

IMPACT OF EXPOSURE CONDITIONS ON THE MECHANICAL PROPERTIES OF POLYISOCYANURATE FOAM INSULATIONS

GLEN D. GADDY

The Johns Hopkins University
Baltimore, Md.

WILLIAM C. CULLEN

National Roofing Contractors Association
Rosemont, Ill.

TIMOTHY A. BARBARI

The Johns Hopkins University
Baltimore, Md.

WALTER J. ROSSITER JR.

National Institute of Standards and Technology
Gaithersburg, Md.

The effects of various exposure conditions on tensile modulus, tensile yield strength, compressive modulus, and compressive yield strength of polyisocyanurate foam roofing insulation materials were investigated. The three foams, CFC-11, HCFC-141b, and CFC-11/CO₂ co-blown, tested in this study decreased in density, except the field-aged materials which did not change, with exposure time and no decrease in compressional modulus and compressional yield strength for laboratory exposure. The decreases in density were accounted for by the exchange of the less dense air for more dense blowing agent. The lack of decreases in the compressive properties may be due to a number of factors, including loss of the blowing agent which acts as a plasticizer when dissolved in the polymer and the completion of crosslinking reactions in the polymer. Some field exposed samples showed a decrease in compressional modulus which is attributed to the presence of blowing agent dissolved in the polymer. The extent to which each of these parameters contributes to the observed changes was beyond the scope of this study.

KEYWORDS

Blowing agents, building technology, field exposure, insulation, low-sloped roofs, mechanical properties, polyisocyanurate foam, roofing, temperature exposures.

INTRODUCTION

By the mid 1980s, it became apparent the chlorofluorocarbon (CFC) emissions jeopardize the ozone layer in the stratosphere. The loss of this important ultraviolet (UV) filter led to the signing of the Montreal Protocol in 1987.¹ The Protocol set guidelines and a timetable for the complete phaseout of CFCs and was adopted by more than 50 nations.

The rigid foam industry, as a major consumer of CFCs, has been especially interested in the development of a number of potential replacement blowing agents.¹ The properties which the insulation manufacturers and consumers have been most concerned about maintaining have been thermal properties (thermal resistance) and mechanical properties,² which is the subject of this research. Of equal importance has been containing the cost of the final product and minimizing equipment changes necessary for

the production of suitable insulation boards. These factors have led the producers of the blowing agents to test a number of potential alternatives which have shown promise.¹ Of these, one, 1-dichloro-1-fluoroethane (HCFC-141b) appears to be a suitable substitute for trichlorofluoromethane (CFC-11).^{3,4} Another method used recently by some manufacturers of rigid polyisocyanurate (PIR) foam insulation boards to minimize the use of CFC-11 in their products is the introduction of water into the formulation leading to the formation of carbon dioxide as an additional blowing agent.⁵ This method can greatly reduce the CFC present in the final product, but cannot eliminate it without greatly increasing its thermal conductivity.

Major changes in the formulation of a building product often raise concerns about its long-term serviceability. This was the case when the roofing industry considered the use of polyisocyanurate foams formulated with alternative blowing agents. As a consequence, a joint industry/government research project was conducted at Oak Ridge National Laboratory (ORNL) to determine the viability of alternative blowing agents. This project primarily addressed the thermal performance of experimental foams made with alternative blowing agents. One phase consisted of the construction of low-sloped roofing systems with the experimental foams incorporated as the thermal insulation. This field study allowed evaluation of the foam boards during rooftop installation. In general, the newer products withstood application without damage and performed well during the relatively brief period of their service.

Considerable effort^{1,2,6} has been given to characterizing the thermal performance of experimental foams. However, to date, little has been published regarding their mechanical properties and the changes they undergo during exposure in service or under artificial conditions in the laboratory. This paper presents the results of a study on the mechanical properties of these foams, including two blown with an alternative agent or method (i.e., HCFC-141b and CFC-11/CO₂ co-blown), and one that was conventionally blown with CFC-11. Data are provided on their density and tensile and compressive properties for both new (unaged) products and materials exposed in the laboratory and in the field. The foams exposed in the field were from the experimental roof at ORNL.

EXPERIMENTAL

Materials

Three foam samples (Nos. 1-3) were included in the study. All were rigid boards possessing facers and having a nominal 32 kg/m^3 (2 lb/in.^3) density. The nominal thickness of the boards including facers was 50mm (2 in.).

Sample Nos. 1 and 2 were those boards used in the field study at ORNL. They were produced with HCFC-141b and CFC-11 blowing agents, respectively. Two sets of these boards, both new and exposed, were provided for this study by ORNL.

The field-exposed boards had been in service for 16 months in the experimental roof. Two layers of boards were mechanically attached to a steel deck and covered with either a mechanically attached or fully-adhered ethylene propylene diene terpolymer (EPDM) membrane. The boards included in the present study were taken from the top layer only. Fourteen samples of approximately 400mm x 400mm (16 in. x 16 in.) were removed from the roof by ORNL staff and sent to The Johns Hopkins University for testing.

During the field study, ORNL staff continuously measured temperatures in the roofing system above and below each insulation layer and calculated weekly averages. One of the authors of this paper, Cullen, also participated in the ORNL study and provided the temperature data reported.⁷

Sample No. 3 was a commercially available product co-blown with CFC-11 and CO_2 . Since it was not included in the ORNL study, no data on field exposure is presented.

Sample Dimensioning

Because the new boards were received in 1200mm x 2400mm (4 ft. x 8 ft.) pieces, they were cut into sections of approximately 300mm x 300mm (12 in. x 12 in.). The field-exposed boards were received in sections of approximately 400mm x 400mm (16 in. x 16 in.) and were tested without further sectioning. The facers were removed from all the boards and the foam thickness was reduced to approximately 25mm (1 in.) using a band saw, planer, and sander before exposure.

Laboratory Exposure of the Unaged Foams

For each of the foam boards (Nos. 1-3) six of the unaged, dimensioned samples were exposed to the following conditions:

- $75 \pm 2^\circ\text{C}$ ($167 \pm 2^\circ\text{F}$), $10 \pm 5\%$ Relative Humidity (RH)
- $60 \pm 2^\circ\text{C}$ ($140 \pm 2^\circ\text{F}$), $75 \pm 5\%$ RH

The samples were exposed for one, five and 25 weeks. Mechanical properties of the samples were determined between two and seven days after removal from the exposure conditions. During this time the samples were kept at an ambient room temperature $25 \pm 2^\circ\text{C}$ ($77 \pm 3.5^\circ\text{F}$) and relative humidity $45 \pm 5\%$.

Laboratory Tests

Prior to conducting the laboratory tests, foam specimens having dimensions of 25mm x 25mm x 25mm (1 in. x 1 in. x 1 in.) were prepared for testing from the samples described above (both new and exposed).

Five properties were measured:

- Density for ASTM D-1622,⁸
- Compressive yield stress (or strength) per ASTM D-1621,⁹
- Compressive elastic modulus per ASTM D-1621,⁹
- Tensile yield stress (or strength) per ASTM D-1623,¹⁰ and
- Tensile elastic modulus per ASTM D-1623.¹⁰

For each test, five replicate specimens were tested. Each test was conducted according to the ASTM test method except where described herein.

RESULTS

Temperature Conditions of Field-Exposed Foams

The average weekly temperatures as measured by ORNL at the top and bottom of each insulation layer are shown in Figures 1 and 2 for the CFC-11 and HCFC-141b foams, respectively. The temperature data are for foams installed under the EPDM membrane. The figures show temperatures over almost one year (49 weeks from September to September). This represents the first 12 months of field exposure of the foam boards; temperature data were not available for the last four months that the field specimens were in service. It was considered to be more appropriate to show average weekly temperatures than maxima and minima for summarizing the temperatures experienced by the foams in service. Although temperatures above the top layer of insulation reached at times about 90°C during the summer, the periods of such extremes were relatively brief (data not shown).

As evident in Figures 1 and 2, the temperature data are approximately the same for HCFC-141b and CFC-11 foams, indicating little effect on the temperature due to blowing agent. Weekly average temperatures reached about 38°C over weeks 30 to 45 (summer). Similarly, the average weekly temperature at the midpoint between the two insulation layers (i.e., below the top layer of the foams included in this study) attained about 32°C . Thus, Figures 1 and 2 show that the field-exposed foams experienced, on the average, summertime high temperatures that were much lower (about 25°C) than the temperatures to which the foams were subjected in the laboratory. The laboratory study was intended to investigate the stability of the foam specimens under more severe exposure conditions.

Properties of the Field-Exposed Foams

Table 1 compares the density, and compressive and tensile properties measured for the unexposed and field-exposed Sample Nos. 1 and 2. Sample No. 3 is not included in the comparison, because it was not incorporated in the experimental roof at ORNL as noted above. With the exception of the density, data are given for foams installed under both mechanically attached and fully-adhered EPDM membranes. The ranges of values are one standard deviation based on five replicates.

Examination of Table 1 shows that the foam samples Nos. 1 and 2 were unchanged over the brief exposure of 16 months. With two exceptions, only small changes occurred in the measured properties. One exception was the compressive modulus of both samples under both membranes. This property decreased about one-third during field expo-

sure. The other exception is the tensile yield strength of the foam exposed under the EPDM membrane. In this case, a decrease in tensile strength of about 40 percent was observed. Reasons for the observations regarding the slight loss of compressive modulus and tensile strength (foams under EPDM only) are not proposed because the data are too limited (i.e., they represent only one point in time).

In general, the data presented in Table 1 reflect the performance of the experimental roof to date, which as been described as quite satisfactory.¹⁰ Consistent with this description, the measured mechanical properties have been generally stable. It would be of interest to determine the mechanical properties again after more time in service.

Properties of Laboratory-Exposed Foams

The results of the tests of the foams (Nos. 1, 2 and 3) exposed in the laboratory are shown in Figures 3-7. Here the measured property is plotted versus time of exposure. The data points are the average of five replicates, the error bars in each figure represent one standard deviation, and confidence level of 0.95.

Figure 3 shows density for each sample. Other work has shown that density decreases with increasing time of exposure.¹¹ Figures 4 and 5 show tensile yield strength and tensile modulus, respectively. The standard deviation of the results is greater than any change resulting from exposure. Consequently, it cannot be determined whether changes in tensile properties have occurred.

Figures 6 and 7 show the yield strength and modulus, respectively, for compression. The yield strength of the material, as defined by the transition from elastic to plastic behavior, changed little, while the modulus increased 30-40 percent over the first five weeks of exposure, with the exception of HCFC-141b. After that time, a slight further increase occurred. The greatest increase was for 75°C (167°F)/10%RH CFC-11 blown foam. All foams showed an initial decrease in the modulus with 75°C (167°F)/10%RH exposure followed by a longer term increase.

DISCUSSION

Density

Density is the single most important determinant of the mechanical properties of foams.¹² For example, Gibson and Ashby¹² found modulus to be a function of density. Hilyard's text¹³ shows evidence that small increases in density result in large increases in mechanical properties.

Since decreases in density were found for all laboratory exposed samples, the mechanism by which these occur must be discussed. The widely accepted mechanisms that contribute to changes in density are low density gas diffusion in and high density gas diffusion out of the cells,¹² and reactivity of the polymer comprising the foam walls and struts.¹⁴ Both processes are known to be temperature dependant. The two mechanisms are often in competition with one another, resulting in one causing a decrease in density and the other an increase.¹⁵

Gas diffusion in foams is characterized by the exchange of a blowing agent for the atmospheric gases.¹⁶ This is a concentration driven exchange which may have a considerable driving force. If the atmospheric gas has a lower density than the blowing agent, then the foam density will de-

crease. The influx of air (rapid) and outward movement of the blowing agent (slow) is in agreement with the presence of density changes in the laboratory exposed samples and the absence of changes in in-service samples, which had less total temperature exposure and corresponding less activation energy for diffusion. The impact of polymer reactivity will be discussed with the mechanical property data.

Tensile Properties

The large variability in the tensile data is not unexpected for such measurements of polyurethane foams.⁴ The brittle nature of the foam in concert with the ease of damage during preparation often leads to crack formation near the specimen edges in the form of broken cell walls.⁴ The presence of a series of broken cell walls produces a condition which simulates a crack. Because different specimens have different extents of damage, variability arises in the tensile test results. For practical purposes, the development of cracks at the edges of insulation boards in service should not be important since, in that case, the bulk area may be considered infinite in regards to the edges. Additionally, in the case of insulation boards, the sides are not necessarily cut, reducing the number of broken cell walls and crack nucleation sites. Therefore, tensile results for small samples may not be significant in predicting the behavior of large boards.

Compressive Properties

In contrast to the tensile properties, the laboratory exposures resulted in changes in the compressive strength and modulus values. The values of these properties (Figures 6 and 7) were either constant or increased with exposure. This is the opposite of what would be predicted from the density data, since a decrease in density is usually indicative of a decrease in mechanical properties. Anything but a decrease in modulus must, therefore, be due to changes in foam properties which outweigh the density changes as discussed below.

Generalized Behavior

As defined previously, three competing mechanisms, gas diffusion, polymer activity, and the role of gas diffusion in polymer reactivity have been identified as occurring simultaneously in the foam. They probably are responsible for the decrease in density not being accompanied by a decrease in modulus.

While the role of changing cell gas composition is widely acknowledged in changes in the thermal resistance of polyisocyanurate foams,⁵ its role in changes of mechanical properties is less understood.⁴ The most important property of a gas when determining its effect on mechanical properties is compressibility. The more compressible a gas, the less contribution it will make to the mechanical properties of the foam.¹⁵ It is beyond the scope of this paper to measure the cell gas composition of the foams. However, as previously discussed, it is well known that air diffuses in and the blowing agent diffuses out of the cells at different rates.⁴ Furthermore, it is also known that the diffusion process may result in a decrease in the mechanical properties of the foam.¹⁶ On this basis, the role that the cell gas

composition has on the increase in mechanical properties can be discounted.

The changes in mechanical properties may therefore be due to one or both of the blowing agents diffusing out of the foam and continued reaction of the polymer. The blowing agent present in the polymer as it diffuses out would serve to plasticize the cell walls resulting in the initial decrease observed for compressive modulus of the heat exposed material (and the exposed-in-the-roof materials). As the blowing agent continued to diffuse out of the foam, the competing polymer reaction predominates leading to the higher moduli values observed. This diffusion phenomenon can be shown by Fourier Transform Infrared Spectroscopy and will be the subject of a future publication. The leveling of the curve after five weeks may be due to the slowing of the reactions due to the diminishing number of sites available for crosslinking.

In this study, both of these mechanisms occurred together, therefore, it was impossible within the scope of this study to discern which mechanism contributed more to the change in mechanical properties. Further study is needed which utilizes analytical techniques such as thermal analysis and spectroscopy to characterize changes in the chemical and physical properties of the foams at various times. This work is underway and will be presented at a future date.

SUMMARY AND CONCLUSIONS

The three foams, CFC-11, HCFC-141b, and CFC-11/CO₂ co-blown, tested in this study decreased in density, except the field-aged materials which did not change, with exposure time and no decreases in compressional modulus and compressional yield strength for laboratory exposure. The decrease in density was accounted for by the exchange of the less dense air for more blowing agent. The lack of decreases in the compressive properties may be due to a number of factors, including loss of the blowing agent which acts as a plasticizer when dissolved in the polymer and the completion of crosslinking reactions in the polymer. Some field exposed samples showed a decrease in compressional modulus which is attributed to the presence of the blowing agent dissolved in the polymer. The extent to which each of these parameters contributes to the observed changes was beyond the scope of this study.

ACKNOWLEDGMENTS

The authors would like to thank the following organizations for their support of this program: The Johns Hopkins University, the National Institute of Standards and Technology (NIST), and the National Roofing Contractors Association (NRCA) for sponsorship; the Oak Ridge National Laboratory for samples; and the Society of the Plastics Industry and Polyisocyanurate Insulation Manufacturers Association for discussions and encouragement. Special thanks go to Dr. Tinh Nguyen and Robert Zarr at NIST, Thomas Lee Smith at NRCA, and Robert Blanpied and Andrew Green at Atlas Energy Products for their contributions.

REFERENCES

¹ Baumann, G.F., "Are Alternative Blowing Agents Technically Viable for Polyisocyanurate Roof Insulation?," Proceedings of

- 33rd Annual Polyurethane Technical/Marketing Conference, October 1990, pp. 232-33.
- ² Blanpied, R.H. and Knis, S.A., "The Technical Viability of Alternative Blowing Agents in Polyisocyanurate Roof Insulation Part 1: Processing and Physical Properties," Proceedings of 33rd Annual Polyurethane Technical/Marketing Conference, October 1990, pp. 234-38.
- ³ Knis, S.A. et al, "Novel Polyisocyanurate Foams for Roofing and Sheathing," Proceedings of 33rd Annual Polyurethane Technical/Marketing Conference, October 1990, pp. 260-65.
- ⁴ PIMA Research Report, Allied-Signal, Morristown, N.J., October 1991.
- ⁵ Oertel, G., Editor, Polyurethane Handbook, Hanser Publishers, Munich, Germany, 1985.
- ⁶ Christian, J.E. et al, "The Technical Viability of Alternative Blowing Agents in Polyisocyanurate Roof Insulation Part 3: In-Situ Thermal Aging and Performance in Different Roof Systems," Proceedings of 33rd Annual Polyurethane Technical/Marketing Conference, October 1990, pp. 247-59.
- ⁷ Cullen, W.C. and Smith, T.L., "Mechanical Performance of Polyisocyanurate Roof Insulations Blown With HCFC Blowing Agents," Proceedings of the Polyurethanes World Congress, July 1991.
- ⁸ "Apparent Density of Rigid Cellular Plastics," ASTM D1622, Volume 8.02, Annual Book of ASTM Standards, 1983.
- ⁹ "Compressive Properties of Rigid Cellular Plastics," ASTM D1621, Volume 8.02, Annual Book of ASTM Standards, 1983.
- ¹⁰ "Tensile and Tensile Adhesion Properties of Rigid Cellular Plastics," ASTM D1623, Volume 8.02, Annual Book of ASTM Standards, 1983.
- ¹¹ Zarr, R.R. and Nguyen, T., "Effects of Humidity and Elevated Temperature on the Density and Thermal Conductivity of a Rigid Polyisocyanurate Foam," Proceedings of SPI 34th Annual Polyurethane Technical/Marketing Conference, October 1992, pp. 422-30.
- ¹² Gibson, L.J. and Ashby, M.F., Cellular Solids, Pergamon Press, Oxford, U.K., 1988.
- ¹³ Hilyard, N.C., Mechanics of Cellular Plastics, Macmillan, New York, N.Y., 1982.
- ¹⁴ Jellinek, H.H.G., Editor, Aspects of Degradation and Stabilization of Polymers, Elsevier, Amsterdam, The Netherlands, 1978.
- ¹⁵ Shakleford, J.F., Introduction to Materials Science for Engineers, Macmillan, New York, N.Y., 1985.
- ¹⁶ Glicksman, L.R. and Page, M., "Long-Term Performance of Closed-Cell Foam Insulation," Proceedings of Thermal Performance of the Exterior Envelopes of Buildings V, December 1992, pp. 81-90.

PROPERTY VALUE ^a							
HCFC-141 ^b					CFC-11		
PROPERTY		Unexposed	Exposed Fully-Adhered	Exposed Mech. Attach.	Unexposed	Exposed Fully-Adhered	Exposed Mech. Attach.
Density	kg/m ³ (lbm/ft ³)	29.7±0.04 1.86±0.01	29.7±0.09 1.86±0.01	29.7±0.09 1.86±0.09	30.1±0.17 1.88±0.01	30.0±0.21 1.88±0.01	30.0±0.21 1.88±0.21
Compressive Strength ^b	MPa (lbf/in ²)	0.152±0.011 22.0±1.60	0.194±0.012 28.1±1.74	0.181±0.010 26.3±1.45	0.188±0.007 27.3±1.02	0.201±0.002 29.2±0.29	0.217±0.019 31.5±2.76
Compressive Modulus	MPa (lbf/in ²)	1.269±0.101 184.1±14.70	0.786±0.006 114.1±0.87	0.740±0.012 107.3±1.45	1.188±0.058 172.3±8.41	0.773±0.019 112.1±2.76	0.711±0.016 103.1±2.32
Tensile Strength ^b	MPa (lbf/in ²)	0.239±0.036 34.7±5.22	0.257±0.057 37.3±8.27	0.152±0.067 22.1±9.72	0.204±0.041 29.6±5.95	0.223±0.019 32.3±2.76	0.187±0.070 27.1±10.2
Tensile Modulus	MPa (lbf/in ³)	1.343±0.033 194.8±4.79	1.379±0.207 200.0±30.03	1.258±0.087 182.5±112.62	1.466±0.087 212.7±12.62	1.485±0.205 215.4±29.74	1.302±0.106 188.9±15.38

^aThe ranges are one standard deviation.
^bStrength at yield.

Table 1 Comparison of the properties of the unexposed and field-exposed polyisocyanurate foams.

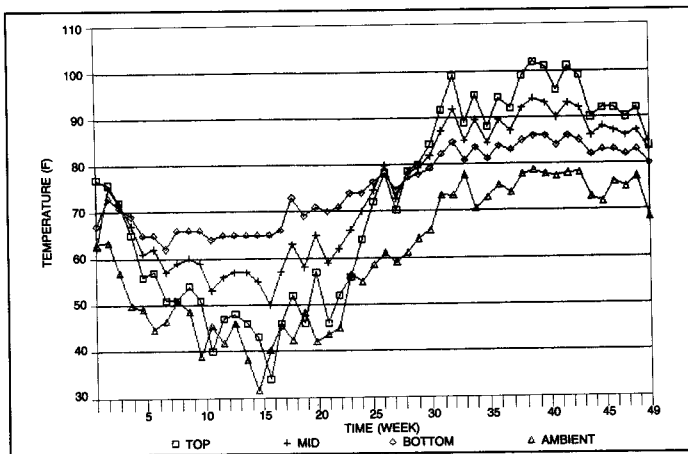


Figure 1 Average weekly temperatures—EPDM over HCFC-141b, October 1990 to September 1991.

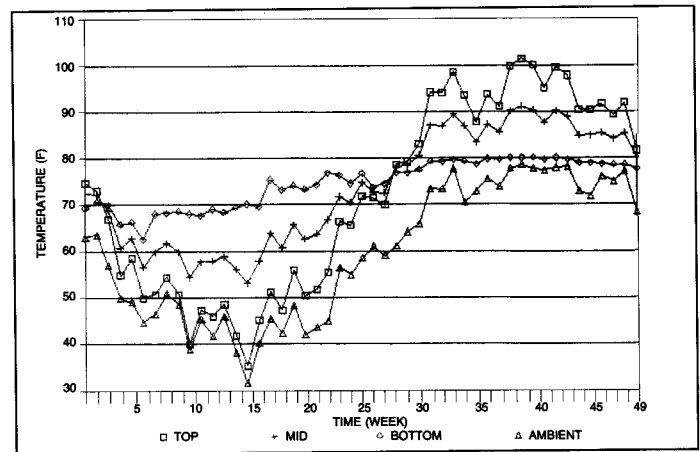


Figure 2 Average weekly temperatures—EPDM over CFC-11, October 1990 to September 1991.

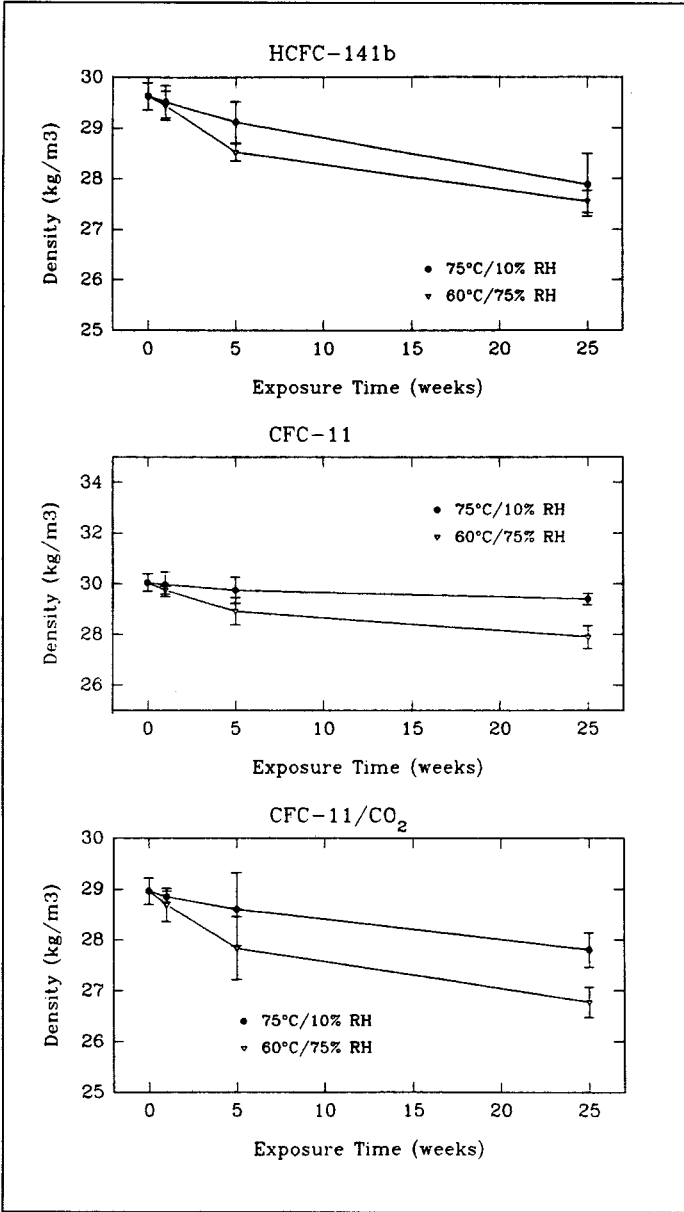


Figure 3 Density vs. exposure time.

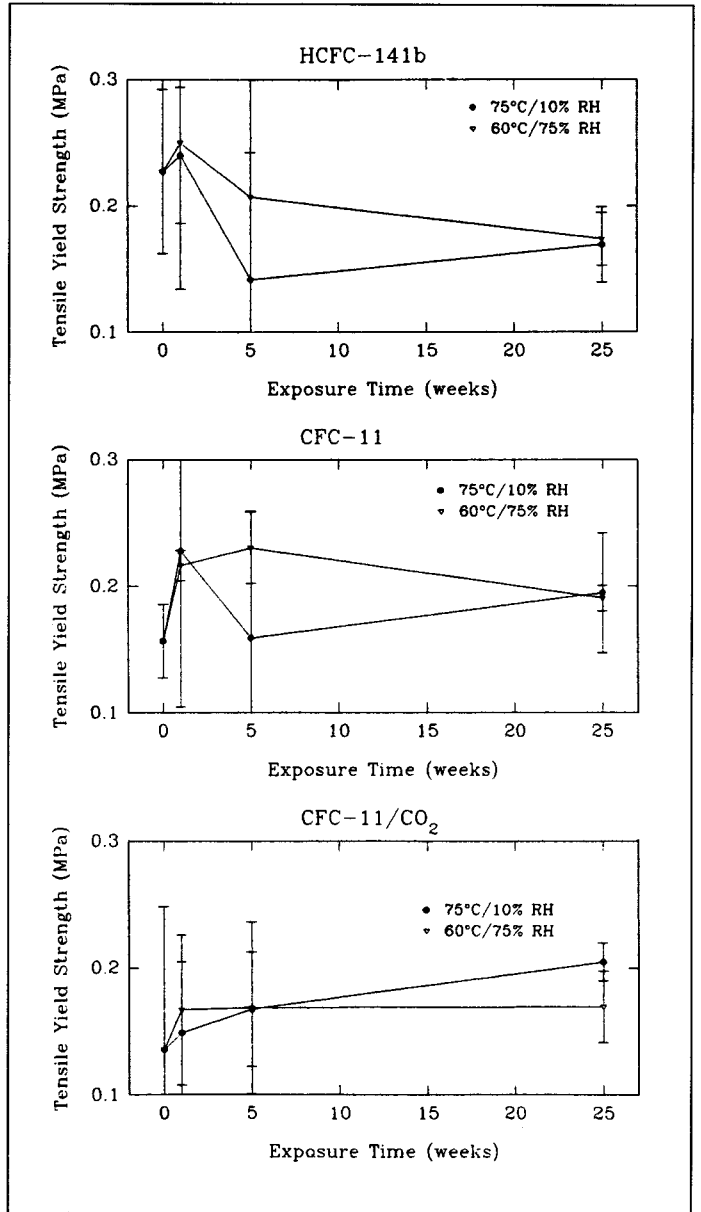


Figure 4 Tensile strength vs. exposure time.

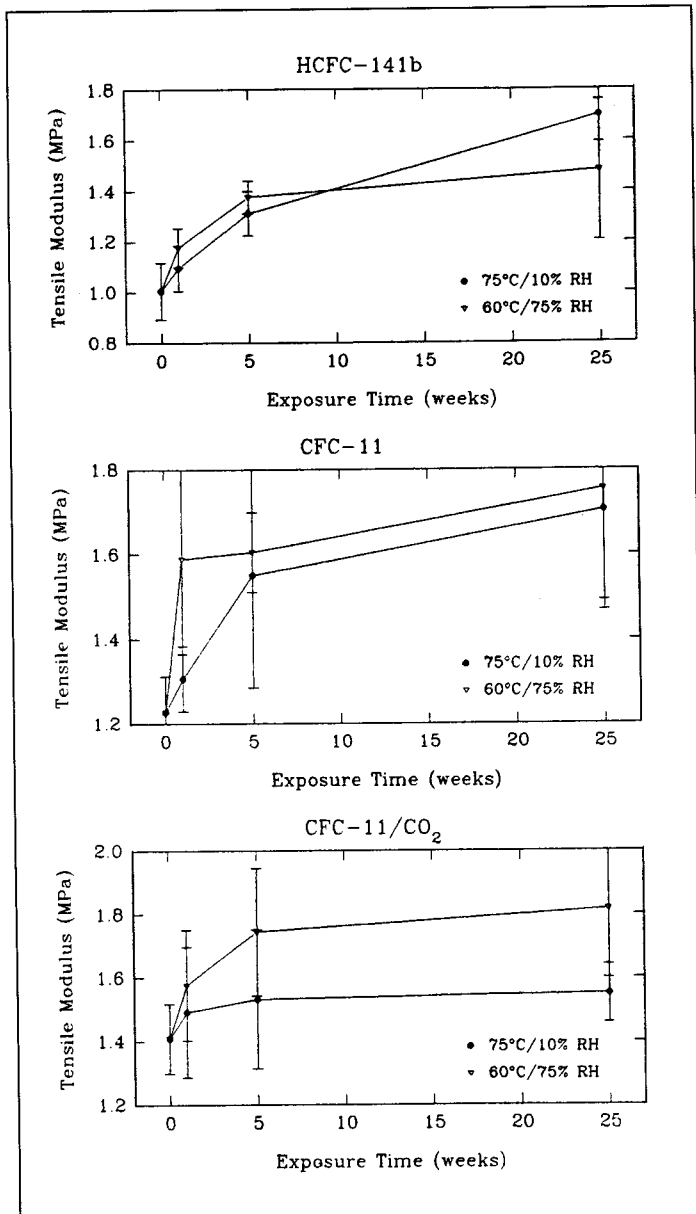


Figure 5 Tensile modulus vs. exposure time.

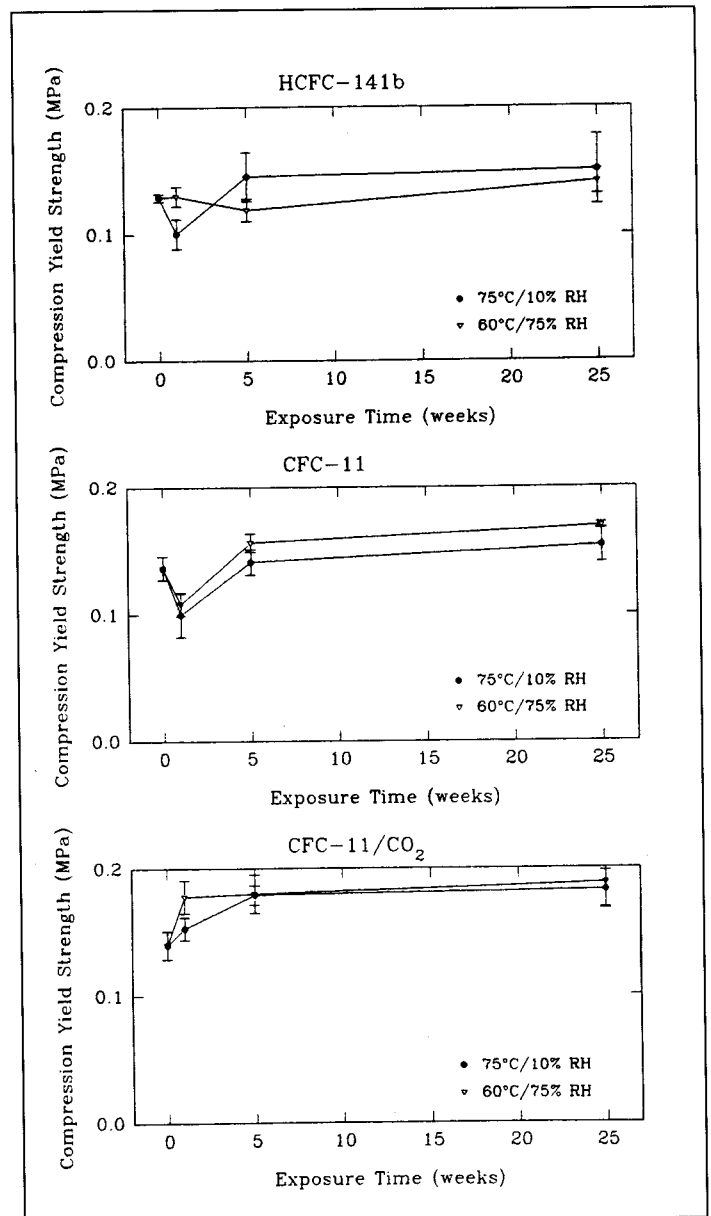


Figure 6 Compression strength vs. exposure time.

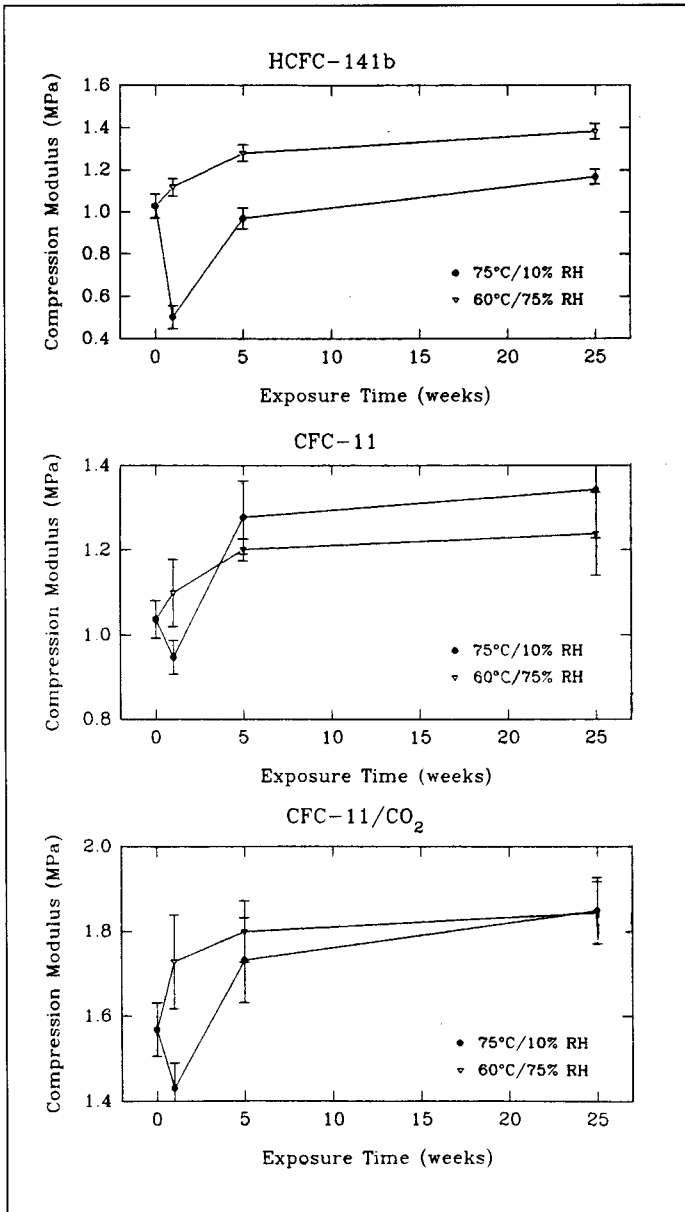


Figure 7 Compression modulus vs. exposure time.