

Effect of Curing Moisture on the Indentation Force Deflection of Flexible Polyurethane Foam

Haifeng Ni,¹ Chee Keong Yap,² Yan Jin³

¹Shanghai Office, Johnson Controls, Incorporated, Shanghai 200051, China

²Tri-Con Industries, Limited, 4000 NW 44th Street, Lincoln, Nebraska 68524

³Wuxi Professional College of Science and Technology, Wuxi 214018, China

Received 5 October 2005; accepted 17 June 2006

DOI 10.1002/app.25798

Published online in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: The moisture effect on the indentation force deflection (IFD) of flexible polyurethane foam was examined through the curing of the foam with different moisture contents. The employed foam was cured at 30, 40, 50, 60, 70, and 80% relative humidity, and the corresponding curing temperature was constant at 23°C. The experiments showed that the measured IFD and support factor of the flexible polyurethane foam decreased, and the hysteresis increased with the curing moisture. A statistical conversion formula was generated experimentally to correct the meas-

ured IFD of the flexible polyurethane foam to eliminate the deviation caused by the moisture effect. The measured IFD was inversely exponentially proportional to the curing moisture. The accuracy of the correction formula was verified by the conditioning of the foam again with different moisture contents. © 2007 Wiley Periodicals, Inc. *J Appl Polym Sci* 104: 1679–1682, 2007

Key words: curing of polymers; foams; indentation; polyurethanes

INTRODUCTION

The load-bearing capacity of flexible polyurethane foam (FPF) is assessed by the indentation force deflection (IFD). It is the holding force required to indent a urethane foam to a predetermined indentation percentage. IFD, as well as the sag factor and hysteresis loss, is the principle quality standard examined in the polyurethane industry. FPF consists of amorphous soft polyol domains and hard urea segments. These hard segments are covalently bonded to the polyol domains by urethane linkages.^{1–4} Moreland and coworkers^{2,5–8} clarified that the IFD of FPF is determined by both the urea phase content and the phase connections between the polyol domain and the urea segments. FPF exhibits time-dependent and rate-dependent behavior^{9,10} during IFD measurements. ASTM D 3574,¹¹ a generally accepted IFD test method, stipulates the measuring procedures: a foam block will be held at three quarters of its initial height after 60 ± 3 s, and the test shall be made at a temperature of $23 \pm 2^\circ\text{C}$ and in an atmosphere of $50 \pm 5\%$ relative humidity (RH).

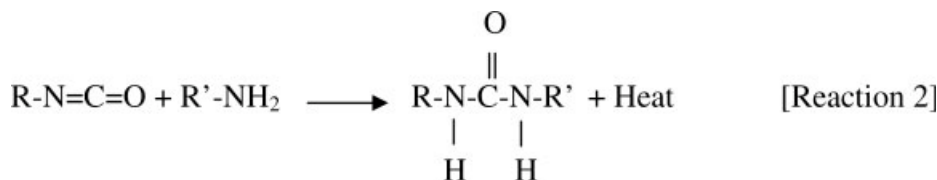
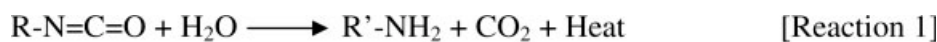
It has been assumed that the IFD of any FPF that has a constant density, cellular structure, and urea segment distribution would be theoretically constant if the mea-

surement followed the same procedures. However, in reality, such an FPF frequently gives inconsistent IFD values. This causes difficulties in material design and selection and confusion in foam quality control. Therefore, the investigation of the mechanisms behind IFD deviations is necessary to correct the deviations and get a consistent IFD of FPF. A general problem has been reported⁸ in industry: if a foam is cured without moisture control under ambient conditions other than those specified in ASTM D 3574, FPF softening will occur in the summer time and the foam will harden in the winter even when the same chemical and manufacturing processes are used.

In this article, we discuss the IFD variations caused by curing moisture. Moisture has an effect on flexible polyurethane in two processes: the blowing process and curing process. In the blowing process, moisture acts as an extra blowing agent, reacting with isocyanate to create amine and carbon dioxide by reaction 1. Less stiffness is expected for the resultant lower density FPF because the moisture induces more carbon dioxide. However, further reactions between the generated amine and isocyanate yield more linear hard urea segments (reaction 2) within the final product. These additional hard segments maximize the chain-slippage resistance of the FPF under compression and thus increase the stiffness of the FPF:

These two competing moisture effects minimize the IFD variations. In the summer time, the IFD variations mentioned here could be overcome by the in-

Correspondence to: H. Ni (nathannee@yahoo.com).



stallation of a dehumidifier to control the moisture content in the blowing area, the reduction of the water ratio in the polyol, or an increase in the toluene diisocyanate (TDI) index to yield more hard urea segments.

The IFD reduction in the blowing process is negligible because the IFD variation caused by blowing moisture is less than 2 kg, whereas that caused by curing moisture can be up to 6 kg when the moisture content is changed from 30 to 60% RH at 23°C. The IFD of FPF decreases with the curing moisture at a constant temperature. The ambient moisture in the curing process functions differently than that in the foaming process because the resultant FPF gains weight in the curing process rather than losing weight in the blowing process.

There is limited published literature regarding the qualitative and quantitative effects of moisture on the IFD of FPF. The mechanisms of the effects of the curing moisture on the IFD variations of FPF are discussed here, and a statistical formula is generated experimentally to correct the measured IFD of FPF.

EXPERIMENTAL

The intent of this research was to study the effects of curing moisture on the IFD of foam. Three separate experiments were designed to implement the tests with an ETH80-2CW environmental chamber. The first one was designed to find the correction formula by curing FPF samples at different moisture contents (30, 40, 50, 60, 70, and 80% RH at 23°C). Ten samples were prepared for each test, and three measurements were made for each sample. FPFs of different densities were then tested to study if the correction formula depended on the foam density or not. These foam pads were finally reconditioned at different moisture contents to verify the validation of the formula.

Sample preparation

A polyether polyurethane system was employed here (see Table I). The chemicals were blended by a one-shot process with a high-pressure hydraulic mixing head. The ambient conditions were $23 \pm 2^\circ\text{C}$ and $50 \pm 2\%$ RH at the foaming line. ASTM D 3574

stipulates that the sample should be larger than $380 \times 380 \times 20 \text{ mm}^3$. Therefore, crushed-block FPF cushions of $500 \times 500 \times 100 \text{ mm}^3$ were prepared with a preheated aluminum close mold ($45 \pm 5^\circ\text{C}$) with a constant machine setup. The density of the foam made in this study was 77.85 kg/m^3 , which was calculated by the foam weight divided by the pad volume. The TDI index was 104, and the demolding time was 12 min. Other samples of different densities were prepared with the same procedure.

Testing

IFD was measured with a Shimadzu AGS-J universal testing machine in accordance with ASTM D 3574. The indentation force and the corresponding time were recorded with a Pentium computer installed with Trapezium2 software. The loading procedure is shown in Figure 1. The y -axis value of A represents the 25% indentation force, the universally recognized foam IFD; the y -axis value of B represents the 65% indentation force, and the y -axis value of C is the recovered 25% indentation force after 65% indentation.

Two other FPF physical properties, the support factor and hysteresis, can be calculated with eqs. (1) and (2)¹¹ with the data in Figure 1. The support factor is defined as the ratio of the foam's ability to support force at different indentation levels. The higher the support factor is, the greater the difference is between the surface firmness and the deep-down support value. Hysteresis indicates the ability of foam to maintain the original support characteristics when being loaded. It represents the energy lost because of the in-

TABLE I
Formulation of the Polyurethane System

Chemical	Parts	OH number	NCO (%)
Polyol resin	100	29	
Water	3.8	2	
DEOA	1.5		
33LV	0.22	560.3	
A-1	0.08		
PC77	0.24		
DC 6070	0.8		
Toluene diisocyanate	49.12		48.2

TDI index = 100.

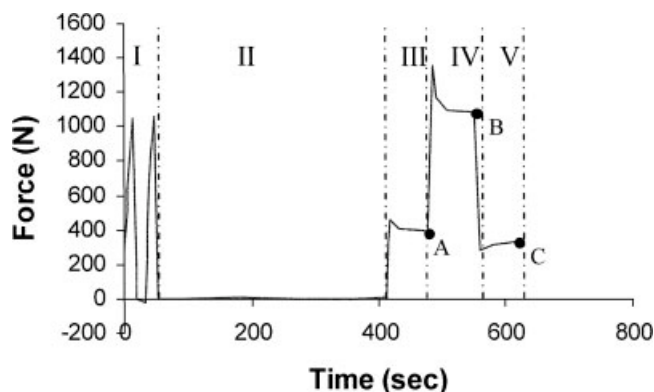


Figure 1 IFD testing procedure for (A) 25% IFD, (B) 65% IFD, and (C) 25% return IFD: (I) 75% indentation prefix stage, (II) relaxation stage (unloading for 360 s), (III) 25% indentation stage, (IV) 65% indentation stage, and (V) 25% return indentation stage. For stage I, the loading speed was 240 mm/min, and the unloading speed was 400 mm/min; for stages III–V, the loading speed was 50 mm/min, and the unloading speed was 100 mm/min.

ternal friction within FPF. The lower the hysteresis is, the better the rebounding ability is of FPF:

$$\text{Support factor} = F_B/F_A \quad (1)$$

$$\text{Hysteresis (\%)} = [100(F_A - F_C)]/F_A \quad (2)$$

where F_A is the 25% indentation force, F_B is the 65% indentation force, and F_C is the recovered 25% indentation force.

RESULTS AND DISCUSSION

Table II lists the experimental results for the curing-moisture effect on FPF. Both the IFD and support factor of FPF are inversely proportional to the curing moisture, but the hysteresis increases with the curing moisture. The change ratio of IFD over the tested moisture contents was about 21%, whereas the corresponding change ratios of the support factor and hysteresis were between 4 and 6%. As eqs. (1) and (2) show, the reason for the small changes in the support factor and hysteresis is that the change ratios of F_A , F_B , and F_C to the moisture are of the same magnitude. High-density FPF is supposed to

have a larger support factor than low-density foam,¹² but this does not agree with our experimental results. The FPF cured at 30% RH and 23°C in this study had the highest support factor but the lowest density. This unconformity indicates that the density increment due to moisture absorption during the curing process does not strengthen but instead weakens the material.

The experimental curve of IFD versus the curing moisture is shown in Figure 2. A statistical correction formula [eq. (3)] is thus induced in Figure 2. This is used to eliminate the curing-moisture effect on FPF. The calculated IFD refers to the IFD of the foam cured in accordance with the conditions stated in ASTM D 3574. The curing temperature employed here was constant at 23°C:

$$\text{IFD} = \text{Measured IFD} \times e^{[0.0049 \times (H-50)]} \quad (3)$$

where H is the relative humidity.

This conversion formula was also found to be effective for FPFs with different foam densities. Figure 3 gives an example of the corrected IFDs of FPFs with different foam densities with various curing-moisture contents. The deviation of the calculated IFD from the IFD of the FPF cured at 50% RH was found to be less than 3%. This indicates that the effect of the foam density, or cellular structures and urea distribution, has already been counted in the measured IFD at the right side of eq. (3). On the other hand, the correction formula was verified by the conditioning of the tested foam at other moisture contents and the measurement of its IFD thereafter. The measured IFD was found to decrease with the moisture condition too. Figure 4 shows the curve of the IFD of the FPF cured at 23°C and 50% RH versus the reconditioning moisture. The calculated curve resulting from eq. (3) matches the experimental curve very well. Moreover, the foam after reconditioning recovered its original IFD after it was conditioned with its first curing-moisture content. This may suggest that no chemical reaction occurred and/or the framework collapsed during the curing process. However, this has not been confirmed here and needs further investigation.

The absorbed moisture functions as a plasticizer and promotes the formation of hydrogen bonds to

TABLE II
Physical Properties of FPU's Conditioned at Different Moisture Contents at 23°C

RH (%)	Density (kg/m ³)	25% IFD (N)	Support factor	Hysteresis (%)
30	77.82 ± 0.18	415.36 ± 3.12	2.716 ± 0.034	15.235 ± 0.089
40	78.03 ± 0.21	407.91 ± 3.08	2.834 ± 0.041	15.543 ± 0.086
50	78.51 ± 0.16	382.54 ± 2.51	2.788 ± 0.039	15.724 ± 0.091
60	78.77 ± 0.18	363.74 ± 3.02	2.776 ± 0.029	15.837 ± 0.107
70	79.14 ± 0.17	347.02 ± 2.44	2.761 ± 0.032	15.935 ± 0.136
80	79.67 ± 0.19	328.60 ± 2.57	2.754 ± 0.025	16.172 ± 0.113

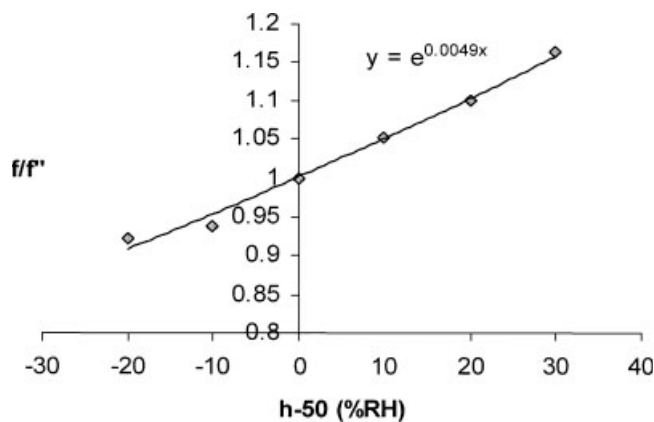


Figure 2 Relationship of $h - 50\% \text{ RH}$ and f/f' , where h is the relative humidity at 23°C , f is the tested IFD, and f' is the IFD measured by the ASTM standard. This shows how the correction formula is induced.

the hard urea segments.^{13–16} These hydrogen bonds strengthen the phase connectivity and provide the hard urea segments with additional disruption choices under compression, which promotes chain slippage and mobility.⁸ During the curing process, the absorbed moisture causes a phase transition in the FPF from a dynamically constrained state to a dynamically relaxed state because of many hydrogen bonds formed between the absorbed water molecules and hard urea segments within FPF, but there is no phase-content change. These covalent bonds are believed to be not strong enough and thus susceptible to break in the dehumidifying process, and this makes the FPF stiff again.

CONCLUSIONS

FPF is composed of soft polyol domains and hard urea segments. The physical properties of FPF rely on the urea phase content and phase connectivity within the foam. The IFD and support factor decrease, but the hysteresis increases, with the curing moisture. Additional hydrogen bonds are formed

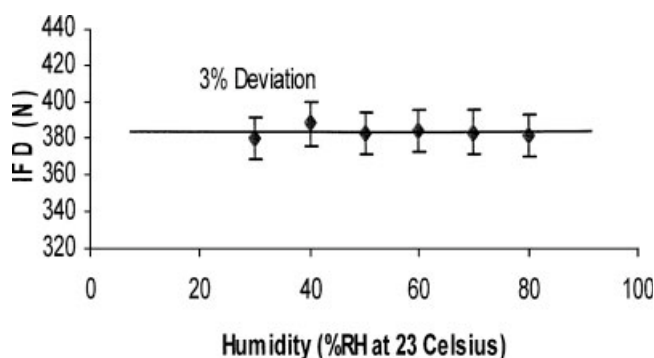


Figure 3 IFD values corrected by the formula in the $\pm 3\%$ range beyond the standard IFD.

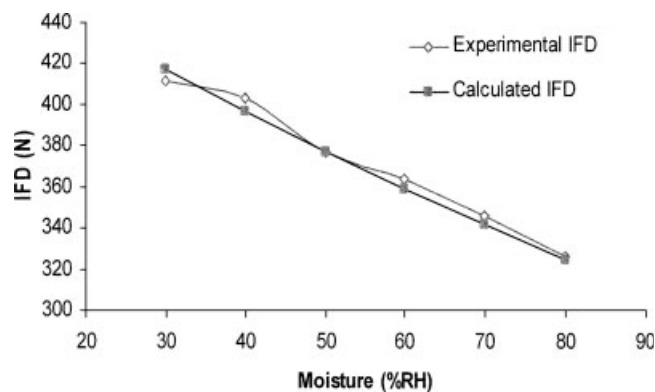


Figure 4 Experimental IFD values of PPFs cured at 23°C and $50\% \text{ RH}$ first and then reconditioned with different moisture contents.

between the water molecules and hard urea segments when the ambient moisture is absorbed into FPF. These covalent bonds, available for disruption, prompt the slippage of the soft polyol segments and thus make the foam less stiff. The generated hydrogen bonds change the phase connectivity in FPF. A correction formula has been deduced experimentally to eliminate any IFD variation caused by the curing-moisture effect, and the calculated IFD is inversely exponentially proportional to the curing moisture.

The authors thank Tri-Con Industries, Ltd., for material and apparatus support.

References

- Zhang, L.; Huang, J. *J Appl Polym Sci* 2001, 81, 3251.
- Aneja, A. Ph.D. Dissertation, Virginia Polytechnic Institute and State University, 2002.
- Brecl, M.; Žigon, M.; Malavašič, T. *Acta Chim Slov* 1999, 46, 43.
- Herrington, R.; Hock, K. *Flexible Polyurethane Foam*, 2nd ed.; Dow Chemical: Midland, MI, 1998.
- Kaushiva, B. D.; Wilkes, G. L. *J Appl Polym Sci* 2000, 77, 202.
- Moreland, J. C.; Wilkes, G. L.; Turner, R. B. *J Appl Polym Sci* 1994, 52, 549.
- Moreland, J. C.; Wilkes, G. L.; Turner, R. B. *J Appl Polym Sci* 1994, 52, 569.
- Dounis, D. V.; Moreland, J. C.; Wilkes, G. L.; Dillard, D. A.; Turner, R. B. *J Appl Polym Sci* 1993, 50, 293.
- Singh, R.; Davies, P.; Bajaj, A. *Nonlinear Dyn* 2003, 34, 319.
- Farkas, P.; Stanciu, R.; Mendoza, L. *J Cellul Plast* 2002, 38, 341.
- Standard Test Methods for Flexible Cellular Materials—Slab, Bonded, and Molded Urethane Foams; ASTM D 3574; ASTM International: West Conshohocken, PA, 1995.
- Joint Industry Foam Standards and Guidelines: PFA. <http://www.pfa.org/jifsg/jifsgs4.html>.
- Paul, W. S.; Heng, L. W.; Chan, K. T.; Ong, J. *Pharm Pharm Sci* 2003, 6, 334.
- Towns, J. K. *J Chromatogr A* 1995, 705, 115.
- Wu, C.; McGinity, J. W. *Eur J Pharm Biopharm* 2000, 50, 277.
- Aulton, M. E.; Abdul-Razzak, M. H.; Hogan, J. E. *Drug Dev Ind Pharm* 1981, 7, 649.