HEAT LOSSES FROM A SLAB-ON-GROUND STRUCTURE WITH A LOW TEMPERATURE FLOOR HEATING SYSTEM IN NORDIC CLIMATE

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Summary

The main objective of this research is to determine the effect of a low temperature floor heating system on the total heat loss via the slab-on-ground structures in Nordic climate. The research is based on long-term field test measurements of two new row houses in Southern Finland. One of the houses has a low temperature floor heating system and the other, a reference building, has a traditional radiator heating system. Temperatures of the slab and adjoining fill or drainage layers underneath the surveyed apartments are measured during a one-year period. The measured values are later compared to the heat loss determined by the Standard EN-ISO 13370.

According to the results, the average temperature of a slab-on-ground with a low temperature floor heating system is 6…10 –degrees higher during the heating season than the average slab temperature of a traditionally heated building. This increases the heat losses into the ground. According to the comparison the annual heat flow via a ground slab increases by 45 %, if the average slab temperature rises by 6 –degrees. According to the comparison between the field test results and theoretical calculations, the standard EN ISO 13370 can be used, with relatively accuracy, to estimate the annual average heat flow rates into the ground. The standard is also an indicative tool to estimate the effect of a floor heating system on the total heat loss into the ground in comparison to the similar unheated floor structure.

1. Introduction

1.1 Background

Unlike any other part of the building envelope, the slab-on-ground structure is continuously in contact with a relatively cool subsoil surface, which acts as a heat sink continually conducting heat from the slab and foundation. Several analytical (Muncey et al. 1978, Claesson et al. 1991, Delsante et al. 1983, Hagentoft 1988) and semi-analytical (Krarti et al. 1988, Chuangchid 2001) as well as empirical methods (Mitalas 1987) have been developed to predict the heat loss from slab-on-ground floors. The literature includes also several field and large scale tests concerning the heat loss and thermal behavior of the concrete slab-on-ground structure with floor heating (Lood 1996, Athientis 1993 ,Adjali 2000). The heat loss via ground from a slab-on-ground structure is compounded of a part through the ground to the outside air, a part into the subsoil itself and a part into the groundwater. The effect of the outside air on the subgrade temperatures and further on the temperature gradient over the slab and heat flow rate is strongest near the edge of slab as the thermal conditions under the mid section of a slab remain more constant throughout the year. Presumably this phenomenon emphasises on heated slab-on-grade structures during the winter months in heating season as the slab temperature and the heat flow rate to the ground increases simultaneously with the decrease of the monthly mean outdoor temperature. The main objective of this study is to compare the heat flow rates via the ground floor from buildings that have either a traditional radiator heating system or a floor heating system embedded inside the ground floor slab. The objectives are achieved by a series of field measurements in which the temperature field under a slab-on-ground structure in two new row houses is measured starting from the beginning of the first heating season.

1.2 Heat Loss via Slab-on-ground Structure

In this research the total heat loss via a slab-on-ground structure is determined from the temperature data gathered by field tests. The test data includes the temperatures of the heated slab or indoor air and the fill temperatures underneath a slab structure. The total heat flow through the slab is calculated by using the measured temperature difference $\Delta T = T_{internal} - T_{fill}$ (K) and the nominal thermal resistances R (m^2K/W) of the structural layers in between. Density of heat flow rate q (W/m^2) to the ground can be defined by equation (1):

$$q = \frac{\Delta T}{R} \,. \qquad (W/m^2) \qquad (1)$$

1.3 Standard EN ISO 13370

The measured flow rates are compared to the theoretical heat losses determined by the European Standard EN ISO 13370 (1998), which gives methods of calculation of heat transfer coefficients and heat flow rates for building elements in thermal contact with the ground, including slab-on-ground floors. It applies to building elements below a horizontal plane in the bounding walls of the building situated at the level of inside floor surface. The given calculation method includes the steady-state part of the heat transfer and the part due to periodic seasonal variations in temperature on monthly basis. Standard does not apply to shorter period of time.

2. Field tests

This research is based on long-term field test measurements of two new row houses in Southern Finland. Temperature changes of the fill layer beneath the slab structure, as well as the temperatures of the indoor air, the concrete slab and the outdoor air are registered three times a day during over a yearlong survey period. One of the buildings, the reference case 1, is heated with radiators and the other, the case 2, has a low temperature floor heating system.

2.1 Reference case 1

The reference case 1 represents a row house with a typical slab-on-ground structure where one-meter high block footing is filled with compacted gravel. The subsoil in the site is silt or silty clay. The slab includes h_s = 80 mm thick massive concrete slab and h_i = 50 mm insulation layer of expanded polystyrene (EPS) underneath (Fig.1 a). One meter wide strip along the exterior wall lines has an additional horizontal EPS – insulation h_i = 50 mm. In addition, h_i = 100 mm thick horizontal expanded polystyrene frost insulation surrounds the building perimeter. The building has a radiator heating and the basic balanced ventilation systems. The instrumentation is assembled during the construction period in a single apartment in two measuring points. The apartment extends across the building and has two external wall lines with a length of L = 10 m. The width of the examined apartment is B =9,8 m and the total floor area A = 98 m^2. One of the measuring points is located underneath the centre part of the slab (measuring point A) about 3,5 meters from the nearest external wall line and the other at the outer corner of the building (measuring point B) approximately 0,5 meters from the nearest wall.

Field test results from the reference case 1 are presented in Fig.2. The measured fill temperatures are presented in comparison to the average diurnal outdoor temperature measured at the site. The building was completed in late January and therefore also the heating system was first switched on at that time. The unfinished building was occasionally unheated during early winter and therefore the detected initial fill temperatures were relatively low, also beneath the centre part of the slab (point A). However, the fill temperatures rise rapidly after the radiators were turned on and the thermal balance between the building and the subsoil is reached by the following August.

Below the slab centre the fill temperature vary between T_{max}=+19°C in late August and T_{min}=+16.5°C in January. The annual temperature change is therefore ΔT=2.5°C. At the slab edge the annual temperature variation is much stronger: the maximum fill temperature was detected in late August T_{max}=+19°C and the minimum in mid January, T_{min}=+7.5°C, yielding to the total annual temperature variation of ΔT=11.5°C. The average indoor temperature during the heating season was $T_{int} \approx$+21°C.

2.2 Case 2

The case 2 is another row house in Southern Finland. The instrumented apartment resembles the reference case 1, as it extends across a B = 11 m wide building and has two external wall lines with the length of L =10 m. The total floor area of the studied apartment is A = 110 m^2. The slab-on-ground structure includes a heated concrete slab h_s = 80 mm with an even h_i = 150 mm expanded polystyrene (EPS) insulation (Fig. 1 b). The slab structure is built on top of h_f = 800mm thick gravel fill. Subsoil at the site is silt. The slab has a low temperature floor heating system with embedded heating pipes applying water as a heat conduction medium. A single cross-section perpendicular to the exterior wall line is instrumented with temperature gauges. Instrumentation includes five measuring points with four thermocouple-elements attached to the plastic assembly bar and buried into the fill layer before the construction and several semi-conductor thermoelements assembled in different levels inside the concrete slab. Results of the field test are presented in Fig. 3. The slab edge in Figure 3 represents the measuring point located 0,3 meters from the nearest external wall line and the slab centre the point 3,5 meters from the same wall line. The first heating season of the building started in mid November as soon as the thermal envelope of the new building was sealed. To dry out the in situ cast concrete slab before flooring assembly the power in the floor heating circuit was increased in February, which is clearly visible in the measured slab temperatures. Thermal balance between the slab and the subsoil is achieved during the first heating season and the following summer. During this time the fill temperature slowly increases, and the maximum temperature beneath the slab centre is achieved in late September T_{max}=+19°C. The slab temperature at the time is T_{slab}=+25°C. By mid January the fill temperature has decreased only by one degree to T_{min}=+18°C. At the slab edge the maximum temperature in late August was T_{max}=+18°C and the minimum value during the following winter T_{min}=+12,5°C. The corresponding annual temperature difference at the slab edge is ΔT=5,5°-degrees.

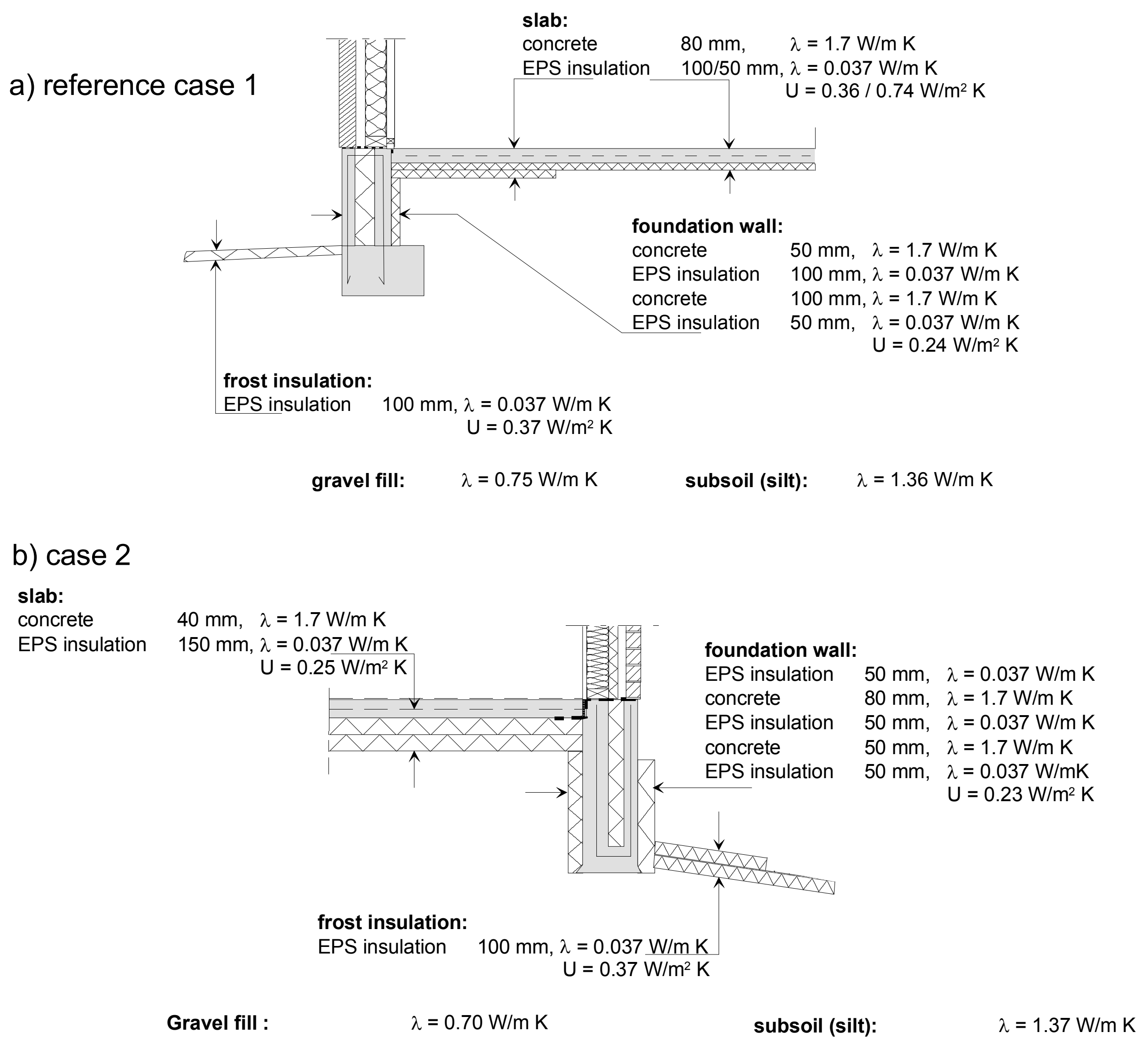

Figure 1 Nominal thermal conductivities of the wall/floor junction, slab, frost insulation and the adjoining soil layers of the two reference cases and the thermal transmittance values (U –value) of different structural components:

a) reference case 1 with a radiator heating system,

b) case 2 with a floor heating system.

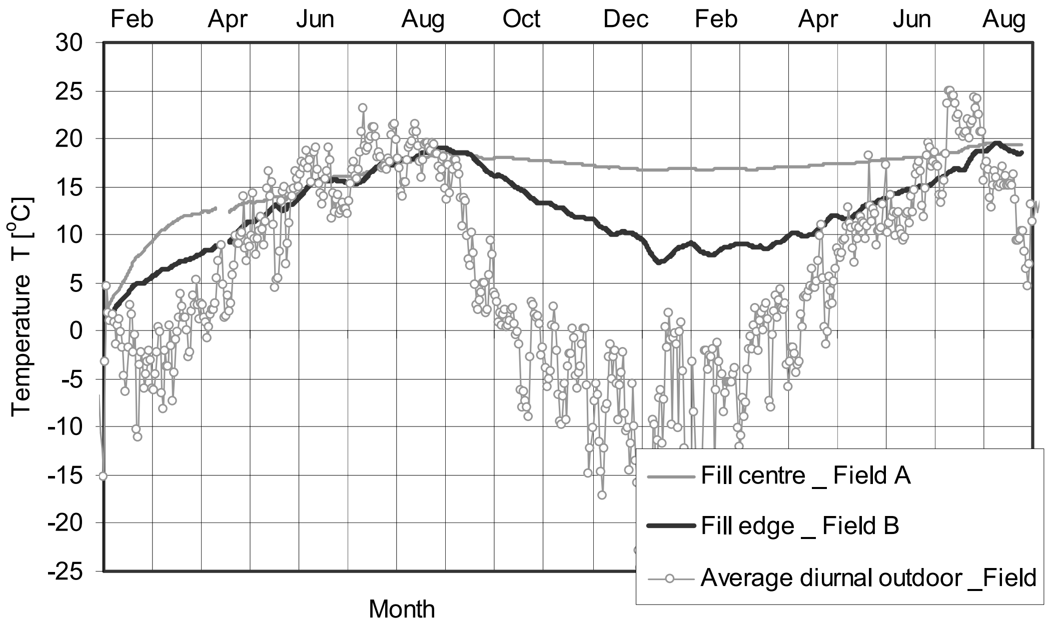

Figure 2 Reference case 1 – a row house with a radiator heating system. Field test results defining temperature changes of the fill layer underneath the slab-on-ground structure.

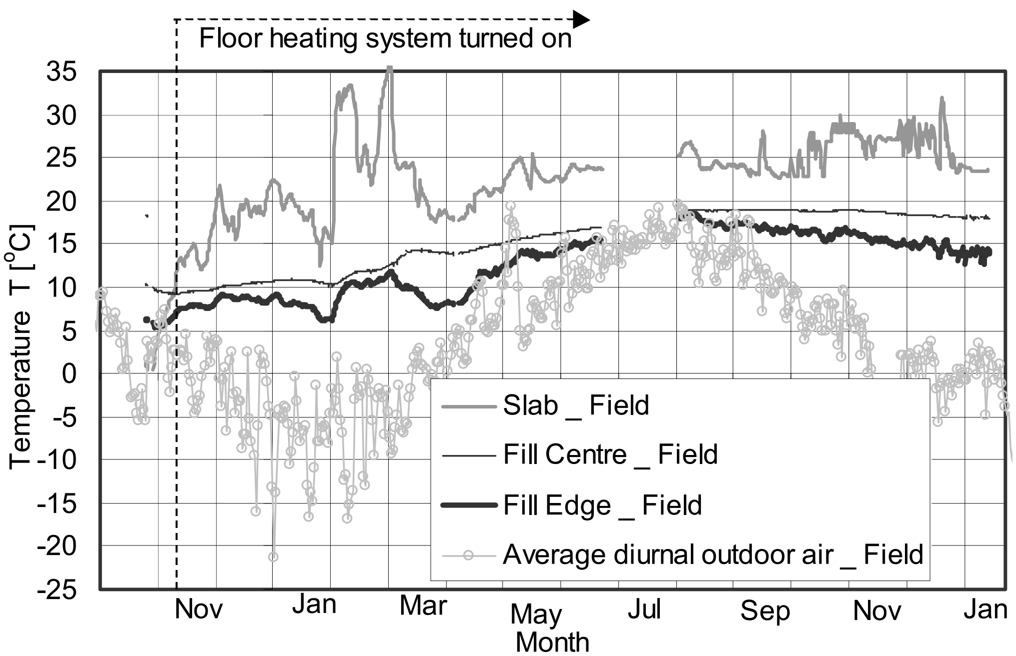

Figure 3 Case 2 – a row house with a floor heating system. Field test results defining temperature changes of the fill layer underneath the slab-on-ground structure.

3. Heat flow rates

Heat flow rates through the slab structure are calculated from the field test results according to the equation (1). The reference building 1 is heated with radiators and therefore the main heat source of the structure is the indoor air. Thus, the applied temperature gradient ΔT at the case 1 is the temperature difference between the measured indoor air temperature and the measured fill temperature at the location of interest. R is the total thermal resistance of all structural components between these two measuring points including material resistances of the thermal insulation, the concrete slab as well as the surface resistance of the slab.

With the case 2 the heating elements embedded inside the ground floor are located approximately in the middle of the concrete slab. These elements are the only heat source of the building, and therefore the required temperature gradient *ΔT* at the case 2 is the temperature difference between the middle point of the concrete slab and the fill temperature at the location of interest. *R* is now the total thermal resistance of structural components including thermal insulation and a half of the thickness of the concrete slab. Calculated thermal resistances of ground floors for the cases 1 and 2 are presented on Table 1. The density of heat flow rate is examined at the centre and at the edge of the slab using the thermal data presented in Figures 2 and 3. The examined period starts from September and continues till late summer the following year. The determined values of heat flow rates via the ground slab are presented for the reference cases 1 and 2 in Figures 4 and 5, respectively.

The flow rates determined by EN ISO 13370 are determined using the estimated thermal conductivities of subsoil at the sites (Table 1) and by applying thermal resistances of footing walls as vertical edge insulation surrounding the perimeter of the floor (Fig. 1,Table 1). This provided the greatest reduction in heat loss including the case 1, which also had additional horizontal edge insulation (Fig.1).

Table 1 Thermal resistances R of the ground floor structures and the thermal conductivity λ of subsoil in heat flow rate calculations

	Case 1		Case 2	
	Slab edge	Slab centre	Slab edge	Slab centre
Thermal resistance R of ground floor (m^2 K/W)	2.78	1.4	4.0	4.0
Thermal conductivity λ of subsoil (W/m^2K)	1.1		1.35	
Thermal resistance R of footing wall (m^2 K/W)	4.0		4.0	

3.1 Reference case 1

In Figure 4 the determined heat flow rates for the reference case 1 are presented together with the calculated estimation for the monthly average flow rate according to the standard EN ISO 13370. The calculated value is given as a monthly flow rate divided by the total floor area of the studied apartment ($q = \Phi_m/A$).

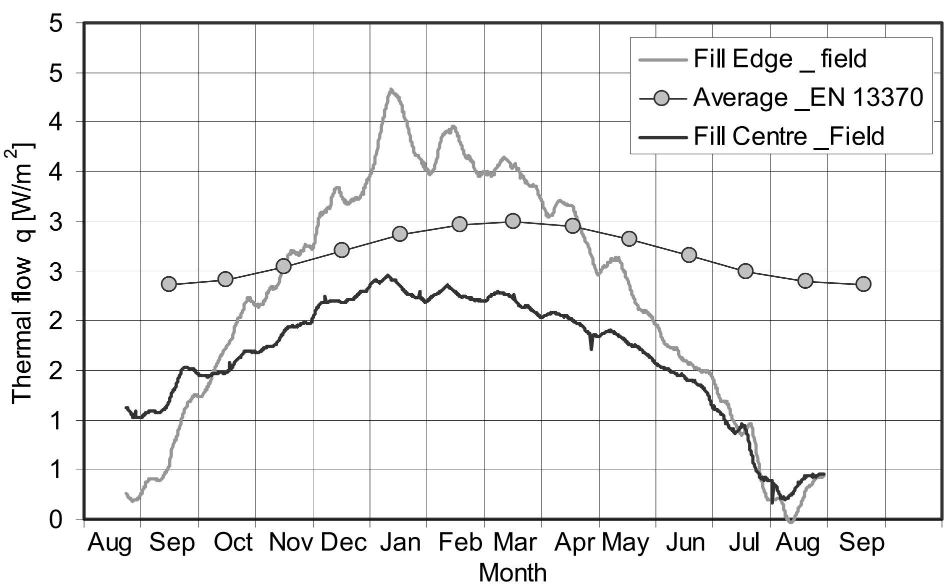

Figure 4 Reference case 1 – a row house with a radiator heating system. Measured heat flow rates into the ground at the slab edge and centre in comparison to the monthly average flow rate estimation for the entire floor area calculated by EN ISO 13370.

According to the field measurements, the annual average heat flow rate at the slab centre is approximately q_{ave} = 1.7 W/m^2 and at the slab edge q_{ave} = 2.2 W/m^2. The average heat loss via the slab edge is approximately 22% higher than through the slab centre. The maximum rate values are detected in mid winter between January and March. The maximum rate at the slab edge is q_{max} = 4.4 W/m^2 and at the slab centre q_{max} = 2.5 W/m^2. Thus, in winter the average heat loss at the slab edge is approximately 34 % higher than at the centre part of the slab. According to the EN ISO 13370 the estimated average annual heat flow rate for the entire floor area is q_{an} = 2.7 W/m^2 ($q_{an} = \Phi_{av}/A$).

3.2 Case 2

Figure 5 presents the heat flow rates determined from the field test data for the case 2. Due to the sudden increase in heating power in February (Fig. 3) the determined flow rates have a corresponding peak season in mid winter. The maximum detected flow rate at the slab edge at that time is only 17 % higher, q_{max} = 6 W/m^2, than at the slab centre q_{max} = 5 W/m^2. The average annual flow rate at the slab edge is q_{ave} = 2.4 W/m^2 and at the slab center q_{ave} = 2.1 W/m^2. According to the EN ISO 13370 the estimated average annual heat flow rate of the floor area was q_{an}= 3.1 W/m^2.

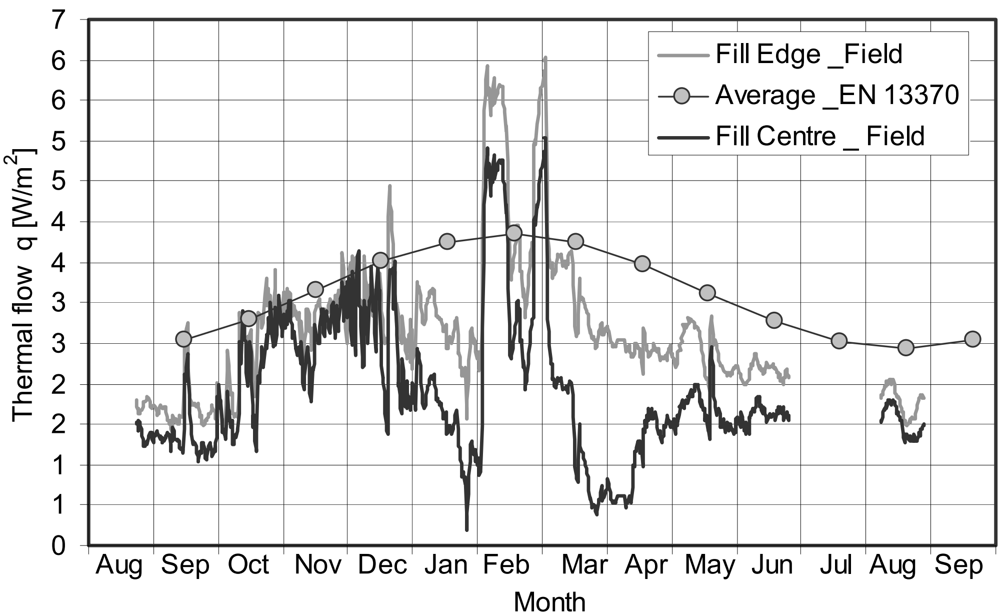

Figure 5 Case 2 – a row house with a floor heating system. Measured heat flow rates into the ground at the slab edge and centre in comparison to the monthly average flow rate estimation for the entire floor calculated by EN ISO 13370.

4. Comparison and discussion

The two reference cases described earlier in this paper have two different heat distribution methods: a traditional radiator heating system (reference case 1) and a low temperature floor heating system (case 2). Both of the case buildings have a typical Finnish slab-on-ground structure with an in situ cast concrete slab, an underneath insulation layer (expanded polystyrene, EPS) and a tall separate footing wall structure based on concrete footings (Fig. 1). Due to the different heating methods applied in these buildings, the heat flow rates into the ground also form differently. In the reference case 1 the ground slab acts as any other part of the building envelope while the heat flow occurs between the heated indoor air and the surroundings of the building: the subsoil and the external environment. The slab temperature is relatively low during the winter, even lower than the indoor air, T_{slab} = 19…20°C, due to the thermal resistance of the flooring material and the surface resistance.

In the case 2 the function of the ground slab is completely different. The concrete slab itself acts as a heat distribution element in the building. Therefore the slab temperature during the heating season is considerably higher than with the reference case 1. During the second heating season from late September till January the measured slab temperatures varied between T_{slab} = 25…30°C. The higher slab temperature increases the heat loss into the ground.

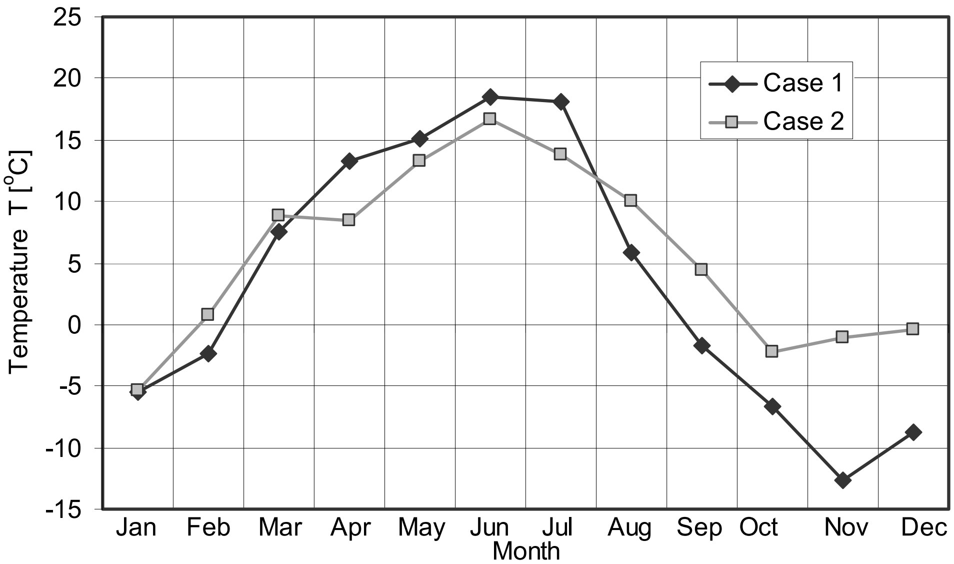

Figure 6 Monthly mean external temperatures of the reference cases 1 and 2 measured at the test sites.

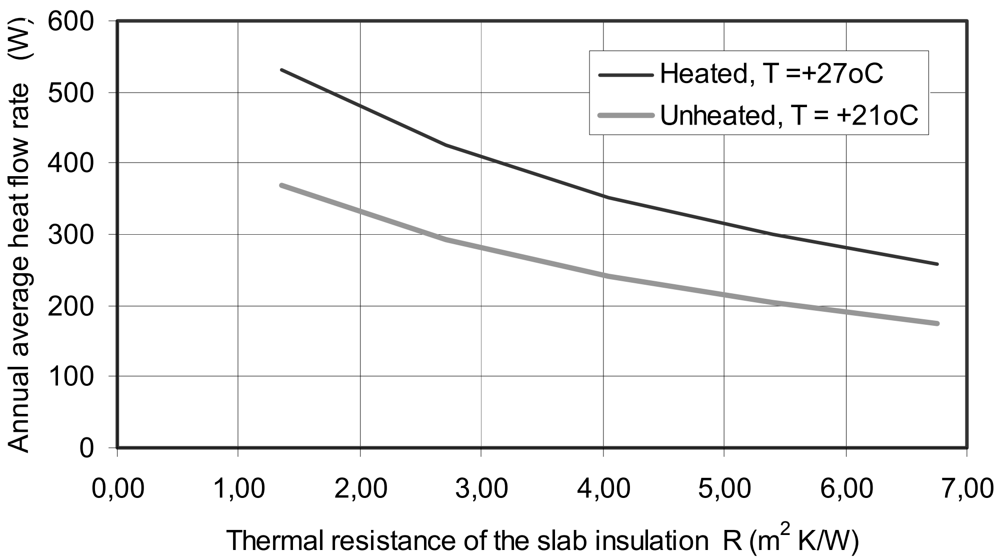

Figure 7 Theoretical annual average heat flow rates into the ground from a building with different average slab temperatures: T_{slab}=27°C or T_{slab}=21°C.The thermal resistance of the slab insulation vary between R_{min} = 1.36 m^2 K/W and R_{max} = 6.76 m^2 K/W.

This is clearly evident after a simply comparison between the results and conditions of the two studied cases. The thermal resistance of the slab insulation in reference case 2 was R_{edge} = 4.0 m^2 K/W, which is considerably higher than with the case 1 (R_{edge} = 2.78 m^2 K/W). At the same time the external temperature conditions between the cases were somewhat different for the favour of the case 2 as presented in Figure 6. The average outdoor temperature during the field measurements of the case 1 were considerably lower during the heating season, the fall and winter, which should increase the heat loss especially through the slab edge. Yet the determined flow rates via slab edges are almost equal as the annual average flow rate through the slab edge in the case 1 was q_{ave} = 2.2 W/m^2 and with the case 2 q_{ave} = 2.4 W/m^2. In slab centre, where the thermal resistance of the case 1 was even lower than at the slab edge (R_{centre} = 1.4 W/m^2K), the corresponding values were q_{ave} = 1.7 W/m^2 and q_{ave} = 2.1 W/m^2, respectively.

The monthly average flow rates (Fig. 4 and 5) and the annual mean flow rates determined by the standard EN ISO 13370 yield to the similar conclusions. The average annual flow rate calculated for the case 1 (q_{ave} = 2.7 W/m^2) is slightly lower than the corresponding value for the case 2 (q_{ave} = 3.1 W/m^2).

In addition to the field test measurements a limited series of theoretical calculations is performed. The method presented by the standard EN ISO 13370 for the calculation of the annual average heat loss rate is used. Three otherwise equal buildings are assumed to have either a floor heating system embedded into the slab structure or a traditional radiator heating system. The average annual slab temperature of the radiator heated building is assumed to be T_{slab} = 21°C and the corresponding slab temperature of the building with a floor heating system T_{slab} = 27°C. The average external temperature in all cases was T_{ext} = 5°C and the thermal conductivity of the subsoil λ = 1.1 W/m K. The thermal resistance of the footing wall was a constant R = 4.0 m^2 K/W. The thermal resistance of the all-over insulation beneath the slab structure vary between R_{min} = 1.36 m^2 K/W and R_{max} = 6.76 m^2 K/W. The results of the comparison calculations are presented in Figure 7.

According to the comparison result the annual average heat loss into the ground increases approximately 45 %, if the average slab temperature rises by 6 –Celsius degrees. The average flow rate into the ground from an unheated ground slab (T_{slab} = +21°C, Φ = 369 W) with the thermal resistance of R = 1.36 m^2 K/W (h_i = 50 mm EPS –insulation) equals the average flow rate of a heated ground slab (T_{slab} = 27°C) with a thermal resistance of R = 3.92 m^2 K/W (h_i = 145 mm EPS insulation). The difference between the slab resistances is almost 200 %. Thus, the theoretical calculations yield to the similar conclusions than the performed comparison of the field test data. The average flow rate of an unheated slab with the resistance of R = 2.70 m^2 K/W (Φ = 293W) equals the rate from a heated slab having a resistance of R = 5.67 m^2 K/W. Now the difference between the resistances is only 110 %. Further more, if the initial resistance of an unheated slab is R = 4.05 m^2 K/W (Φ = 242 W), the required thermal resistance of a heated slab is just 83 % higher, R = 7.43 m^2 K/W.

5. Conclusions

During the heating season the average slab temperature of a heated ground slab with a low temperature floor heating system is considerably higher than the average slab temperature of a traditionally (radiator) heated building. According to the field test measurements the temperature difference can be up to ΔT =10°C. The higher slab temperature increases heat losses into the ground. According to the performed theoretical calculations, the annual average heat loss into the ground slab increases approximately 45 %, if the average slab temperature rises by 6 –Celsius degrees. The comparison of the field test data yields to the similar conclusions. Therefore the thermal resistance of a slab-on-ground structure with an embedded floor heating system should be considerably higher than the resistance of an unheated ground slab. The sufficient thermal resistance of a ground slab structure is dependent on the climatic and the subsoil conditions at the particular site. The standard EN ISO 13370 presents a method to estimate, with relatively accuracy, the annual average heat flow rates into the ground. The standard can be used, at least, as an indicative tool to estimate the effect of a floor heating system on the total heat loss into the ground in comparison to the similar unheated floor structure.

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