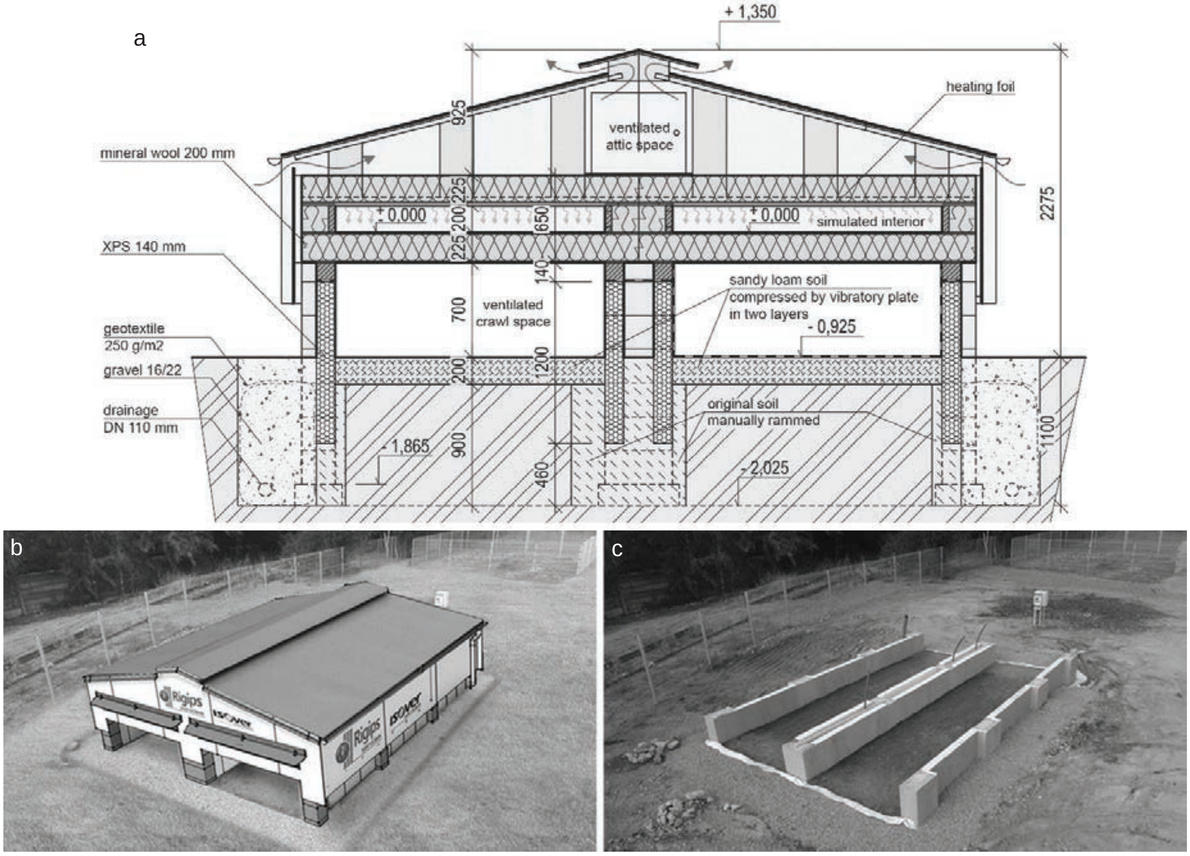

Fig. 3. (a) Section plane of the experimental crawl space; (b) Visualization of the finished building; (c) Actual state of construction.

The crawl space will be monitored by temperature and relative humidity sensors, heat-flux sensors, anemometers and capillary pressure sensors in the soil. Ambient conditions are monitored by a meteorological station on the plot.

The pair of symmetrical sub-floor spaces allows the direct comparison of different experimental set-ups under identical boundary conditions.

The first round of experiments will aim at the effect of various ground covers, see Table 1. The ventilation will be natural, provided by frontal openings as depicted in Fig. 3 (b). The initial phase (Step 0) will show whether the ventilation openings can be left unrestricted or a reduction would be needed to keep the air change rate within the desired limits of approximately 1.0–3.0 ach. Each experimental step will be evaluated on the basis of mould growth index for the lower cladding of the base floor using the empirical VTT model suggested by Viitanen et al. [4,5].

Table 1. The schedule for the first round of experiments aimed at the effect of various ground covers.

Step	Space A	Space B
0	Initial phase with identical configuration of both experimental spaces to ensure there are none or minimum differences in their hygrothermal behavior. Uncovered ground surface. Possible changes in size of ventilation openings.	
1	PE foil	Uncovered ground surface
2	PE foil	15 cm of light-weight clay aggregate
3	PE foil + 15 cm of light-weight clay aggregate	15 cm of light-weight clay aggregate

2.2. Laboratory experiments

The laboratory experiments are carried out to provide additional material data. A particular interest is in hygrothermal properties and mould growth sensitivity of building materials commonly used for cladding of the base floor (wood, particle boards, gypsum fiberboards, cement-bonded boards, etc.). The first round of experiments is aimed at sorption isotherms and water vapour diffusion resistance factors, see Fig. 4. A measurement of water absorption coefficients and thermal conductivities will follow. In addition, sorption and retention isotherms, hydraulic conductivity, thermal conductivity, and volumetric heat capacity of the soil from underneath the crawl space are measured. The measured material properties will be used as inputs for numerical HAM models. The sensitivity of cladding materials to mould growth will be tested using the following procedure: (1) cultivation and identification of moulds taken from the experimental site, (2) UV sterilization of material samples, (3) exposure of material samples to moulds under 10 °C, 90 % RH and 23 °C, 80 % RH, (4) evaluation of mould growth rate using optical microscope.

Fig. 4. (a) Samples for sorption; (b) Samples for diffusion; (c) Soil samples for retention.

2.3. Numerical models

The experimental data will be used for verification and validation of a 2D HAM numerical model. A reliable numerical model is especially needed here since the field experiments are lengthy and it is difficult to perform all the possible combinations of ground covers and ventilation regimes. A numerical model also allows to extend the analyses to different climatic conditions, building geometries, soil types, ground water table levels, wind exposures, etc. The dynamic 2D HAM model used here is based on the scheme presented in [15]. The model consists of three domains: (1) base floor structure, (2) ventilated cavity, and (3) ground under and around the building. The model has been extended to include a detailed radiation sub-model based on analytically determined view factors within the discretized cavity and a sub-model for natural ventilation based on orientation of the openings towards wind direction. The model will be further improved to include more detailed moisture transfer description for the floor structure and the ground.

The methods presented in [16,17] and [18] will be used. A complex 2D model is however rather difficult to use in engineering practice. Therefore it will be examined to what extent it is possible to simplify the model and provide an easier-to-use lumped parameters model.

3. Conclusions

The literature survey showed that several design principles can lead to moisture-safe and mould-free operation of modern crawl spaces with well insulated base floors. In cold climates, vapour-tight and thermally insulating ground covers in combination with low speed natural ventilation proved to keep the crawl space sufficiently dry all year round. The moisture safety here can be further strengthened by using adaptive mechanical ventilation and a low emissivity finish on the base floor. In warmer and humid climates the complete encapsulation, i.e. sealing the ground surface as well as the perimeter of the crawl space in combination with no ventilation, might be the only option.

Crawl spaces have become increasingly popular in Central Europe too, especially for timber buildings. However, a lack of engineering guidelines and poor knowledge of physical principles often leads to inconvenient design. Therefore a complex research project consisting of a full-scale experiment, laboratory measurements, and numerical simulations has been started. Its main objective is to check which design principles are suitable for Central European conditions, but also cost-effective enough to compete with the regionally traditional slab-on-ground foundations.

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