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Published in:
Proceedings of the 8th Symposium on Building Physics in the Nordic Countries

Publication date:
2008

Document Version
Publisher's PDF, also known as Version of record

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KEYWORDS: Building envelope; EPS; Prefabricated elements; Strip foundation, Double brick wall, Single-family house, non-freezing ground

***SUMMARY*:**
A new prefabricated lightweight element was designed for a strip foundation that was demonstrated on site as the base of a single-family house with a double brick wall. The element was placed on a stable surface underneath the top soil layer, just 0.25 m underneath the finished ground surface. The prefabricated element was designed to fulfil the requirements of low energy consumption required by the new Danish Building Regulations. The base of the house was cast in one working operation and completed within two working days. The element, made of expanded polystyrene, was designed to be handled on site by one man. A non-freezing ground was established by using outer insulation located at the outer plinth. Temperatures were measured at measurement points located at the outer plinth and onwards from these points underneath the building. In addition the soil temperature, the temperature within the concrete floor slab and indoor and outdoor temperatures and relative humidity were measured.

1. Introduction

In 2005 the Danish Government presented an action plan that aimed to promote significant results in the energy field. This action plan will have an impact on Danish energy-saving initiatives in the years to come (Ministry of Transport 2005). The action plan includes a description of the Danish energy sector in the years up to 2025. One subject in the strategy is the climate policy related to the Kyoto Protocol, United Nations (1998), which entered into force on 16 February 2005. As part of the internal distribution of obligations within the EU, Denmark must reduce its emissions of greenhouse gases by 21% compared with 1990 emissions (Olesen, *et al.* 2004).

The draft plan in particular focuses on energy consumption in buildings, where the largest and most cost-effective potential for energy savings lies. The most important initiative is a tightening of energy provisions in the Danish Building Regulations (Danish Enterprise and Construction Authority 1995).

The tightening of energy provisions in the Danish Building Regulations will apply both to new and existing buildings. Besides strengthening the current regulations in 2006, the plan paves the way for a further strengthening in 2010 and in 2015. The tightened energy provisions were entered in the Danish Building Regulations on 1 January 2006 and came into force on 1 April 2006, and they are expected to result in an energy reduction of 25 % for new buildings compared with the former building regulations. The new energy provisions incorporated in the Danish Building Regulations (Danish Enterprise and Construction Authority 2008) have had an impact on energy consumption in buildings, in that the regulations focus on the building envelope as well as individual building components. One focus area has been heat loss through the strip foundation of a building. In order to meet the new energy consumption requirements and the need to improve innovation and efficiency in the building environment, an alternative solution to the strip foundation traditionally used in Denmark and built 0.9 m below the finished ground surface was tested on site.

The alternative solution was a prefabricated element made of expanded polystyrene that was demonstrated used as strip foundation and the base of a single-family house with a double brick wall. The prefabricated element was to meet the same performance requirements as traditional solutions.

Methods for establishing stable non-freezing ground underneath the building, taking advantage of natural geothermal energy, (Steiner 2004), were described and instructions were drafted of how to handle the element on site.

2. Temperature Measurements

The temperature was measured using type T thermocouples and a datalogger, type 605. The junction of the thermocouples was covered with epoxy. Data from the datalogger were transferred to a PC and a computer program processed the results. The datalogger was placed outdoors in a waterproof plastic container located over and above the finished ground surface. The plastic containor was sealed to ensure a dry clean location for the datalogger. The plastic container included an electrical supply for the datalogger as well as a 10 W heating element. Measurement points were located on site underneath the strip foundation, at the outer plinth and underneath the insulation layer in the ground deck, and cast in the concrete floor slab of a building. In addition one measurement point was located in the soil, approximately 0.4 m underneath the ground level. Measurement points were not exposed to direct sunlight and were well away from any heat producing appliances. The temperature was recorded every hour.

3. Meters for Measurement of Indoor and Outdoor Climate

The indoor an outdoor climate was measured by means of small dataloggers. Data from the individual dataloggers were transferred to a PC and a computer program processed the results. Dataloggers were placed at locations approximately 2.5 m above the ground level, not exposed to direct sunlight and away from any heat or moisture producing appliances. The climate was recorded every hour. The indoor and the outdoor climate was determined by the indoor and the outdoor temperature, together with the indoor and the outdoor relative humidity.

4. Materials Used for the Strip Foundation

The prefabricated elements were made of expanded polystyrene to form an element that could be used as strip foundation of a house of up to two storeys. Elements were produced as one coherently shaped element through a production including an injection molding process. The expanded polystyrene is produced from a mixture of about 5-10% gaseous blowing agent (most commonly pentane or carbon dioxide) and 90-95% polystyrene by weight. The solid plastic is expanded into a foam through the use of heat, usually steam. The polystyrene is filled with trapped air, which gives it low thermal conductivity. This makes it ideal as a construction material used as insulation in building systems, (Petersen 1986). In the following the expanded polystyrene will be referred to as EPS. The calculated thermal conductance is 0.034 W/mK.

The EPS element was specially designed to form the strip foundation that together with the ground deck represents the base of a traditional double brick wall with insulation, see FIG. 1a). However, the EPS element is unique in its design though it can also be used for a traditional wood-stud wall, or combinations of lightweight concrete, brick and wood-stud walls with insulation (Valdbjørn Rasmussen 2007). The prefabricated element was produced as units of 1.2 m in length and 0.6 m in width. The prefabricated element has a density of 33.0 kg/m^3.

5. Performance-based Criteria for the Design of Strip-foundation Element

The prefabricated element of EPS has been designed to comply with the new Danish Building Regulations (Danish Enterprise and Construction Authority 2008), which allow very little heat to be lost through the strip foundation between the ground deck and the exterior wall. In the following the heat loss through the strip foundation will be referred to as the surplus heat loss, [W/mK]. The surplus heat loss is defined as the heat loss that can be attributed neither to the one-dimensional heat loss through the ground deck nor to the exterior wall. Surplus heat loss through the joint between the ground deck and the exterior wall is to a great extent related to the design of the strip foundation (Janssens A. *et al.* 2007).

Buildings that meet the new energy provisions of 1 January 2006, which came into force on 1 April 2006 and are incorporated in the Danish Building Regulations (Danish Enterprise and Construction Authority 2008), must in practice, when using heating in the concrete floor slab, normally not exceed a surplus heat loss of 0.12 W/mK. When using conventional heating in the building, the surplus heat loss must not exceed 0.15 W/mK. Danish Building

Regulations require the overall coefficient of heat transmission of the ground deck and the exterior wall to be equal to or less than 0.12 W/m^{2}K and 0.2 W/m^{2}K respectively.

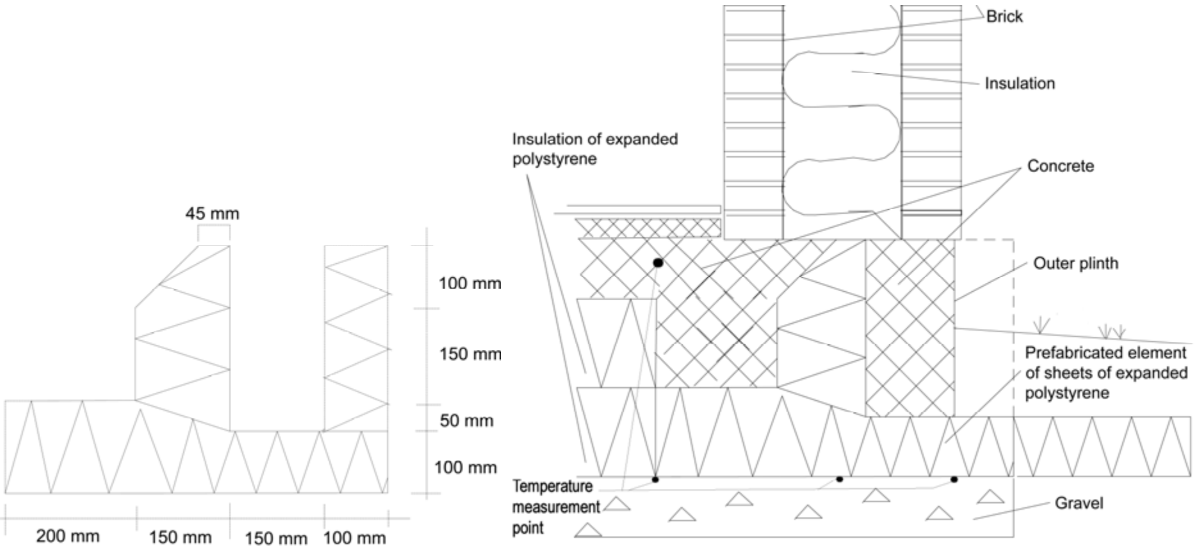

FIG. 1 a): left, the prefabricated element made of EPS, b):right, the EPS element used as the strip foundation of a traditional double brick wall separated by mineral-based insulation.

Calculations of the surplus heat loss through the prefabricated element were carried out by using a PC and the finite difference program HEAT2 version 5.0 in accordance with the method described in Danish Standards 2002. Calculations are dynamic with the outdoor temperature changing throughout the year, see FIG. 2.

FIG. 1b) shows the prefabricated element of EPS used as the strip foundation of a traditional double brick wall, separated by mineral fiber insulation, with an interim insulation of 0.17 m^{2}K/W. Stainless steel rods of 5 mm in diameter were put through the EPS, every 0.6 m, forming the mechanical fastening point of the concrete for the outer plinth and the concrete floor slab. The contribution of the mechanical fastening to the surplus heat loss through the strip-foundation element is 0.002 W/mK (Danish Standards 2002, Table A.3.2).

The overall coefficient of heat transmission of the exterior wall was 0.2 W/m^{2}K. The surplus heat loss was calculated to be 0.14 W/mK for a building with heating in the concrete floor slab. Calculations were carried out with a temperature of the concrete floor slab of 30 ^{o}C and with an interim insulation to the soil of 1.5 m^{2}K/W, which allows the overall coefficient of heat transmission of the ground deck to be 0.1 W/m^{2}K. Using conventional heating in the building, the surplus heat loss was calculated to be 0.13 W/mK. For the calculations, the temperature towards the concrete floor slab was 20 ^{o}C with an interim insulation to the ground deck and soil of 1.67 m^{2}K/W, which allows the overall coefficient of heat transmission of the ground deck to be 0.09 W/m^{2}K.

Calculations were carried out with the specific heat capacity of the soil and the thermal conductivity of the soil set to 2.0 MJ/m^{3}K and 2.0 W/mK, respectively.

6. Ensuring Stable Non-freezing Ground Underneath the EPS Element

Ensuring stable non-freezing ground underneath the building is necessary for maintaining the stability of the structure and avoids settling cracks. To ensure stability of the strip foundation, it is important that temperatures lower than -1 °C do not occur in any layer susceptible to frost underneath the building during a cold winter (Danish Standards 2001). Temperatures below -1 °C underneath the capillary breaking layer during a cold winter could cause frost deformations of the soil underneath, and this would increase the risk of the strip foundation settling. Boards of EPS from the outer plinth of the strip foundation were used to form the part of the prefabricated element called the outer insulation. At the vicinity of a corner of a building, the necessary outer insulation was designed on the basis of the experience using the PC finite difference program HEAT2 for 2D and 3D calculations. Calculations showed that if the temperature was determined to be +1.6°C along the facade of the building this was equal to -1°C at the vicinity of a corner of the building. Experience was gained from calculations on different types of foundation all dug at lower depth. Temperature characteristics for a cold winter were fed into the model using a design value of 100 years, based on the descriptions given in the Danish Standards 2001. The lowest average temperature of a month was decreased from -0.5 °C in a normal year to -7.3 °C in a cold year (Rose 2006), see FIG. 2.

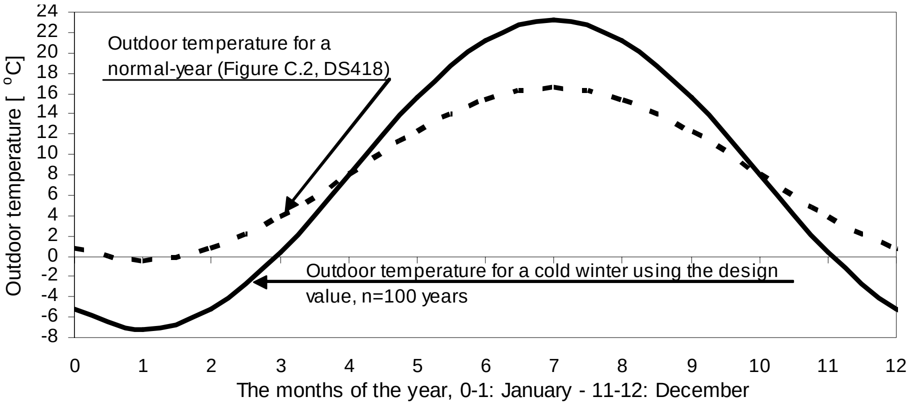

FIG. 2 Variation of the outdoor mean month temperature for a normal year and for a cold year in Denmark.

Outer insulation was designed for three different cases describing the indoor temperatures, 1) an indoor temperature of 20 °C, 2) an indoor temperature equalling the outdoor temperature but not lower than 5 °C and 3) an indoor temperature equalling the outdoor temperature.

Along the facade of a building, calculations showed that an outer insulation of EPS (0.1 m in thickness and extending 0.4 m in front of the outer plinth of a building facade just 0.15 m under the finished ground surface) was sufficient to keep the soil just underneath the gravel layer from freezing during a cold winter, while keeping an indoor temperature equal to the outdoor temperature.

At the vicinity of a corner of a building there was a need for extending the outer insulation if the indoor temperature was not kept at 20 °C. Keeping an indoor temperature at 20 °C in the building, it was calculated that it was adequate with an outer insulation of EPS, 0.1 m thick and extending 0.4 m in front of the outer plinth just 0.15 m under the finished ground surface in order to keep the soil just underneath the gravel layer at the vicinity of a corner of a building from freezing during a cold winter. If the indoor temperature was kept equal to the outdoor temperature but not lower than 5 °C, it was sufficient with an outer insulation of EPS, 0.1 m thick and extending 0.7 m in front of the outer plinth just 0.15 m under the finished ground surface, in order to keep the soil just underneath the gravel layer at the vicinity of a corner of a building from freezing during a cold winter. However, maintain an indoor temperature equal to the outdoor temperature, an outer insulation of EPS (0.1 m thick and extending 0.9 m in front of the outer plinth and just 0.15 m under the finished ground surface) was able to keep the soil just underneath the gravel layer at the vicinity of a corner of a building from freezing during a cold winter. It was recommended that the vicinity of the corner includes the area in the ground in front of the corner and the area along the facade of a building, at least covering the extra length of outer insulation along the outer plinth around the corner.

7. Performance on Site and Location of Temperature Measurement Points

In most locations in Denmark a stable ground of glacial deposits (moraine) is found underneath a top soil layer of approximately 0.2 to 0.4 m in thickness. The top soil layer was removed in an area covering the ground of the building. Material at least up to a depth 0.35 m underneath the top soil surface had to be dug up. The excavated area was then covered with a 0.1 m capillary breaking layer of gravel, which was stamped in order to form the stable base for the building. Temperature measurement points were mounted and the prefabricated elements were mounted as the strip foundation. The strip foundation elements were held together with large stable-shaped pieces of plastic, 0.3 m of EPS in two layers was mounted inside the strip foundation serving as insulation underneath the concrete floor slab. Before casting the concrete, iron was mounted preventing shrinkage crack development, as a net in the concrete floor slab and as wires performing circular reinforcement in the concrete forming the outer plinth. Wires were located in the moat formed by the two vertical boards of EPS in the prefabricated elements. Wires of stainless steel

rods, 5 mm in diameter were put through the inner vertical boards of the prefabricated elements of EPS every 0.6 m, in order to attach the concrete at the outer plinth cast in the moat to the concrete floor slab. Concrete was cast and levelled. After a few hours, when the concrete was stable in shape, the outer vertical boards of the prefabricated elements of EPS were removed exposing the outer surface of the concrete moat as the outer plinth. The removed outer vertical boards of EPS were used as the outer insulation on the ground around the outer plinth, see FIG 1. The base of the house was cast in one working operation and completed within two working days. The strip foundation was handled on site by one man.
On site, temperatures were observed at locations in the zone between the capillary break layer of gravel and the layer of EPS. Temperature measurements were made at measurement points located along two lines. Firstly, along a line taking its starting point at the north/eastern corner, under the strip foundation at the outer plinth and onwards from this point at a 45^{o} angle horizontally, underneath the building. Temperature measurement points were located along the straight line $\sqrt{2}$ *(0, 0.2, 0.5, 1 and 2) m from the outer plinth corner. Secondly, along a line taking its starting point 3 m from the north/eastern corner along the side of the building facing east, under the strip foundation at the outer plinth and onwards from this point along a straight line at a 90^{o} angle horizontally, underneath the building. Temperature measurement points were located along the straight line 0, 0.2, 0.5, 1 and 2 m from the outer plinth, see FIG. 1b). In addition the temperature of the concrete floor slab of the building was observed at four points along the two straight lines, where temperatures were measured, just above the measurement point located $\sqrt{2}$ *0.5 m and $\sqrt{2}$ *2 m from the outer plinth on the first line and above the measurement point located 0.5 and 2 m from the outer plinth on the second line, see FIG. 1b). Temperature measurements along the two lines located horizontally and temperature measurements within the concrete floor slab were carried out underneath the same room of the building. Furthermore the soil temperature was measured 2 m from the north/eastern corner along the side of the building facing east in front of the strip foundation 0.2 m from the outer plinth 0.4 m below the ground level.

8. Indoor and Outdoor Climate

The indoor and the outdoor climate was measured at locations in the shadow. The first winter the building was under construction. The second winter the building was ready for occupation and not heated. Results from the temperature and relative humidity measurements indoors and outdoors are shown in FIG. 3. Measurements are shown as mean values of measurements made over a 6-hour period.

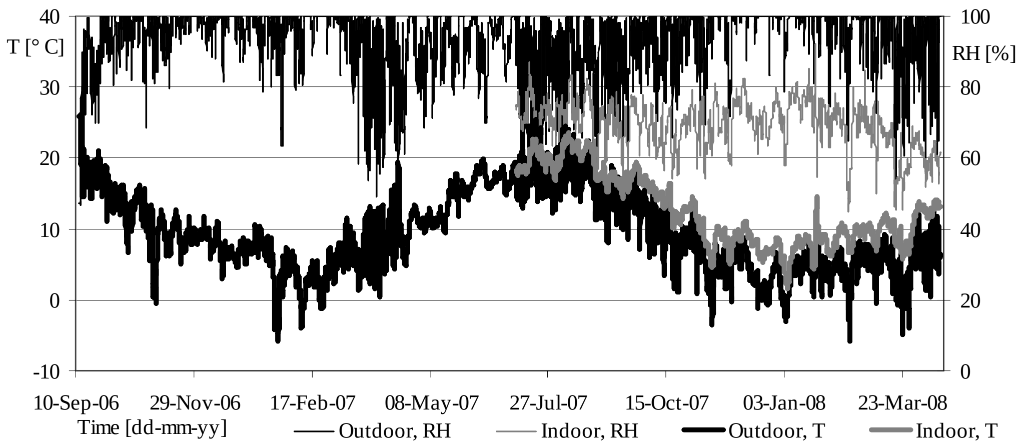

FIG. 3: Temperature and relative humidity measured indoors and outdoors at shady locations. Measurements are shown as mean values of measurements made over a 6-hour period.

9. Temperatures Calculated at Measurement Points

The outdoor temperature has an impact on the temperature at the measurement points in between the capillary break layer of gravel and the layer of EPS underneath the building. Table 1 shows the lowest temperatures calculated at the measurements points facing the east-facing facade for the strip foundation shown in FIG. 1b). Calculations were carried out for the tree different cases describing the indoor temperature, denoted 1), 2) and 3) for a normal year and for a cold year.

TABLE. 1: Lowest temperatures calculated at measurement points facing the east-facing facade. Measurement points were located under the strip foundation from under the outer plinth and onwards from this point along a straight line 0, 0.2, 0.5, 1 and 2 m underneath the house referred to as Facade #1, Facade #2, Facade #3, Facade #4, Facade #5, respectively.

Measurement points	Facade #1	Facade #2	Facade #3	Facade #4	Facade #5	Inside
Normal year	5.0 °C	6.0 °C	7.2 °C	8.4 °C	9.9 °C	20 °C
Normal year	4.0 °C	4.7 °C	5.5 °C	6.4 °C	7.5 °C	$\geq$5 °C
Normal year	3.8 °C	4.4 °C	5.1 °C	5.9 °C	6.9 °C	Outdoor
Cold year	1.7 °C	3.2 °C	5.0 °C	6.9 °C	9.3 °C	20 °C
Cold year	0.7 °C	1.9 °C	3.4 °C	5.1 °C	7.0 °C	$\geq$5 °C
Cold year	0.2 °C	1.2 °C	2.4 °C	3.9 °C	5.7 °C	Outdoor

10. Results

Results from temperature measurements on site between the capillary break layer of gravel and the layer of EPS underneath the building are shown in FIG. 4 and FIG. 5. FIG 4 shows temperature measurements at 5 locations along the line that starts at the north/eastern corner, from under the strip foundation at the outer plinth and onwards from this point at a 45° angle, in the following referred to as Corner #1, Corner #2, Corner #3, Corner #4 and Corner #5 respectively, located along the straight line $\sqrt{2}$ * (0, 0.2, 0.5, 1 and 2) m from the outer plinth. FIG. 5 shows temperature measurements at 5 locations along a line that starts 3 m from the north/eastern corner along the side of the building facing the east-facing facade, from under the strip foundation at the outer plinth and onwards from this point at a 90° angle, also referred to as Facade #1, Facade #2, Facade #3, Facade #4, Facade #5 respectively, located along the straight line 0, 0.2, 0.5, 1 and 2 m from the outer plinth. Measurements are shown as mean values of measurements made over a 6-hour period.

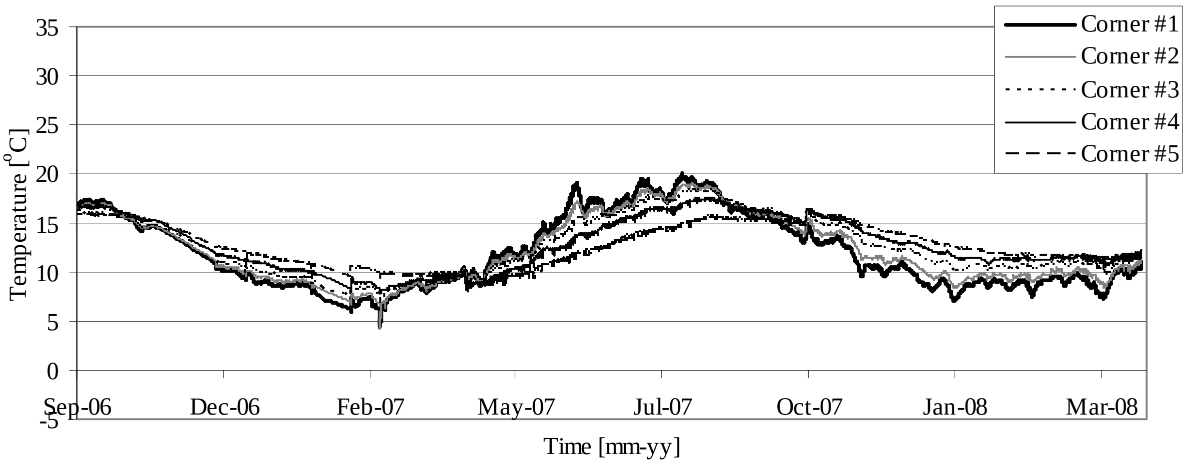

FIG. 4. Temperature measurements at 5 locations along the line that starts at the north/eastern corner, from under the strip foundation at the outer plinth and onwards from this point at a 45° angle.

Results from temperature measurements on site within the concrete floor slab of the building and within the soil are shown in FIG. 6. The measurements at the 4 locations within the concrete floor slab vertically above the locations Corner #2, Corner #5, Facade #2 and Facade #5, are referred to in the following as Corner #1 concrete, Corner #2 concrete, Facade #1 concrete and Facade #2 concrete. In the following, measurement of the soil temperature is referred to as Soil. Measurements are shown as mean values of measurements made over a 6-hour period.

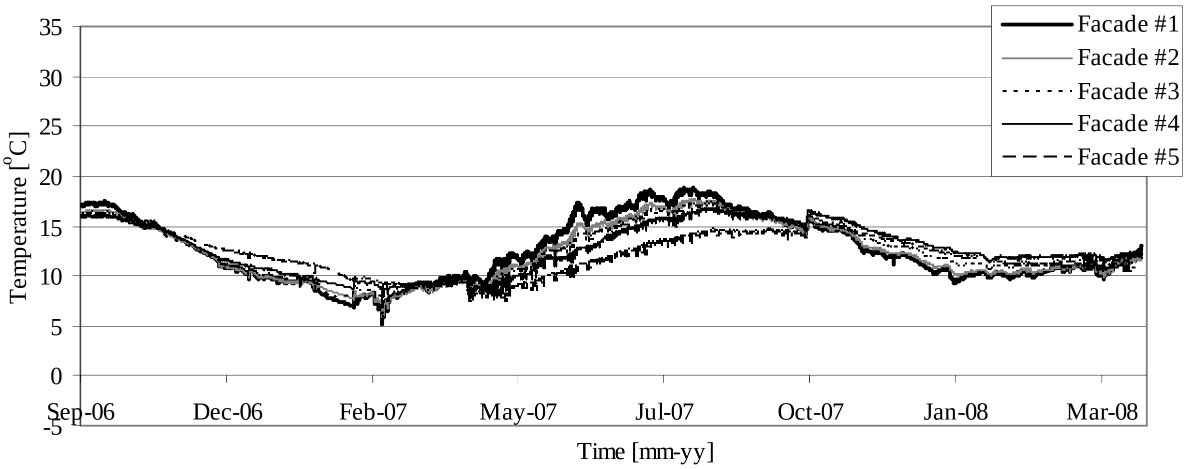

FIG. 5. Temperature measurements at 5 locations along a line that starts 3 m from the north/eastern corner along the side of the building facing the east-facing facade, from under the strip foundation at the outer plinth and onwards from this point at a 90^o angle.

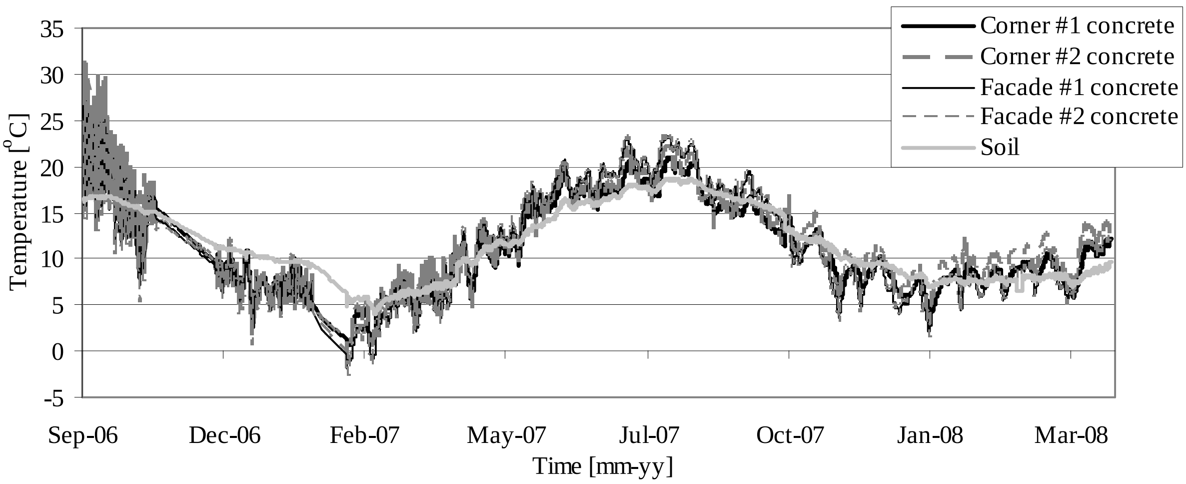

FIG. 6. Temperature measurements within the concrete floor slab of the building and in the soil.

11. Summary and Conclusion

The study investigated the performance of a new prefabricated lightweight element used as strip foundation of a single-family house with a double brick wall. The element meets the requirements for low energy consumption outlined in the new Danish Building Regulations (Danish Enterprise and Construction Authority 2008) for a single-family house with a double brick wall using conventional heating. It was shown that the element could be built on stable ground of a capillary breaking layer of gravel underneath the top soil layer, just 0.25 m underneath the finished ground surface. For a real-life situation the base of the house was cast in one working operation and completed within two working days. The strip foundation was handled on site by one man. The house was open and under construction during the first winter of investigation and ready for occupation but not heated the second winter, see FIG. 3 to FIG. 6.

Stable non-freezing ground underneath the building was ensured by using insulation located at the outer plinth. Temperature measurements on site, FIG. 3 to FIG. 6 indicate case 2), a house with an indoor temperature equalling

the outdoor temperature but not lower than 5 °C exposed to outdoor temperature for a normal-year. As listed in TABLE 1, case 2) normal-year shows that the method for calculating the temperatures under the strip foundation, outlined by Danish Standards (Danish Standards 2001 & 2002), was calculated to be comparable with the measurements on site. However, using the PC finite difference program HEAT2 for 2D and 3D, calculations were shown to provide conservative results determining the need of outer insulation that would ensure stable non-freezing ground underneath a building. Furthermore, it was demonstrated that outer insulation is needed to ensure stable non-freezing ground underneath the house, which is necessary for maintaining the stability of the structure and preventing settling cracks during a cold winter by taking advantage of natural geothermal energy.
Designing a strip foundation element to meet the requirements of low energy consumption, this study has demonstrated that the strip foundation must provide full and continuous cover of insulation of the heated part of a building.

12. Acknowledgement

Sundolitt A/S, Denmark, has supported this field study.

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