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Publisher's version / Version de l'éditeur:
https://doi.org/10.1177/109719639301700207
Journal of Thermal Insulation and Building Envelopes, 17, 2, pp. 78-88, 1993-10-01

Predicting Field Thermal Performance of a Modified Resol Foam from Laboratory Data

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ABSTRACT: With safety testing of new blowing agents being near completion and new types of thermal insulating foams entering the market, predicting the long-term thermal performance of these foams becomes important. In this respect, the experience gained under a 1987–1988 project on CFC blown, modified resol foams may prove invaluable as predictions derived four years ago can now be compared with data obtained on material exposed on experimental roofs.

This comparison indicates that the prediction of long-term thermal performance based on the initial thermal resistance determined on full thickness specimens combined with the effect of aging determined on thin layers agreed with results obtained on the foam aged under field conditions.

INTRODUCTION

THE MANUFACTURER'S OBJECTIVE to warrant long-term thermal performance of a modified resol foam insulation led to a joint project with NRC on methodology for predicting thermal performance under field conditions. In the course of the investigation, it became apparent that the methods used in existing Canadian and American standards were not universally correlating laboratory and field performance [1,2]. This project aimed, therefore, at developing an accelerated test procedure, predicting long-term thermal performance of this foam product and comparing it with the field measurements. The thin layers (slicing) approach developed during this project, cf. Bomberg [3], was later applied by Kumaran and Bomberg

1065-2744/93/01 0078-11 $06.00/0

[4] to research on sprayed polyurethane [5]. The NRC methodology includes the slicing technique originally introduced by Isberg [6], but is much broader in many regards.

To predict long-term thermal performance under field conditions, the NRC methodology involves determination of three performance aspects:

1. The initial thermal performance of the foam product
2. Effect of time on thermal performance of the foam (aging)
3. Effect of environmental factors on the rate of the aging process

The initial thermal performance of the foam product is defined by the mean value and standard deviation of thermal resistivity (inverse of thermal conductivity) measured on many full thickness boards. These boards are sampled from at least three different production batches. The effect of time on thermal performance is determined on thin layers and presented as dependence of a dimensionless thermal resistivity on the aging period. The dependence is called a normalized aging curve.

In addition to aging curves determined on thin layers stored in the laboratory, the aging curves are also determined on thin specimens exposed to thermal and humidity gradients. As work was performed before the development of the current methodology, the effects of environmental conditions were not measured on slices but on full thickness boards.

MATERIALS AND METHODS

Three batches of modified resol foams, sampled over a period of two months and called product 1, were coded as IC 791, IC 792, IC 793 and compared with an 18-month-old batch of the same product (IC 788 batch).

To quantify effects of environmental factors, thermal resistance tests were performed on specimens exposed to the following conditions:

1. Isothermal aging in the laboratory (referred to as 20°C or "laboratory")
2. Effect of temperature gradient alone. Exposure to 80°C on the warm side and room conditions (20°C, 45 ± 5% RH) on the other side of the board resulted in a thermal gradient of approximately 1500 K/m. The same absolute humidity was maintained on both sides. Four specimens were simultaneously placed in a cube and served as dividers between the environment maintained inside the cube and an air-conditioned room (referred to as "dry cube").
3. Effect of moisture in the presence of temperature gradient. This exposure comprised a high relative humidity and a high temperature on the warm side (70°C and relative humidity between 98 and 100% RH) and room

conditions on the other side, creating a thermal gradient of approximately 1250 K/m (referred to as "humid cube").
4. Effect of actual climatic conditions (materials installed in an experimental roof).

Evaluation of long-term thermal performance involved cutting thin material layers (slices). They were prepared in two stages. First, a thin sheet about 2 mm thicker than the required thickness was cut using a horizontal band-saw. This sheet was then mounted on a vacuum table and smoothed with a vertical spindle surface grinder equipped with a Carborundum disc. Suction of air kept the specimen in place while the grinder moved across the surface of the stationary specimen.

The grinding process may destroy some of the cell membranes and increase the fraction of open cells in the layer adjacent to the surface. A concept of "thickness of the destroyed surface layer" (TDSL) was therefore introduced to quantify the effect of surface preparation. For a known surface area, TDSL is defined as a difference between the geometrical and closed-cell (effective) specimen volumes divided by the surface area [7,8].

The effective volume of the specimen is measured with a gas displacement method, and may therefore depend on both the cell openings and the cell size. It implies that a change in TDSL may be caused either by a change in the number of broken cell membranes or by a change in cell morphology. The latter was observed for product 1, where the cell morphology varied between the surface and core layers. Accordingly, TDSL varied from 0.16 to 0.20 mm for surface layers and 0.23 to 0.26 for core layers.

TEST RESULTS

Aging Full Boards under Environmental Exposures

Figure 1 shows aging of full boards of product 1 exposed to the above discussed environmental conditions. While aging is somewhat faster under the highest thermal gradient (dry cube) than under humid cube, the difference is not significant. The difference between the isothermal and thermal gradient conditions is, however, substantial.

Figure 1 shows that when one side of the foam is exposed to elevated temperature (dry and wet cube exposures), the foam ages much faster. This effect lasts for a period of 6–8 months only. After this period, the rate of change in all the curves shown in Figure 1 appears to be identical.

Laboratory Aging of Core Layers in Product 1

Characteristics for core slices cut from batches 788, 791, 792 and 793 are listed in Table 1.

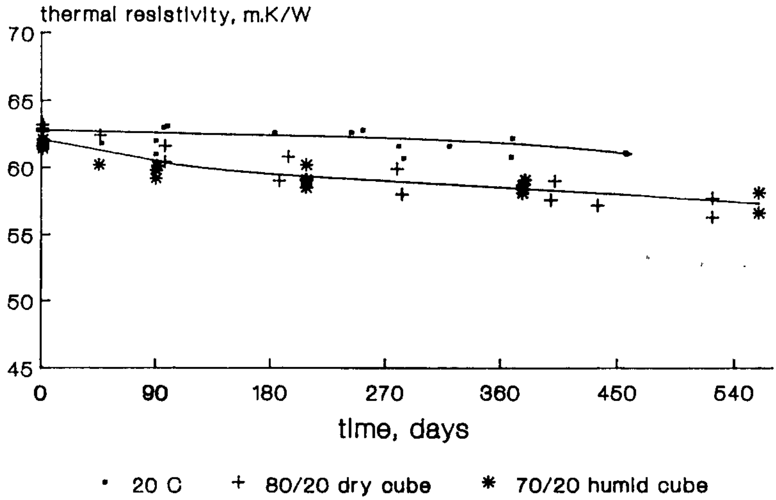

FIGURE 1. Thermal resistivity measured on specimens exposed to three different environmental conditions.

Assuming that the thin foam layer is homogenous, the aging curve established on a thin specimen can be transformed into that corresponding to another thickness of the foam by means of scaling technique [3]. For instance, the thickness of tested core slices varied between 2.3 and 11.1 mm (Table 1), while results shown in Figure 2 correspond to the reference thickness of 10 mm. As Figure 2 shows no systematic differences amongst the recalculated aging curves, one may conclude that scaling may be applied for the cores of this foam product.

If the differences between aging curves are small, it is easy to select the representative aging curve [4]. For instance, as shown in Figure 2, the aver-

Table 1. Material characteristics of the core layers.

Batch	Test Code	Thickness, mm	Density, kg/m³
791	401-180	6.16, 6.19, 8.89, 9.60	32.4, 33.0, 31.8, 32.6
	398-70	8.13, 8.17	32.1, 32.0
	398-79	8.1, 8.2	31.9, 32.2
792	398-157	11.14	35.2
	405-15	5.16, 5.17, 10.07, 10.07	33.9, 33.4, 33.9, 34.5
	405-48	2.33, 2.32, 2.32, 2.32	33.2, 35.5, 36.3, 42.1
793	401-183	5.93, 6.21, 9.20, 9.26	34.1, 33.7, 34.3, 34.2
	401-189	5.13, 5.14	34.5, 34.5
788	405-36	5.05, 5.02	35.7, 35.6

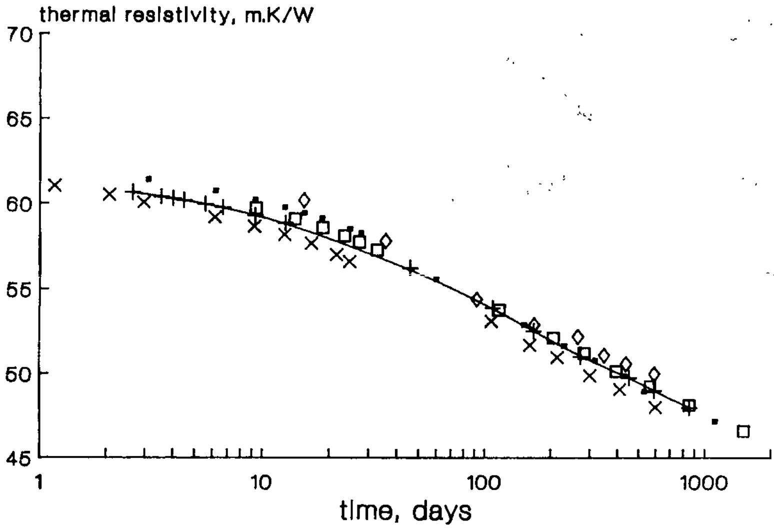

FIGURE 2. The extreme and average aging curves (i.e., thermal resistivity versus time) measured on slices cut from the foam core.

age curve for batch 792 (continuous line) falls in the middle of all test results and may be used to represent aging of the core layers.

Laboratory Aging of Surface Layers of Product 1

Characteristics of tested surface layers are shown in Table 2. Since for the surface layers an average thickness of the destroyed surface layers was 0.2 mm, the effective thickness of the surface layers was 0.4 mm less than the geometrical one. Figure 3 shows results of thermal resistivity measurements on six surface specimens, prepared from batches 791, 792 and 793 and recalculated to the reference thickness of 10 mm.

Table 2. Material characteristics of the surface layers.

Batch	Test Code	Thickness, mm	Density, kg/m^3
791	398-70	7.46, 8.14, 8.37, 8.13	42.6, 41.0, 42.2, 40.8
792	405-15	5.17, 5.17	41.3, 41.8
	405-18	10.06, 10.09	39.5, 40.6
	398-157	10.38, 10.68	40.1, 40.6
793	401-189	5.14, 5.13	42.7, 44.8
	401-186	9.93, 9.91	34.5, 42.6
788	405-36	5.05, 5.02	43.6, 43.1

The differences in both the thermal resistivity values and the rate of aging displayed by various specimens, e.g., batch 791, make direct comparisons difficult. For ease of comparison, these aging curves will be normalized.

To normalize the results, each value of thermal resistivity is divided by its initial thermal resistivity. Since the thermal resistivity measured on thin layers may change rapidly, the initial values used for normalization of aging curves are often determined on thick specimens prior to slicing into thin layers. The initial thermal resistivity, used in these normalized curves, was determined on full board thickness using a 600 × 600 mm Heat Flow Meter (HFM) apparatus. Then the specimen was cut into four smaller squares, and from one of them four slices were cut: two from the core and one adjacent to each surface. These slices were tested simultaneously in a four-station 300 × 300 mm HFM apparatus to give the results shown in Figures 2 and 3.

PREDICTING LONG-TERM THERMAL RESISTANCE WITH THE SCALING TECHNIQUE

Figure 4 shows five normalized aging curves for surface layers (points) and two normalized, representative aging curves, one for core and one for sur-

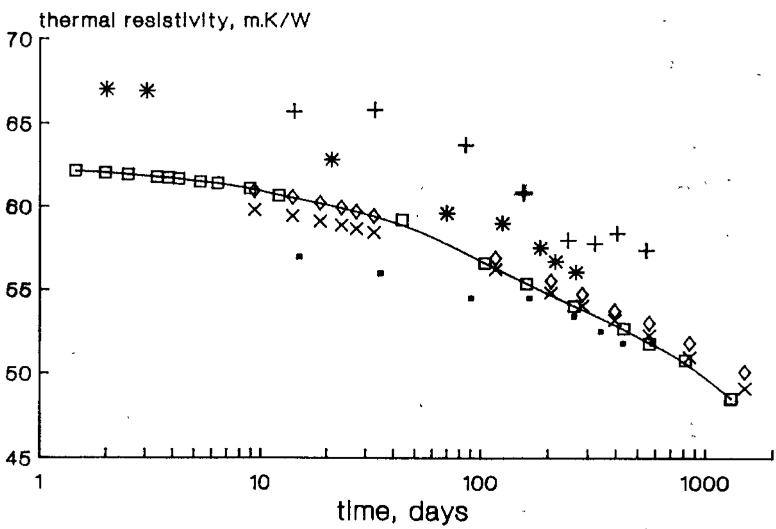

FIGURE 3. The extreme and average aging curves measured on slices cut from the foam surfaces.

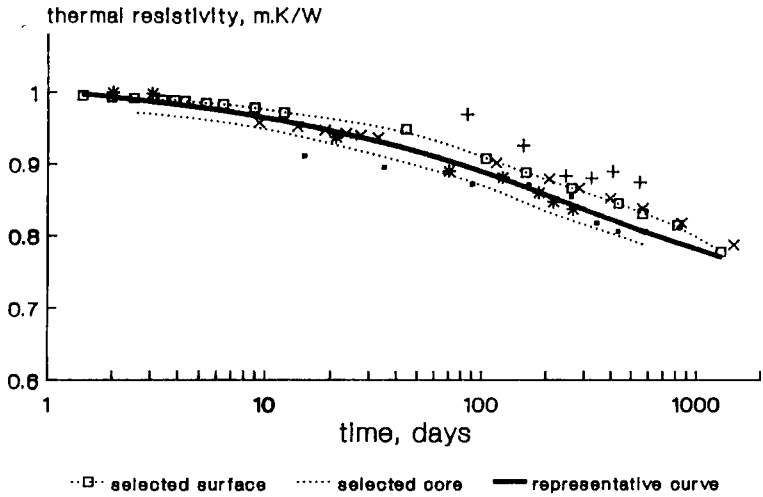

FIGURE 4. Normalized aging curves measured on slices cut from either cores or surfaces of the foam.

face layers (dotted lines). There is a difference between the representative aging curves for core and surface layers. Since the scaling approach can only be used for homogenous materials, one must decide whether this difference is considered significant or not. We have chosen to consider this material as sufficiently homogenous to use the scaling approach. The average of surface and core representative aging curves, shown as a thick, continuous line in Figure 4, is used for further calculations.

The actual thermal resistivity for product 1 is obtained as a product of the aging factor determined from the normalized, representative aging curve and the mean initial thermal resistivity. The initial resistivity values for product 1 are listed in Table 3.

Using the normalized, representative aging curve and the mean value of initial thermal resistivity, the prediction of aging can be obtained for the actual product. The actual board thickness varied from 40 to 42 mm and the mean thickness was approximated as 41.4 mm.

To compare aging of 10 mm (reference thickness) and 41.4 mm thick layers, the scaling factor of $(41.4/10)^2 = 17.1$ is used. For a specified period, e.g., four years (1600 days) of full thickness board aging, the scaling factor of 17.1 will transform it into the period of $1600/17.1 = 94$ days aging of the reference thickness. The aging factor, found from the representative aging curve at the 94 day period, is 0.89. The predicted four year value of thermal resistivity is $0.89 \cdot 62.4 = 55.5$ (m·K)/W.

Table 3. Initial thermal resistivity of batches IC 791, IC 792, IC 793.

Batch/Specimen Codes	Density kg/m³	*R*-Value (m·K)/W	Batch/Specimen Codes	Density kg/m³	*R*-Value (m·K)/W
791-398-19	40.6	63.0	791-398-63	40.1	63.3
791-398-67	40.3	62.7	792-398-151	40.2	63.2
793-401-101	40.5	62.3	792-398-154	40.8	61.9
793-401-104	40.3	62.5	793-401-107	40.9	63.1
793-401-119	40.6	63.3	791-398-39	40.6	62.0
791-398-54	41.0	62.2	791-398-3	40.9	62.2
791-398-7	40.9	62.7	791-398-11	41.2	62.7
791-398-15	41.9	62.9	792-398-171	40.6	62.6
792-398-174	40.4	62.6	792-401-128	40.7	62.3
793-401-110	41.1	62.5	793-398-168	40.6	63.1
793-401-113	40.6	63.3	793-401-131	40.8	63.4
791-398-23	40.6	61.4	791-398-27	41.3	61.8
791-398-31	42.0	61.6	792-398-35	42.0	62.1
792-401-128	40.7	62.3	793-401-110	41.1	62.9
791-398-67	40.3	62.7	792-398-151	40.2	63.2
793-401-101	40.5	62.3	793-401-104	40.3	62.5
792-398-154	40.8	61.9	793-401-107	40.9	63.1
793-401-119	40.6	63.3	791-398-39	40.6	62.0
791-398-54	41.0	62.2			

Total 37 tests, mean *R*-value 62.6

COMPARISON OF PREDICTED AND MEASURED FULL BOARD THERMAL RESISTANCE

Thermal resistivity measurements performed after one and three years in the laboratory and after four years in the experimental roof exposure are listed in Tables 4, 5 and 6.

Table 4. Thermal resistivity of product 1 after one year exposure on the experimental roof and three more years storage in the laboratory.

	One Year of the Field Exposure						Plus Three Years Lab
Batch Code	Density kg/m³	*R*-Value (m·K)/W	Density kg/m³	*R*-Value (m·K)/W	Density kg/m³	*R*-Value (m·K)/W	*R*-Value (m·K)/W
791	41.4	62.0	41.6	61.8	42.3	62.1	59.5
792	41.3	61.1	41.2	60.9	40.2	63.3	59.1
793	41.3	61.1	41.0	60.4	41.3	60.0	57.5

Mean *R*-value after one year: 61.4 (m·K)/W
Mean *R*-value after four years: 58.7 (m·K)/W

Table 5. Thermal resistivity of phenolic foam product 1 after four years exposure on experimental roof.

Batch Code	Density kg/m³	R-Value (m·K)/W	Density kg/m³	R-Value (m·K)/W
791	41.9	59.8	42.0	59.5
792	40.9	58.9	40.6	58.4
793	40.9	57.8	40.9	58.4
		After four years, mean *R*-value 58.8		

Thermal resistivity measured after one and four years of field exposure and prolonged laboratory storage can be compared with that measured initially. The aging of product 1 is very slow; the mean thermal resistivity changes from the initial value of 62.6 (m·K)/W to 61.4 (m·K)/W after one year of storage and to 58.8 ± 0.1 (m·K)/W after four years (cf. Tables 4, 5, 6). These results are very consistent and indicate that there is no significant difference between the laboratory and field aging.

The prediction of long-term thermal performance based on the initial thermal resistance determined on full thickness specimens and aging of thin layers was 55.5 (m·K)/W. This prediction can be compared with the measured results that were 58.8 (m·K)/W for product 1 sampled from the field exposure and 58.9 (m·K)/W for the laboratory samples. Even though the prediction was underestimating the effect of densified skin layer (which initially controls the aging process), the difference between the predicted and measured values is less than 6 percent.

CONCLUDING REMARKS

The proposed approach based on thermal testing full boards and thin layers appears to give the right magnitude of the estimated long-term ther-

Table 6. Thermal resistivity of product 1 after four years of laboratory storage.

Batch Code	Period days	R-Value (m·K)/W	Batch Code	Period days	R-Value (m·K)/W
791	1787	59.5	791	1764	60.1
793	1646	57.9	793	1642	58.6
792	1640	58.5			
		After four years, mean *R*-value 58.9			

mal performance. The methodology proposed four years ago [3,4] has been under constant verification in a number of research projects [8–11]. Findings of this project helped to develop a proposal for an ASTM standard test method. While aging as a function of time appears now to be well understood, the effect of environmental factors on aging rate [12–14] appears to require much more effort.

ACKNOWLEDGEMENT

Deep gratitude is expressed towards Dr. M. K. Kumaran, IRC/NRC, for constructive critique during this project and to Owens Corning Canada (formerly Fiberglas Canada Inc.) for sponsoring a research project with the Institute for Research in Construction of the National Research Council of Canada which led to the development of slicing and scaling methodology. Special thanks are also extended to Mr. John Lackey, IRC/NRC, for performing measurements reported here.

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