In situ Performance of Expanded Molded Polystyrene in the Exterior Basement Insulation Systems (EIBS)

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ABSTRACT: Several different Exterior Basement Insulation Systems (EIBS) were built and instrumented as part of the basement consortium[2] research project. These EIBS specimens were instrumented prior to back filling with soil, and their in situ thermal performance was monitored over two years. Soil temperatures and moisture content were monitored concurrently. Weather data were recorded on a daily basis.

Through analysis of the measured surface temperature records, the presence of water was detected at the outer surface during various periods of heavy rain and major thaws throughout the two-year period. During these periods, the surface of the concrete showed no evidence of water penetration through the insulation layer over most of the height of the basement wall.

Since the test setup involved different thermal insulating materials placed next to each other, the presence of lateral heat flow was inevitable. Both 2-D and 3-D models were used to quantify the lateral heat flow across the edges of different insulating materials. The measured spatial and temporal temperature profiles were used as boundary conditions.

The thermal performance of each insulation specimen was found to remain stable over the two-year period and was not significantly affected by episodes of water movement at the exterior face of the specimens. The thermal resistance of

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[2] The consortium included the Canadian Plastics Industry Association, the Expanded Polystyrene Association of Canada, the Canadian Urethane Foam Contractors Association, Owens Corning Inc., and Roxul Inc.

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many specimens showed small (5% on average) improvement in the second year. This apparent improvement was likely caused by the drier soils in the second year of testing.

The insulation specimens were retrieved after 30 months of exposure in the soil. Moisture content as well as thermal and mechanical properties of the materials were evaluated in the laboratory and compared to initial properties. It was concluded that the specimens did not show signs of deterioration in thermal or mechanical performance.

KEY WORDS: exterior insulation, thermal resistance, thermal performance, heat transfer, basement walls, 2-D model, 3-D model, calculation, analysis, temperature, heat flow, heat loss.

BACKGROUND

INCREASED USE OF basements as habitable spaces, combined with the requirements for energy conservation, initiated development of different insulated basement systems. External basement insulation systems in addition to controlling heat loss may also have a significant effect on the moisture performance and durability of basement walls.

In this context, the Canadian thermal insulation industry, working with the National Research Council, decided to revisit[3] the design and performance of external insulation basement systems (EIBS). Specimens were installed on the exterior of two basement walls of an experimental building located on the NRC Campus in Ottawa. The following specimens were placed on the exterior basement wall in November 1995 and monitored over the period from June 1996 to June 1998: ten expanded polystyrene (EPS), two spray polyurethane foam (SPF), two mineral fiber insulation (MFI), and two glass fiber insulation (GFI).

The research involved a number of material and system issues. On the material side, the project involved existing and new thermal insulation products (under development) placed side-by-side to form virtual test sections. On the system side, different technical solutions were used to protect the above-grade part of the EIBS, and two different conditions for surface water drainage were provided.

Because of the large scope of this project, reporting is performed in four parts:

1. Developing analytical tools to increase confidence in the experimental results and facilitate the analysis of the field data

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[3] For detailed information, see previous publications [2,3].

2. Reporting and analyzing results obtained from the experimental basement
3. Placing the thermal and moisture performance of expanded polystyrene in below-grade application in context of other research, i.e., state-of-the-art review to identify future research needs
4. Reporting and analyzing the system effects in context of other research (state-of-the-art review to identify future research needs on the system side)

The first part of the EIBS project has already been presented by Maref et al. [1]. This paper applies the 2-D and 3-D models to the analysis of the in situ thermal resistance.

RESEARCH OBJECTIVES

The main objective of this project was to monitor changes in the in situ thermal performance of exterior insulation basement systems in relation to:

- prolonged exposure to the below-grade environment
- local environmental conditions, i.e., seasonal changes in soil temperatures, soil moisture content, and surrounding air temperatures

In addition to monitoring in situ thermal resistance, the following performance factors were investigated before and after exposure: thermal resistance of the specimens under standard laboratory conditions and compressive strength. Furthermore, a comparison was made between changes in EPS properties after exposure in the field and changes in EPS properties caused by exposure to environmental cycling performed in a laboratory.

DESCRIPTION OF THE PROJECT

The focus of this project was on changes in the in situ performance rather than on the comparison of in situ thermal resistance with that measured under laboratory conditions. This project examined in situ thermal performance of EPS (two years) and the effect of a prolonged (thirty months) exposure on three types of EPS used in exterior basement insulation systems.

Analytical Approach

If, at any instant, one was able to measure the distribution of temperature and heat flux at several locations through the thickness of the wall, one could calculate the mean apparent thermal resistance of the wall. This is not normally possible, as one can only measure these variables at the wall surfaces; one needs to include an analytical procedure to account for the effect of thermal storage. Typically, such a procedure involves averaging the apparent thermal resistance over a prescribed period of time.

Furthermore, when adjacent sections with different thermal resistance result in a multidirectional heat flow pattern, this procedure must also include a spatial element in the process. To this end, one needs to define a control volume for which all the boundary conditions are known. In this paper, the control volume is the volume enclosed by temperature measurements at the top, bottom, and thermocouple positions on the specimens at either end. As discussed later in the text, this control volume will be used for both the 2-D and 3-D analysis processes.

Installation of Test Specimens

To evaluate in situ performance of the exterior basement insulation, different materials were installed on the exterior surface of a concrete basement. As shown in Figure 1, eight test sections were placed side by side on each of two basement walls (east and west orientation) insulating the wall with approximately 76 mm thick insulation. Of these, five were EPS specimens on each wall. Three types of EPS products were used on each wall (some were duplicated so that each wall had five specimens). These are numbered 1–5.[4] Each EPS specimen was 610 mm wide.

On the interior of the basement wall, a 25 mm layer of expanded polystyrene (EPS) board was installed over the entire surface. At each test section, at three vertical locations of the opposite surface of the wall, calibrated EPS specimens, with identical thickness, were inserted into the interior EPS board. These specimens were used for determination of transient heat flux entering the wall [4].

Thermocouples were placed at the surface of each layer in the wall, in an array consisting of sixteen points per tested section. Typical sensor placement on the west wall is shown in Figure 2. All sections were fully instrumented, with the exceptions of E1, E4, and W1, which allowed measurement of temperature only at mid-height position, and W4 which was instrumented with the calibrated specimens (heat flux meters) only at the mid-height position.

Two different installation methods were used on each of the tested

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[4] The performance of other materials is not addressed in this paper.

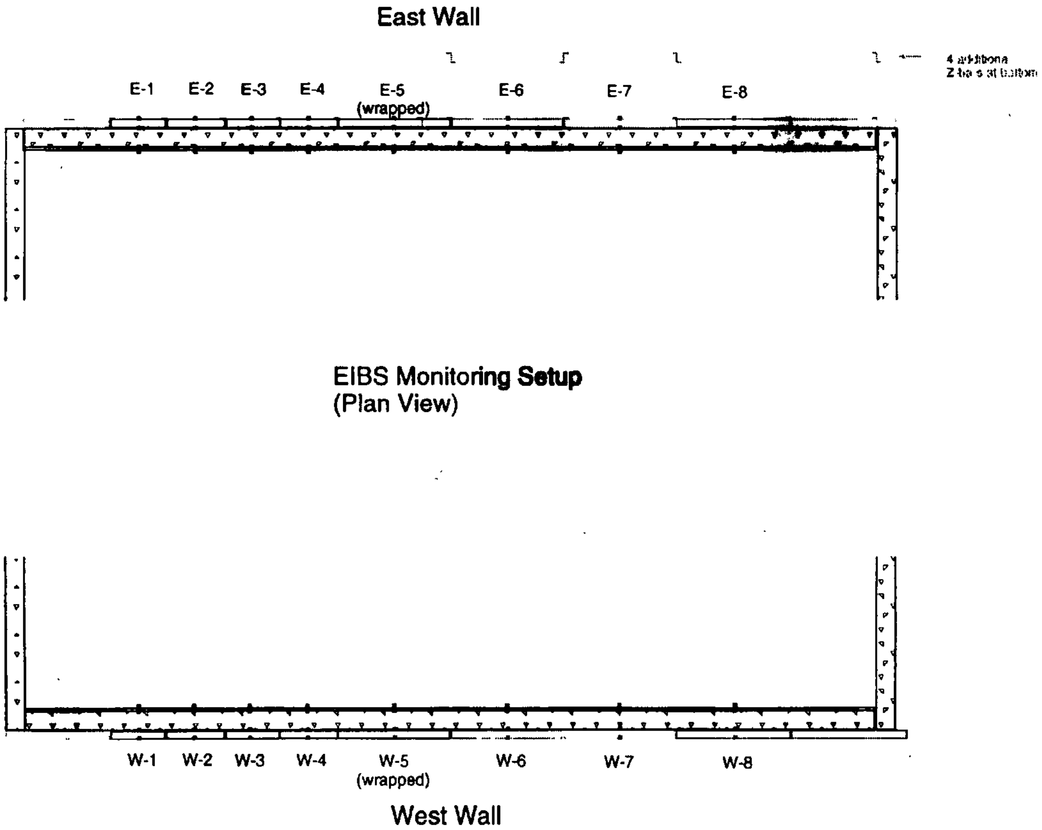


FIGURE 1. Plan view of the EIBS test setup—east and west walls of the test hut.

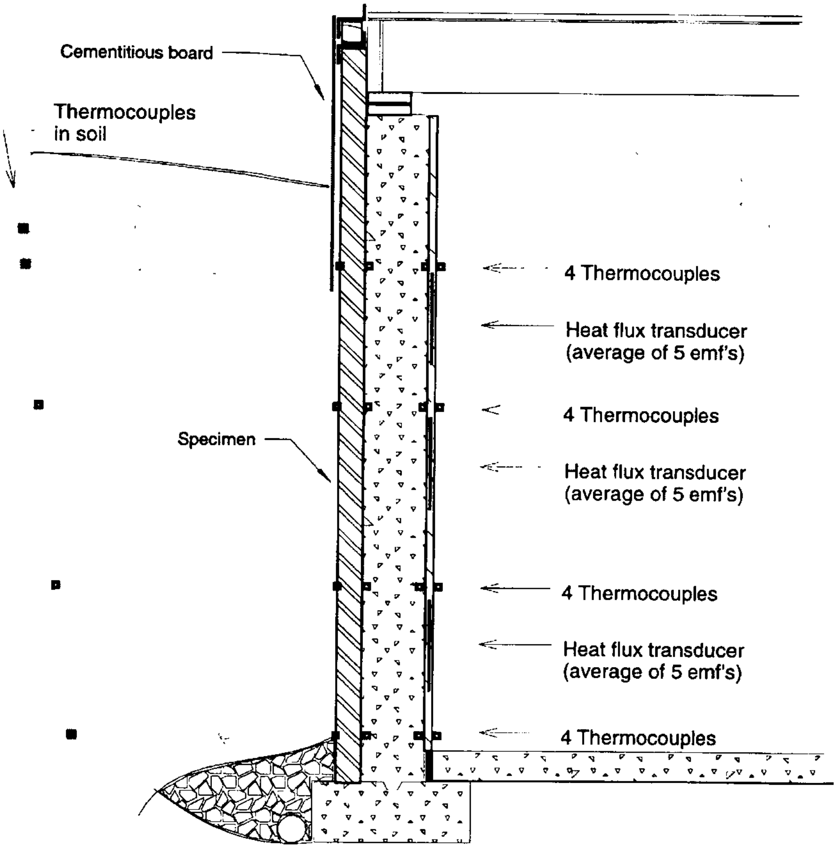


FIGURE 2. Thermocouples and calibrated insulation specimens mounted on the west wall.

walls, labeled System 1 and System 2. System 1, on the west wall (Figure 2), featured two horizontal rows of metal z-bars, separated by a wood spacer, all fastened to the floor header. Once the insulation was in place, the cement boards were fastened to the z-bars and wood spacers. No other fasteners were used, so the cement board was effectively cantilevered (hung) over the insulation specimens. The soil was sloped at 5% grade toward the wall to simulate settled soil conditions. A geotextile cover was used on top of gravel covering the drainage pipe at the west wall.

System 2, on the east wall (Figure 3), featured metal z-bar supports placed vertically between each insulation specimen. The z-bars were fastened directly to the concrete wall and wood header, and the cement board was then fastened on the outside. Each metal z-bar acted as a thermal bridge around the insulation. The grade on this side was sloped 5% away from the basement wall. No geotextile was used over the gravel covering the drainage pipe on this wall.

The parameters monitored in the EIBS project are as follows:

1. Surface temperatures on both sides of the calibrated specimen and the concrete and the test specimens
2. Heat flux across the calibrated insulation specimens
3. Soil temperatures from 1 to 2 m away from the specimens, and at five depths
4. Interior basement air temperature (average of four readings)
5. Exterior air temperature (at north face of building shielded from sun)
6. Relative humidity (RH) of indoor and outdoor environments.

Control of Interior Conditions

The indoor air of the test hut was heated in the winter and cooled in the summer. The indoor temperature was initially set at 21°C. After an initial monitoring period through the first summer, this temperature was reset to 23°C in order to increase the thermal gradients in the wall and thereby increase the accuracy of heat flow measurements in the shoulder seasons. The indoor RH was not controlled, although some summertime dehumidification probably occurred as a by-product of the cooling of the indoor air.

The drainage system featured a sump pump located close to the middle of the west wall. The level of water in the sump was observed to be quite high (at footing level) for the first 200 days of monitoring. On day 215, the sump pump controls were reset to lower the water level in the sump to about 300 mm below the footings.

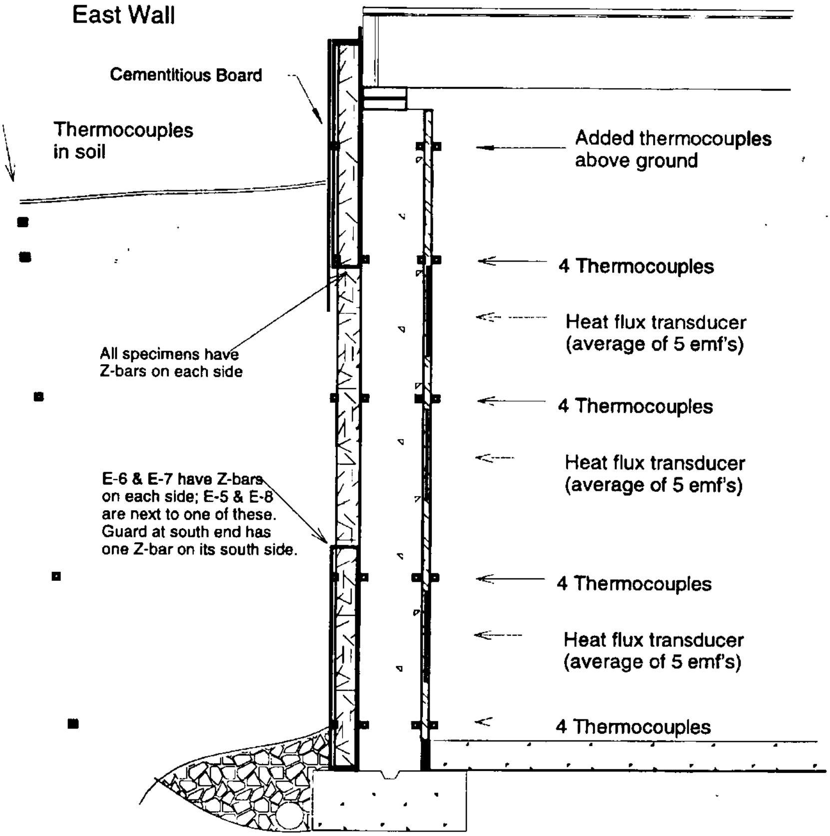


FIGURE 3. Thermocouples and calibrated insulation specimens mounted on the east wall.

Data Acquisition

The instrumentation package consisted of approximately 275 thermocouples, two RH sensors, twenty-one calibrated insulation specimens (heat flux transducers), four junction boxes, a data acquisition unit, and a computer. Data were collected with an automated data acquisition 6-1/2 digit scanning system and a high-precision multimeter to measure separate thermocouples, serial thermopiles, and relative humidity sensors. All thermocouples and power signals were routed through a command module (HP E1406) connected to a PC 486/50 computer. Measurements were taken every 2 minutes and averaged at 10-minute intervals for the wall thermocouples (five readings) and 30-minute intervals for the soil thermocouples (fifteen readings).

This information was stored on a PC hard drive and disks in ASCII files.

Duration of the Experimental Program

The data acquisition system was commissioned in the spring of 1996, and monitoring started after adjusting the air cooling system on June 5, 1996. The data acquisition program was modified to store additional thermocouple readings. Monitoring of the expanded set started on 29 September 1997 and ended on 5 June 1998.

MONITORED RESULTS

Air Temperatures

Figure 4 shows measured temperatures of indoor air, calibrated insulation specimens, concrete, and soil surface in the "mid-position" of the west wall over a period of two years. The spikes in the temperature at the interface between soil and the EIBS correspond to thaw periods with a heavy rainfall. Observe that these effects do not appear to affect the temperature at the concrete surface, because it was protected by the external insulation.

Soil Temperatures

Soil temperatures were measured at five depths at a distance of between 1 and 2 m from the wall. The results for specimen W6, measured at three depths, 150 mm, 740 mm, and 1840 mm below grade, over a two-year period, are shown in Figure 5. The sensor nearer the soil surface shows some diurnal effects and the greatest change from summer to winter. No diurnal

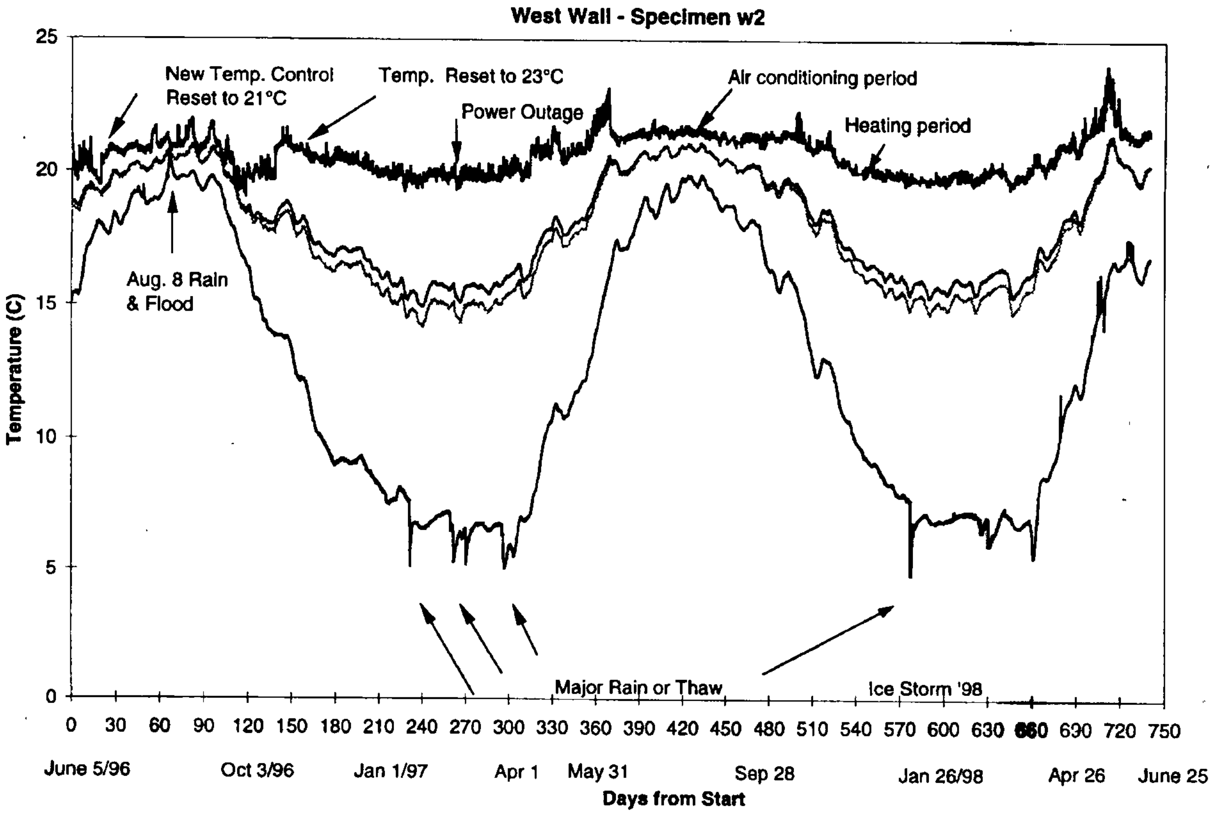


FIGURE 4. Temperature profiles at the mid-position of specimen W2 on the west wall. (Lines from top to bottom are interior wall surface, exterior concrete surface, and insulation/soil interface.)

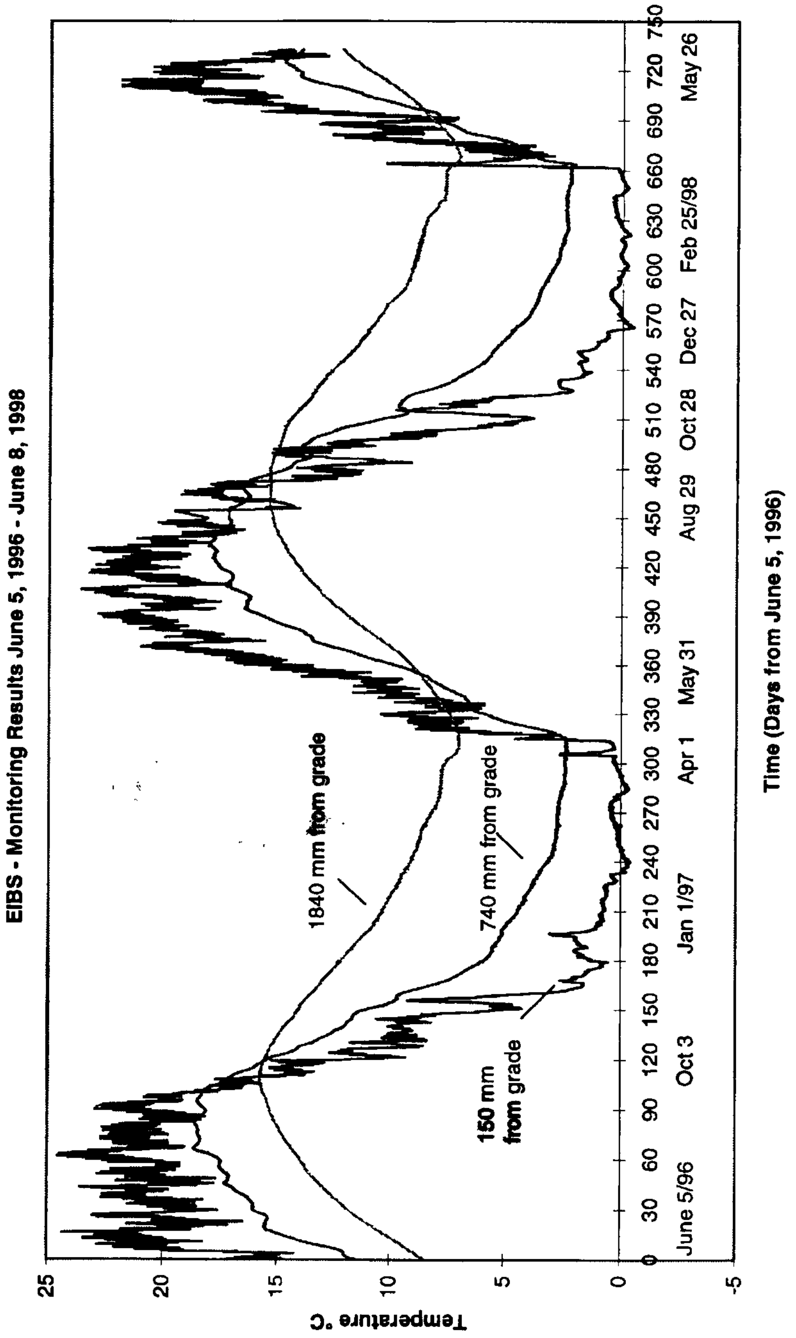


FIGURE 5. The measured temperatures in the soil 2 m from the west wall.

effects, only the annual cycle, can be seen at the two lower depths.

Low frost penetration was observed in both winters. It was approximately 150 mm in the first year and 270 mm in the second winter (not shown in graph). A deep snow-cover, and repeated thaws may be the cause of shallow frost penetration in both heating seasons. In the second winter, an additional temperature measurement was performed 10 m from the house, which showed similar results. This suggests that the effect of basement heat loss on the soil temperature is undetectable, even at a 2 m distance from the house.

Soil Moisture Content

A single TDR (time domain reflectometry) probe was placed at 1 m depth about 2 m from the east wall to record soil moisture content. Figure 6 presents the results of the soil moisture content monitoring over the period from October 1996 to June 1998. It shows that the soil was wet throughout the first heating season and dried somewhat in the summer of 1997. Throughout most of the second heating season, the soil stayed dryer until the spring thaw in 1998.

Temperature Profiles at Mid-Height, Grading Toward the West Wall

Figure 4 shows the two-year temperature records at mid-height of specimen W2 at the interior surface, both sides of the concrete, and the exterior surface of the specimen in contact with the soil. Main control events such as power outages and changes from heating to cooling and back are evident from these temperature readings. The inner surface of the wall was kept near 21°C. The temperatures at both sides of the concrete were quite similar (concrete being a poor thermal insulator). From winter to summer, the temperature of concrete varied from 15°C to 20°C.

The lowest curve in the graph is the temperature representing the insulation/soil interface. The periodic "spikes" in the curve correspond to events of heavy precipitation or winter thaws. The 8 August 1996 rain was a one-in-seventy-five-year event for Ottawa, which caused local flooding around the test hut. During this rainstorm, the temperature at the insulation/soil interface increased, apparently due to warm rainwater moving down the wall. Similar changes were observed at the mid-, low- and bottom-thermocouple positions during the same period, tracing the path of the water movement. These deflections were much less noticeable at the upper position, where the soil temperature was closer to the temperature of the moving water.

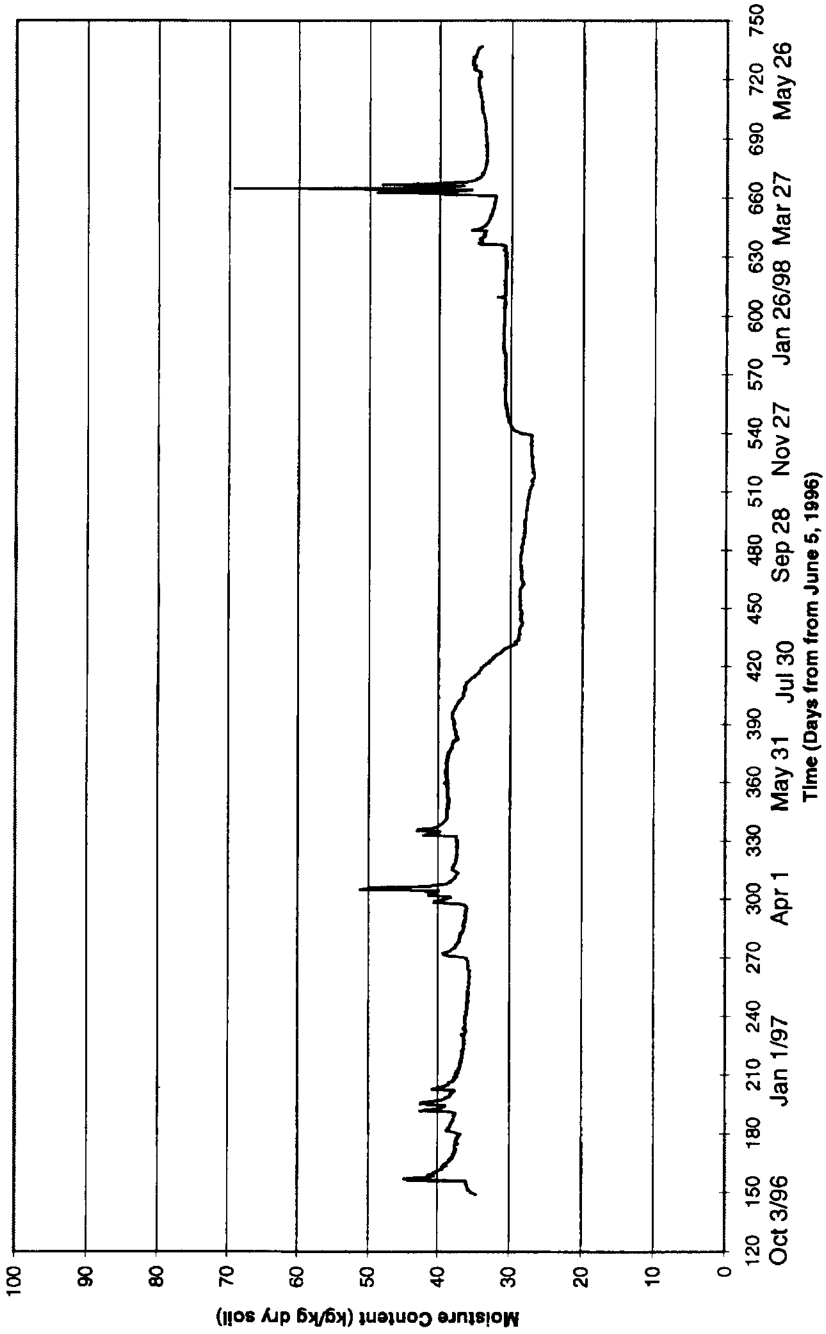


FIGURE 6. Measured soil moisture content over the monitoring period.

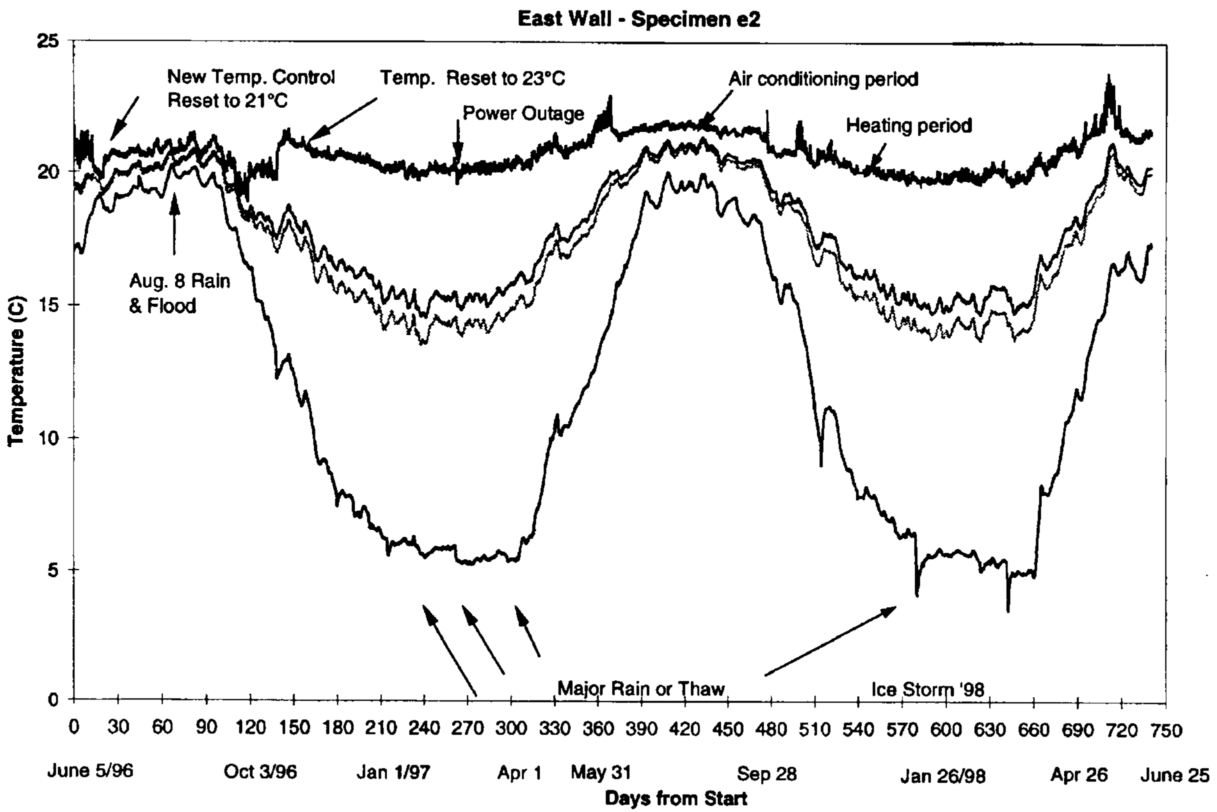


FIGURE 7. Temperature profiles at the mid-position of bottom specimen E2 on the east wall. (Lines from top to bottom are interior wall surface, interior concrete surface, exterior concrete surface, and insulation/soil interface.)

The temperatures in the winter at the soil/insulation interface were decreased because the melt water temperature was initially 0°C, which would cool the soil and insulation at the interface as melt water moved down.

Temperature Profiles at Mid-Height, Outward Grading at the East Wall

Figure 7 shows temperature measurements on the east wall for the same period and specimens that were shown in Figure 4. In the first year, these incidental temperature deviations were often smaller or absent on the east wall where the ground surface was properly graded away from the wall.

In the second year, however, the differences between the east and west walls were less noticeable, and the temperature deviations were then quite noticeable on both walls. A final review of soil slopes near the wall revealed that by the end of the second year, most of the slopes had been affected by settlement.

Temperature Profiles at Vertical Locations

Temperature profiles similar to the ones presented in Figures 4 and 7 were established for three other levels (vertical positions). It was noted that the incidental deviations in the temperature profile at the insulation/soil interface occurred at the same time, suggesting the movement of water along this interface. These temperature deviations are less apparent or nonexistent at the highest location where thermocouples are covered by the cement board (see Figure 1).

With the exception of the lowest location (50 cm up from the basement floor slab), the surface of concrete, which is behind the insulation specimen, generally did not show corresponding temperature deviations during these events, suggesting that most of the concrete wall is isolated from the apparent water movement at the soil/insulation interface.

IN SITU THERMAL RESISTANCE OF EPS

Method to Measure Thermal Resistance in situ

A test method to measure thermal resistance in situ was developed elsewhere [5,6]. This method involves testing two materials placed in contact with each other—a reference material whose thermal conductivity and specific heat are known as a function of temperature and a test specimen with unknown thermal properties. Thermocouples are placed on each surface of the standard and reference materials to measure temperatures, which are then used as the boundary conditions in the heat flow calculations.

The heat flux across the boundary surface between the reference and tested specimens is calculated using a numerical algorithm to solve the heat transfer equation through the reference material. Imposing the requirement of heat flux continuity at the contact boundary, corresponding values of thermal conductivity and heat capacity of the tested specimens are found with an iterative technique. Performing these calculations for each subsequent data averaging period results in a set of thermal properties for the test material which, over the period of measurements, gives the best match with its boundary conditions (temperatures and heat flux). This method was documented and applied for determining the in situ thermal resistance of roof insulation [5].

The 2-D Analysis

The 2-D finite difference analysis was adapted to account for two significant differences in the test setup:

1. The 200 mm thick concrete wall modifies the heat flux leaving the reference specimen by providing heat storage and by permitting the vertical and lateral heat flow in the concrete.
2. Temperatures within the insulation in contact with the ground only showed small variations through the year so that the relationship between specimen thermal conductivity and temperature was omitted.

The 2-D analysis consisted of calculating the horizontal (inside to outside) and vertical heat fluxes (bottom to top) through all materials in the control volume. A finite difference technique was used to solve the heat transfer equations for each point of a nodal network within the control volume.

Using this analysis, the temperature differences across the insulation specimen and the concrete wall were calculated for each measurement interval. The temperature difference across the reference insulation was used to determine the heat flux into the concrete. The analysis was used to assess both the direction and magnitude of heat flux in the concrete as well as the amount of heat stored or released by the concrete and the resulting net heat flux into the insulation specimen. Using this heat flux and a postulated thermal conductivity of the specimen, the resultant temperature differences across the specimen were calculated. The calculated temperature differences were then compared to the measured results for each ten-minute interval. Mean differences between measured and computed values were calculated on a weekly basis. An iterative technique was devised to minimize the mean error between the calculated and measured temperature by adjusting the postulated conductivity of the insulation specimen on a weekly basis.

The factor by which the thermal conductivity was adjusted relative to a laboratory-determined conductivity of the specimen was labeled the "conductivity adjustment factor." The thermal resistance adjustment factors, as well as the reciprocal, were recorded and plotted on a weekly basis. As a final step in the analysis process, the adjustment in thermal resistance of the specimen was normalized to an initial average adjustment for October 1996, the first period of cold weather in the monitoring period.

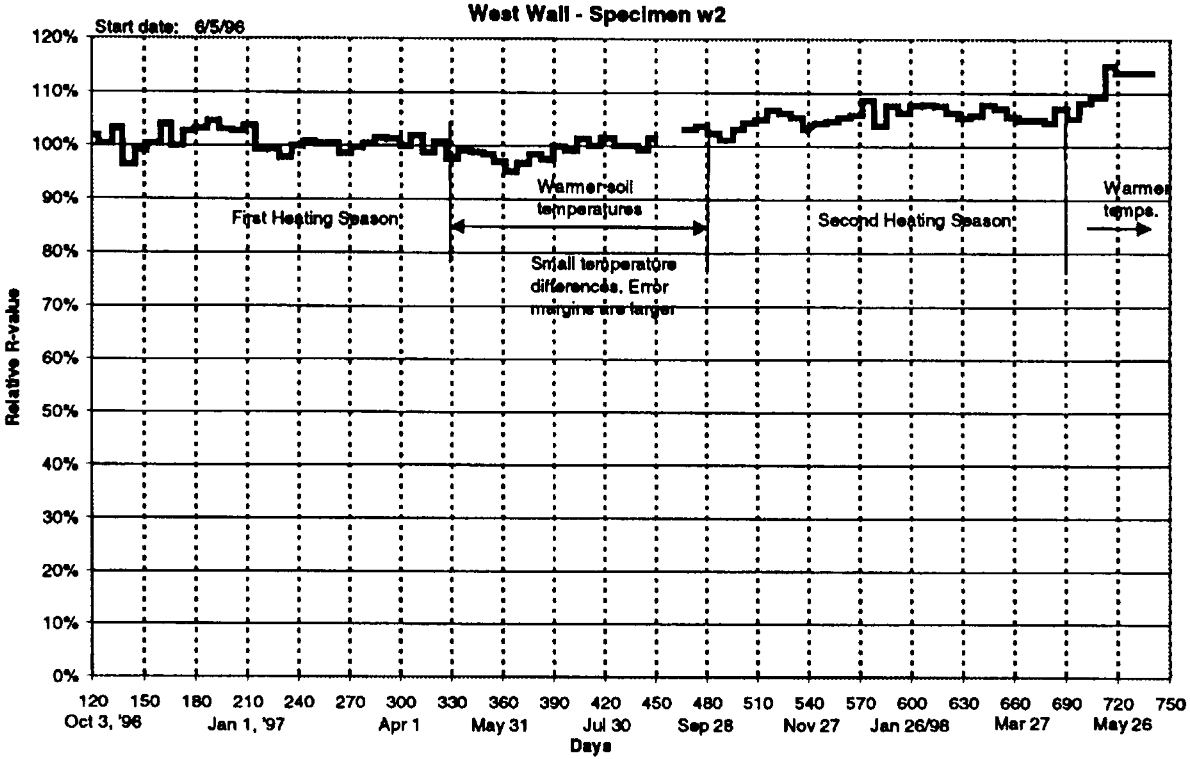
A second, more elaborate method was also developed to assess the heat loss in the third dimension, along the wall, and to suggest what corrections were needed for the 2-D results [1]. The 3-D analysis showed that very little lateral heat flow occurred between the EPS samples and that the 2-D analysis could be used to assess the relative change in in situ thermal resistance with confidence for these specimens.

In situ Thermal Resistance Results

Figures 8(a) through 8(c) show the resulting calculated relative thermal resistance for the specimens on the west wall and Figures 9(a) through 9(c) for specimens on the east wall. The plots show weekly averaged relative thermal resistance over two heating seasons.

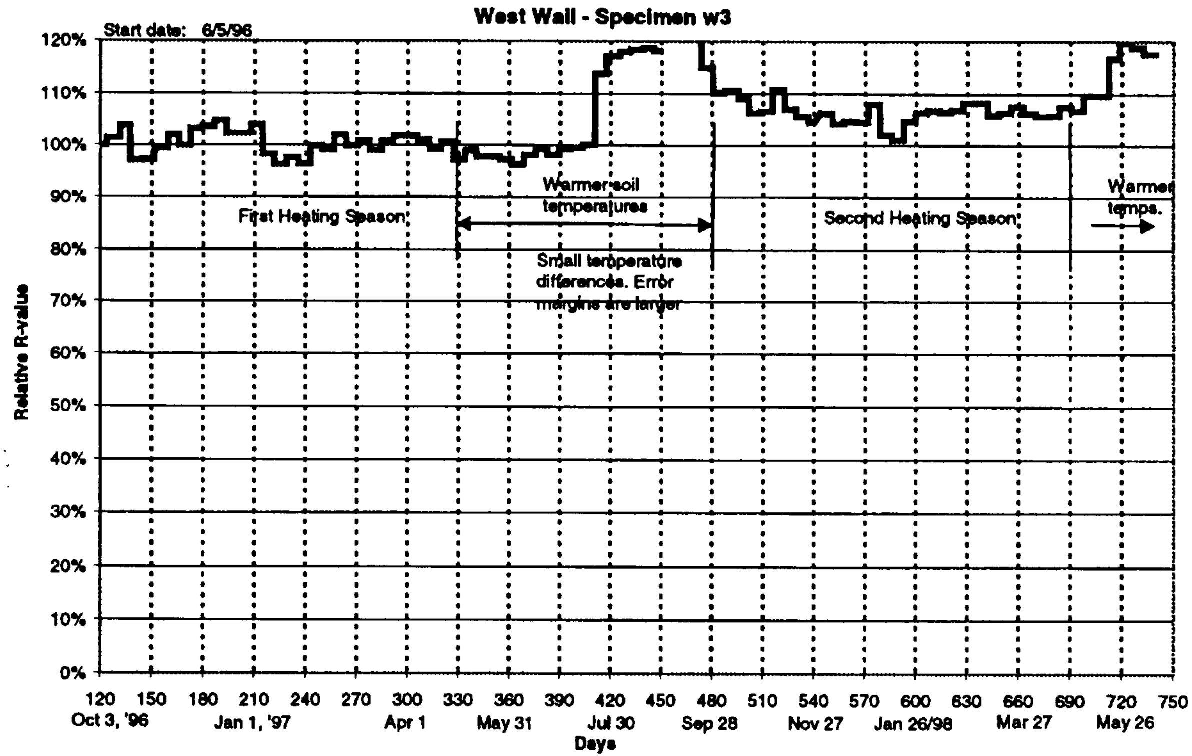
Key observations are as follows:

- Most specimens showed relatively steady performance through the heating seasons. Specimens E2 and E3 showed more fluctuation.
- The second heating season showed equal or improved average heating season performance for all specimens.
- The results for the warm periods are unreliable, since the temperature differences across the specimens were very small (normally $< 0.5°C$). During such periods, thermocouple errors can be as large as the actual temperature difference.
- On day 215, modifications were made to the sump pump that lowered water levels around the footing. Specimens W5 and W4, which were near the sump pump, appeared to have been temporarily affected by this modification.
- Major rain and thaw periods did not appear to significantly affect the thermal performance of the specimens.



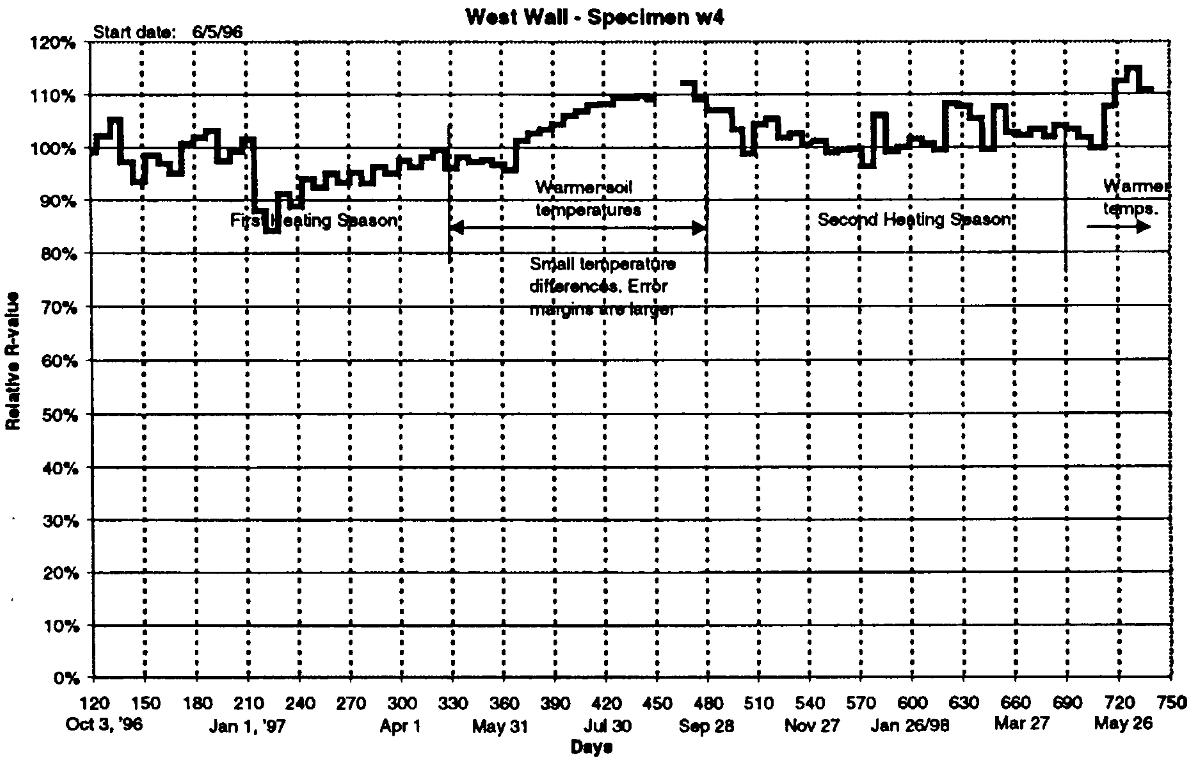
(a)

FIGURE 8. Average relative thermal resistance in the control volume of EPS placed on the west wall and normalized to the initial thermal resistance in October 1996: (a) specimen W2, (b) specimen W3 and (c) specimen W4.



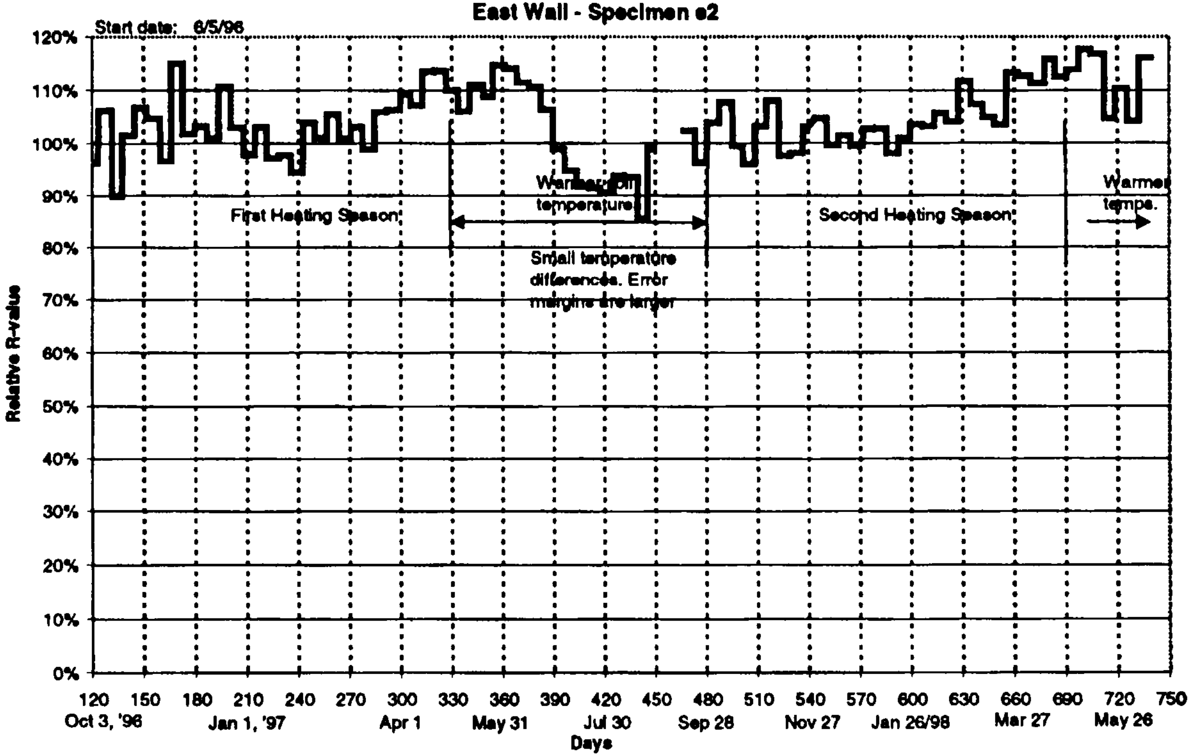
(b)

FIGURE 8 (continued). Average relative thermal resistance in the control volume of EPS placed on the west wall and normalized to the initial thermal resistance in October 1996: (a) specimen W2, (b) specimen W3, and (c) specimen W4.



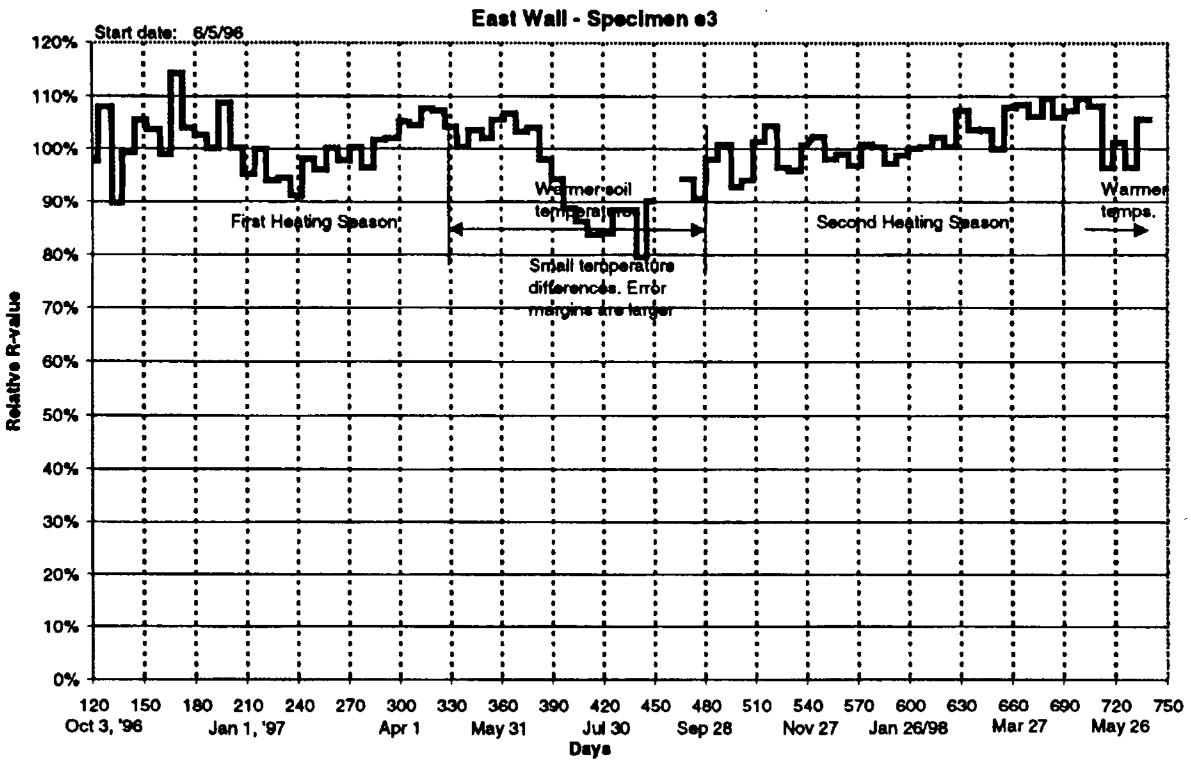
(c)

FIGURE 8 (continued). Average relative thermal resistance in the control volume of EPS placed on the west wall and normalized to the initial thermal resistance in October 1996: (a) specimen W2, (b) specimen W3, and (c) specimen W4.



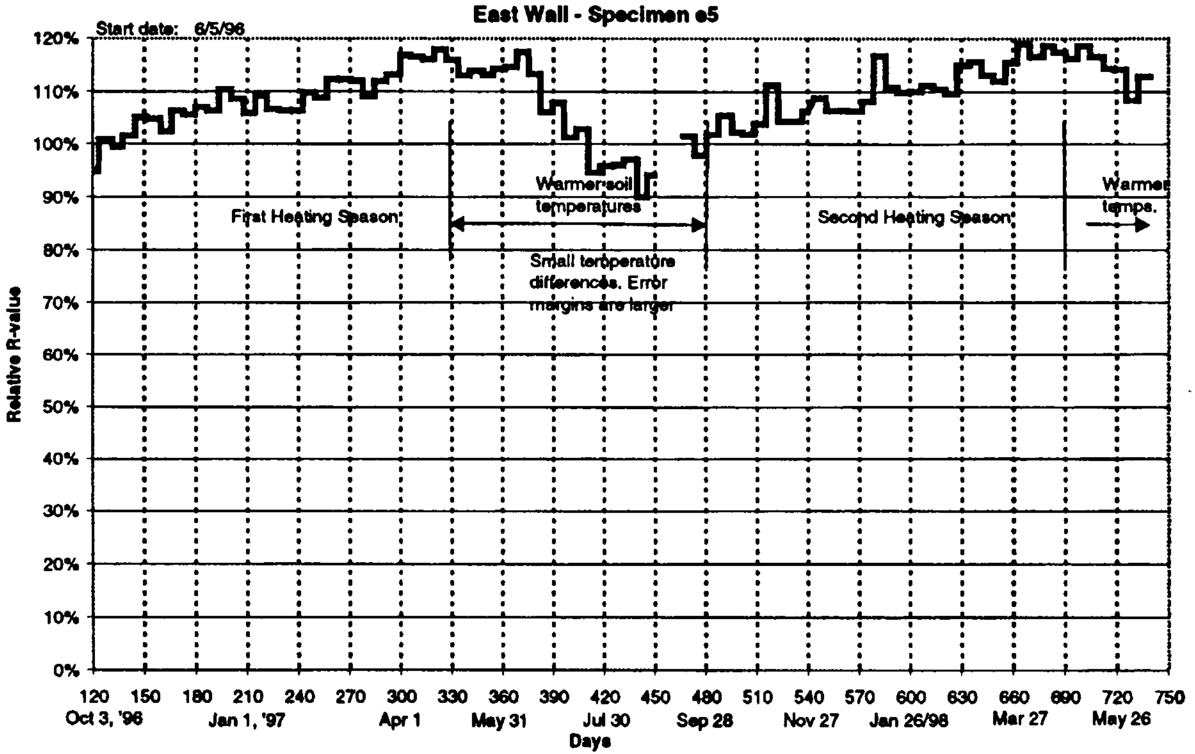
(a)

FIGURE 9. Average relative thermal resistance in the control volume of EPS placed on the east wall and normalized to the initial thermal resistance in October 1996: (a) specimen E2, (b) specimen E3, and (c) specimen E4.



(b)

FIGURE 9 (continued). Average relative thermal resistance in the control volume of EPS placed on the east wall and normalized to the initial thermal resistance in October 1996: (a) specimen E2, (b) specimen E3, and (c) specimen E4.



(c)

FIGURE 9 (continued). Average relative **thermal** resistance in the **control** volume of **EPS** placed on the east **wall** and **normalized to the initial** thermal **resistance** in **October** 1996: (a) specimen **E2**, **(b)** specimen **E3**, and (c) specimen **E4**.

THE EFFECT OF EXPOSURE ON EPS PROPERTIES

Observations during Removal of Specimens

The EPS specimens tested during the EIBS project were removed from the installation on 23 June 1998. The soil was relatively dry to about 1 m depth and was granular in texture once excavated. The lower soil was wet and was excavated in clumps. Standing water was observed below the drain tile. The drain tile was opened for examination at both east and west walls (a geotextile cover was used on top of gravel at the west wall but not at the east wall).

In general, the insulation specimens appeared to be in good condition. Neither the protected portions of the insulation (protected by cement board) nor the main area of the surface of the specimens in contact with the concrete show signs of soil deposition at the surface. Sedimentation was visible but was limited for the most part to portions of the insulation directly in contact with the soil, near power cables and at the lowest level, to about 100 mm above the footing. There was evidence of water movement (resulting in adhesion of soil onto the specimen surface) at some butt and shiplap edges for about a 25 mm distance, but signs of adhesion did not reach the backs of specimens.

Properties Measured after Exposure

Thermal and mechanical properties were measured after exposure. Table 1 summarizes the average thermal resistance of the insulating materials tested initially and after removal from the test walls.

Table 1. Average thermal resistance of EPS specimens before and after exposure, either recalculated to or measured at 25.4 mm thickness.

EPS type	Initial m^2 C/W	Post-exposure m^2 C/W	Difference %
"A"	0.604	0.605	<1%
"B"	0.680	0.683	<1%
"C"	0.710	0.711	<1%

Note: All results are normalized to 25.4 mm thickness using the DIPAC model.[5]

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[5] The DIPAC model to calculate thermal conductivity of cellular plastics as a function of their polymeric composition, blowing agents (if used instead of air), period of aging and temperature and thickness has been experimentally verified (see Bomberg and Kumaran [4]).

In general, these results and others not reported here confirmed that there was no significant change in any of the measured properties—thermal resistance, compressive strength, and water vapor permeability.

CONCLUSIONS

The following observations can be made:

1. For the conditions recorded over the two-year monitoring period in this experiment, the in situ measurements indicated stable thermal performance. This relates to all types of EPS involved in the study. (In most cases, the thermal performance slightly improved during the second heating season, likely because of drier soils).
2. Based on the temperature profiles at the insulation/soil interface and observations of heavy rainfall or thaw periods, the thermal performance of the specimens was not significantly affected by water movement at the specimen/soil interface. It also appears that the EPS insulation protected the concrete during these events (lack of temperature deviations on the inside face during heavy rains and lack of soil deposition on interior surfaces as observed during the removal of the insulation).
3. Thermal conductivity showed no significant difference from that measured on the initial EPS product. When tested in the lab after recovery and drying of the specimens, the compressive strengths of the EPS samples were the same as those of samples tested at the beginning of the test, within the margin of error of the test method. This was consistent with results of the environmental cycling tests.[6]
4. A number of additional tests were performed for comparative purposes. Some specimens were manufactured with grooves on one surface, others with shiplap joints. One EPS specimen was wrapped in the 6 mil polyethylene film with large overlap on joints. Since no evidence of water movement on the back of EPS boards was recorded, the effect of grooves or shiplap joints and other differences between boards could not be established. The thermal performance of the wrapped EPS was not significantly different from EPS specimens without protection. Note, however, that during the removal of specimens, some water was observed behind the polyethylene film.

In effect, one may conclude that the in situ performance, confirmed by laboratory measurements, indicated a high stability of the EPS. Furthermore, although the thermal resistance of the basement system is not dis-

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[6] This issue is discussed in another paper that is being prepared for publication.

cussed in this paper, one may note that installation system #1 (horizontal z-bars attached to header) yielded consistently superior thermal resistance compared to installation system #2 (vertical z-bars attached to concrete).

ACKNOWLEDGEMENTS

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