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The Influence of Environmental Aging upon the Loadbearing Properties of Polyurethane Foams

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Abstract—The effects of environmental exposure upon the loadbearing properties of nine polyurethane foams commonly used for wheelchair cushion construction were studied. Test pieces with and without a stretch cloth cover were aged in the open air at Houston over the period April 26 to October 31, 1982. The indentation resistance of each piece was measured initially and at frequent intervals during the exposure period. Resistance changes between covered and uncovered specimens were not found to be significant. All foams displayed a sharp rise in indentation resistance within the first 2 weeks of aging followed by a gradual decrease to an average 68 percent of the initial value over a 6-month period. These hardness changes were found to be strongly correlated with the density, thickness, and initial indentation resistance of the test pieces. Foams of maximum density and minimum practicable indentation resistance are recommended for wheelchair cushion construction to minimize the adverse effects of envirionmental aging upon the support properties of these devices.

INTRODUCTION

Pressure sores are a major complication of spinal cord injury due to the vulnerability of insensitive skin to the harmful effects of external forces. Most individuals using wheelchairs rely on various forms of wheelchair cushions to reduce the risk of pressure sores. These cushions are intended to redistribute body weight and restrict the levels of pressure and friction acting over the bony areas of the body. The most commonly used cushions are manufactured from plastic foams. Many such cushions are commercially available, and most give assistance in pressure-sore prevention during at least the first few months of their use. All foam cushions, however, deteriorate with age and lose their capacity to distribute body weight effectively (1, 2, 3). Clinical experience has shown that many pressure sores over the sitting area are directly attributable to the use of foam cushions that have worn out and have thus become unsafe to use (4). However, little is known at present about the causes of this deterioration, or about the actual length of the useful life of different commercial cushions, or whether measures may be taken by consumers and manufacturers to prolong cushion life. No objective accounts were found of the relative merits of different foam cushions in retaining their supportive properties with use. Traditionally, changes in the loadbearing properties of the foam cushions have been attributed primarily to the effects of repetitive compressive loading leading to fatigue softening of the polymeric matrix. This study has examined the possible contribution of environmental aging and exposure to ultraviolet light in the outdoor environment to the softening phenomenon.

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MATERIALS AND METHODS

An experiment was devised to examine the following hypotheses:

1. Polyurethane foam wheelchair cushions undergo softening during environmental exposure in conditions of heat and humidity even when not subject to the repetitive compressive loading associated with use by the occupant of a wheelchair.
2. The changes in the support properties of polyurethane foam wheelchair cushions associated with environmental aging may be partly attributed to the effects of ultraviolet exposure in direct sunlight.
3. Cloth covers used to protect wheelchair cushions significantly influence hardness changes associated with environmental exposure.

To test the hypotheses, environmental aging was adopted as a method for simulation of the condition present within wheelchair cushions due to the conditions of high temperature and humidity present in Houston during the summer months (Table 1).

Nine polyurethane foams commonly employed in the fabrication of mattresses and wheelchair cushions were selected, with densities ranging from 1.3 to 3.5 lb/ft^3 (20-55 Kg/m^3) and indentation resistances of 30 to 65 lb (130-290 N) (25% ILD). See Table 2. Test pieces measuring 6 inches × 6 inches (0.15 m × 0.15 m) were prepared, ranging from 3 to 4 inches (0.076-0.10 M) in thickness. Two identical test pieces were prepared from each polyurethane foam, one test piece being covered with a stretch fabric commonly employed in the manufacture of cushion covers. Prior testing demonstrated that the cushion covering reduced the intensity of sunlight incident upon the surface of the foam to approximately 10 percent of ambient levels in a range of outdoor conditions. In each case the duplicate test piece was left uncovered. The total array of 18 test pieces was suspended from a rack in the outdoor environment at Houston for a period of 6 months from April 26 to October 31, 1982. At the commencement of the aging period and at regular intervals thereafter, the hardness* of each test piece was measured using a 2-inch (0.051 m) diameter indentor which deformed each test piece to a depth equivalent to 50 percent of its initial thickness. For a range of polyurethane foams, the Standard Indentation Loading Deflection (ILD) test (ASTM D1564) was performed in addition to the hardness-measurement procedure using a 2-inch diameter indentor. This enabled calibration of the 2-inch indentor results in units equivalent to ILD hardness at 25 percent indentation depth.

Each test piece was preflexed twice to approximately 80 percent compression and then allowed to rest for 10 seconds prior to each hardness measurement in order to increase the reproducibility of each reading. Because the test deformation was based upon the initial thickness of each specimen, no allowance was made for the slight shrinkage associated with each of the uncovered test pieces. At the completion of the exposure period, all specimens were examined for evidence of surface changes and environmental degradation.

TABLE 1
Environmental conditions during the period of aging of the test pieces

Month	Average Temperature	Relative Humidity
April	70.1°F	74.6%
May	74.7°F	76.6%
June	79.4°F	75.6%
July	81.9°F	75.3%
August	82.7°F	75.0%
September	77.7°F	79.1%
October	68.2°F	74.9%
Total	77.3°F	76.1%

TABLE 2:
Initial Properties of the polyurethane foams selected for environmenta aging

Foam Number	Indentation resistance (25% ILD, lb)	Density (lb/ft^3)	Thickness (inches)
1	32.8	2.32	2.9
2	53.5	1.63	3.9
3	49.2	2.88	4.2
4	54.6	1.33	3.8
5	62.3	1.61	3.9
6	36.1	1.81	4.0
7	62.3	3.12	4.1
8	48.0	3.61	3.0
9	67.6	1.58	4.0

RESULTS

Superficial examination of the test pieces at the conclusion of the environmental aging revealed marked differences between test pieces that had been covered in comparison with their uncovered counterparts. The bare test pieces had been discolored to a depth of approximately a quarter of an inch (6 mm). The surface layers in some cases crumbled during examination. In comparison with its covered pair, each bare test piece displayed a loss in thickness that averaged 7 percent (range: 0-17%) without a corresponding change in density, which suggested that surface loss of polymer occurred during exposure of the uncovered test pieces.

The indentation resistences of all test pieces were found to vary markedly with duration of aging, though each test

*The expression "hardness" is used here as a convenient synonym for indentation resistance. This comment is made in consideration of the fact that some readers, particularly those with a strong engineering orientation, may tend to associate "hardness" with tests of the properties of metals and other "hard" materials and thus find it incongruous, at first, finding the term applied to a material usually considered as "soft."

piece displayed the same basic patterns of hardness changes (Fig. 1). In each case the foams hardened rapidly over the first 10 days, returning to around the initial hardness after the 4th week of environmental exposure. A relatively stable level of indentation resistance was then maintained from the 6th to the 13th week followed by an abrupt softening. The hardness of the test pieces then decreased gradually until the completion of the experiment. The individual sets of hardness data were characterized by four variables: (i) the initial hardness prior to aging (lb); (ii) the maximum increase in hardness during aging (%); (iii) the change in hardness after 2 months of exposure (%); and (iv) the change in hardness after 6 months of exposure (%).

In terms of these parameters, no significant difference was found at the 5 percent level between the response of the covered and uncovered test pieces to aging (Fig. 2). Consequently, the results obtained with these subgroups were pooled for analysis of additional variables. Initially, a multivariate analysis was performed to determine the degree of statistical correlation between variables describing the initial properties (initial "hardness," density, and thickness) and the aging response of the test pieces—it being noted that although each test piece displayed a similar general pattern of aging response, the indentation resistances varied over a range of up to 40 percent above and below the mean values. The multivariate analysis demonstrated a very strong correlation ($P<0.001$) between all the variables characterizing the aging response and the initial indentation resistance of the test pieces (Table 3). Foams of greater initial indentation resistance were observed to harden less in the first few weeks of aging and to have softened more after 2 and 6 months of exposure (Fig. 3, 4). This is demonstrated most clearly when the test pieces are divided into two groups of foam (Fig. 5): "initially soft" (25 percent ILD: 33-52 lb (150-236 N), mean = 43 lb) and "initially hard" (25 percent ILD: 52-68 lb (236-390 N), mean = 58 lb (264 N)).

The indentation resistance/exposure profiles of these two groups are significantly different at the 5 percent level for virtually every measurement of indentation resistance taken over the 6-month aging period, the difference being most profound over the first 3 months of exposure.

The density of the test pieces also significantly affected the response to aging, independent of the influence of initial resistance. Denser foams displayed a greater rise in hardness early in the exposure period and maintained a significantly greater level of indentation resistance up until the end of the 3rd month beyond which time density did not appear to greatly affect the observed hardness levels (Fig. 6). Thickness of the test pieces was also found to be significant. The thicker test pieces hardened less initially but were also associated with a greater loss of indentation resistance at 2 months. Thickness did not significantly affect the indentation resistance of test pieces after aging for 6 months.

A factor analysis showed that up to 93 percent of the observed variation of parameters characterizing the response of the test pieces to aging could be explained through the combined effects of the initial indentation resistance, density, and thickness of the test pieces. The maximum change in indentation resistance of the test pieces was predicted at the start of the exposure period by the expression:

$$\text{maximum indentation resistance (\% of initial value)} = 164 - 1.72\,H_i + 7.85\,D - 14.1\,T$$

where H_i = initial indentation resistance (25% ILD, lb)
D = density of test piece (lb/ft³)
T = thickness of test pieces (inches)

Values predicted by that expression were in close agreement with those observed in the experiment ($R = 0.963$), large changes in hardness being associated with thinner test pieces and soft foams of higher density.

The indentation resistances observed after 2 months of aging ranged from +124 percent to 67 percent of the initial value (mean 94 percent) and were predicted by the expression:

$$\text{Indentation resistance at 2 months (\% of initial value)} = 159\% - 0.97\,H_i + 8.34\,D - 9.3\,T$$

This expression predicted values that correlated well with these observed in the experiment ($R=0.937$) as seen in Figure 7. Foams that had softened most at 2 months were found to be primarily those of greatest initial indentation resistance and secondarily those of low density. The combination of higher density, i.e. 2.5-3.5 lb/ft³ (39-55 Kg/m³), and low initial indentation resistance, i.e. 25-35 lb (114-159 N) at 25 percent ILD, was associated with up to 50 percent less hardness loss after 2 months of exposure.

In contrast, hardness changes after 6 months correlated

TABLE 3
Correlation coefficient for variables characterizing the test pieces prior to aging and during environmental exposure with corresponding levels of statistical significance.

	Maximum* indentation resistance	Indentation* resistance at 2 months	Indentation* resistance at 6 months
Indentation resistance	−0.862 ($p<0.001$)	−0.748 ($p<0.001$)	−0.774 ($p<0.001$)
Density of test pieces	0.376 ($p<0.05$)	0.530 ($p<0.05$)	0.079 ($p>0.05$)
Thickness of test pieces	−0.655 ($p<0.01$)	−0.658 ($p<0.01$)	−0.433 ($p<0.05$)

*All values normalized with respect to the initial indentation resistance of each test piece.

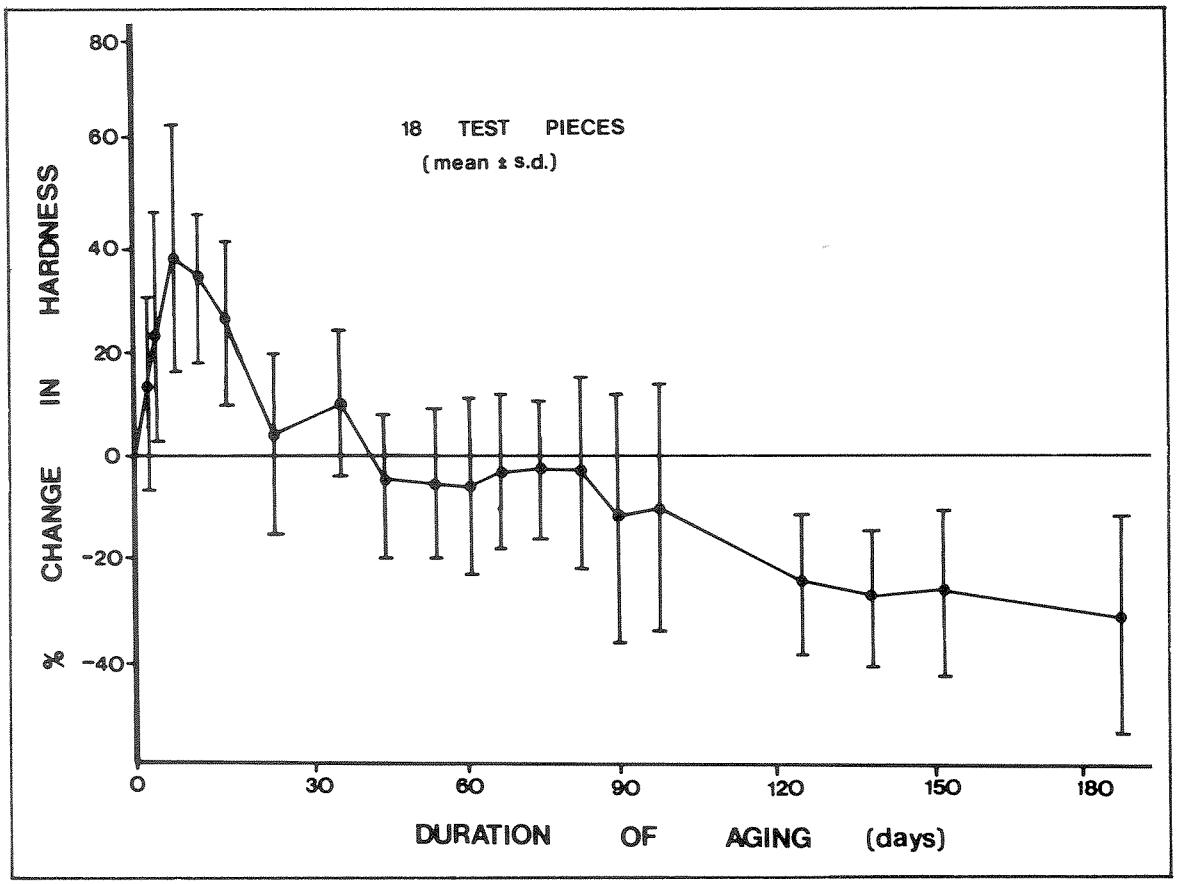

FIGURE 1.
Indentation resistance of all test pieces during period of aging (mean ± standard error).

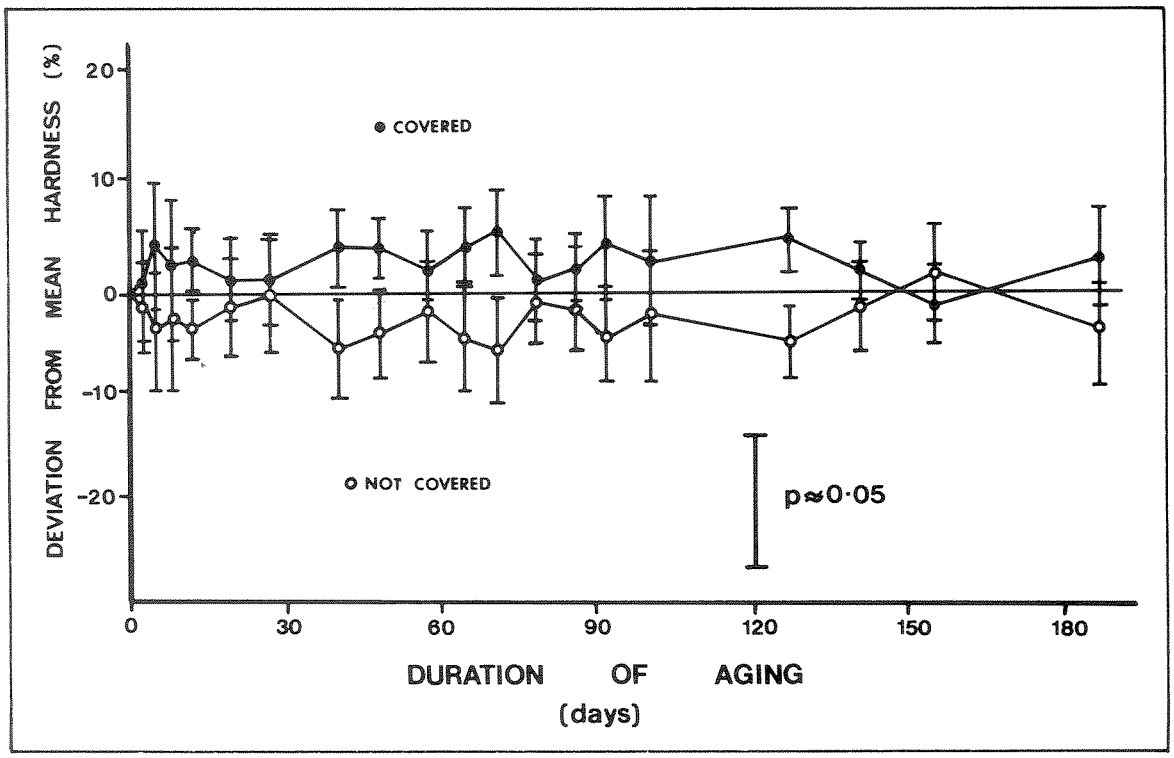

FIGURE 2.
Deviations from mean indentation resistance values associated with covered and uncovered test pieces.

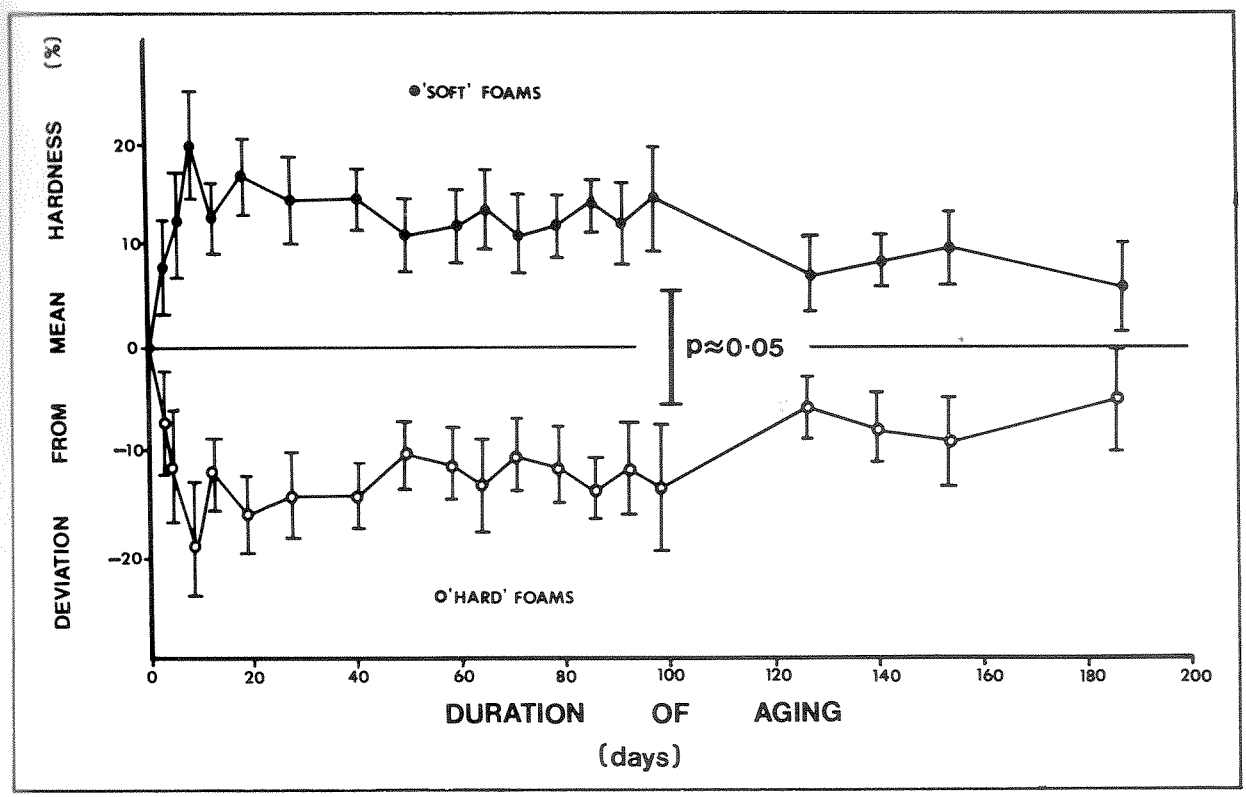

FIGURE 3.
Deviations from mean indentation resistance values associated with "hard" and "soft" test pieces.

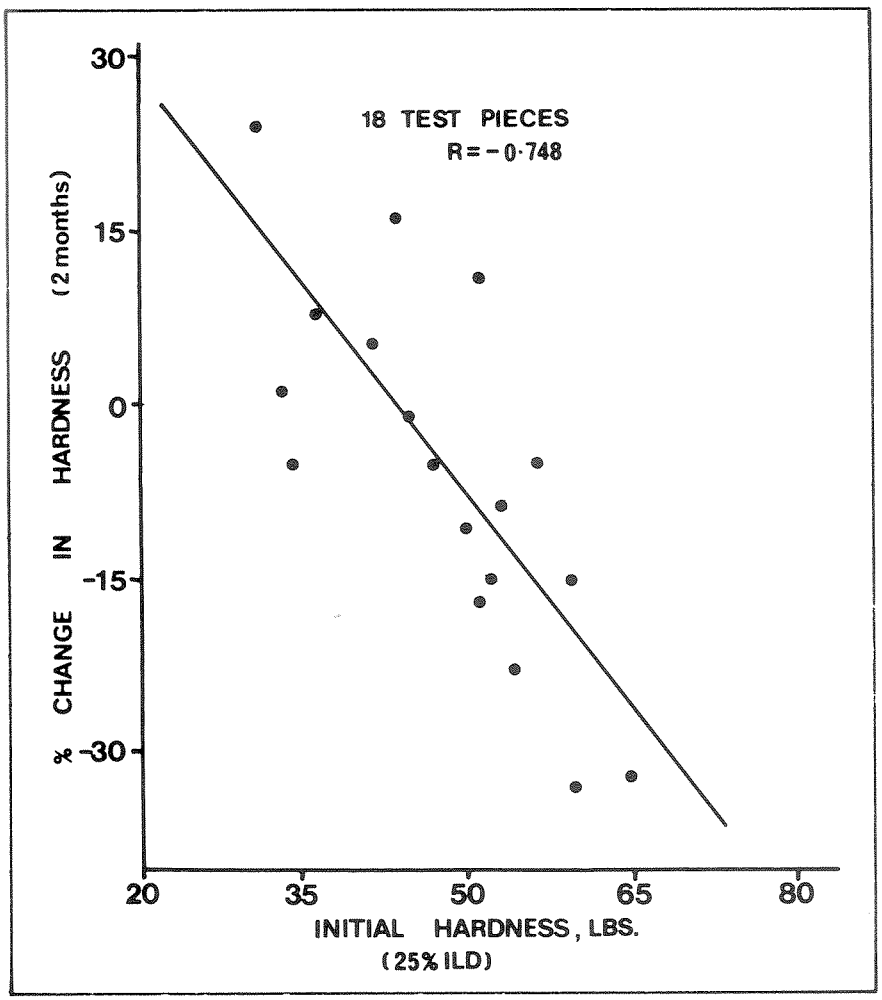

FIGURE 4.
Observed relationship between the initial indentation resistance of the test pieces and the change in hardness present after 2 months of aging.

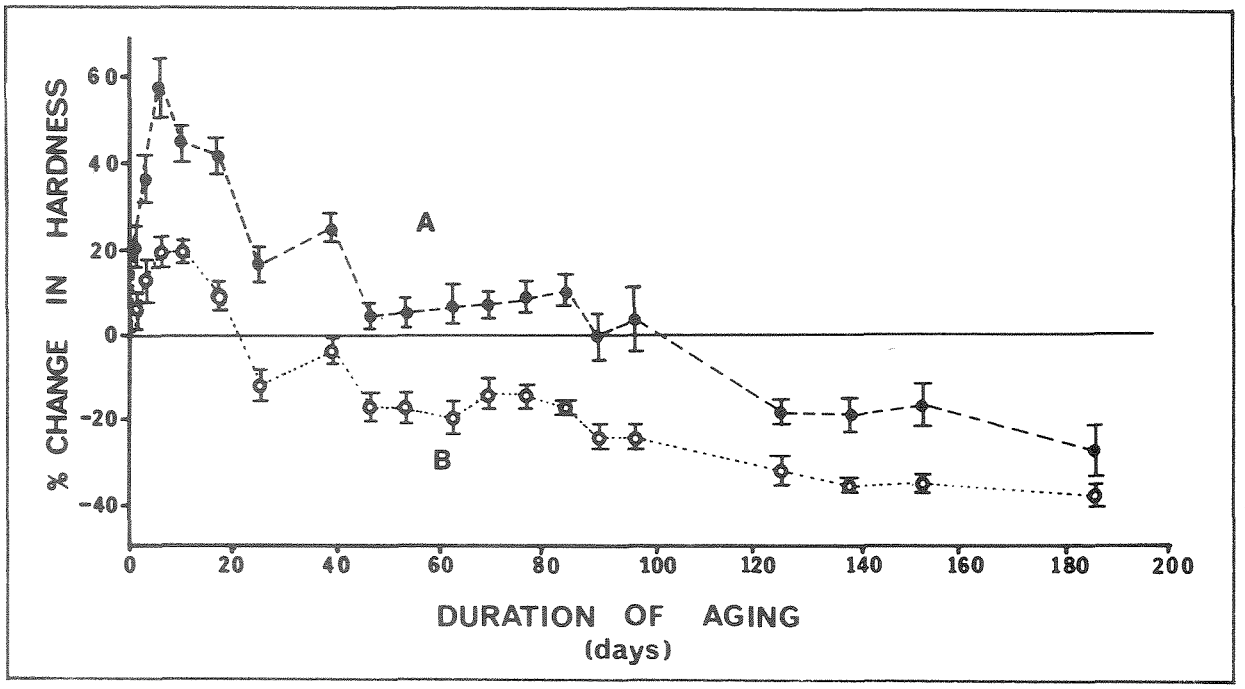

FIGURE 5. Changes in indentation resistance of "hard" (B) and "soft" (A) test pieces.

less significantly with variables characterizing the foams initially. The expression:

indentation resistance at 6 months (% of initial value) $= 121 - 97\ H_i$

was found to fit the data most closely, explaining 60 percent of the observed variation at this point. After 6 months, indentation resistances varied from 109 to 57 percent (mean 72 percent) of the initial values, and were not significantly influenced by density or thickness. Harder foams were observed to soften most with exposure of this duration.

DISCUSSION

Foam wheelchair cushions and mattresses often deteriorate with use, leading to a loss of indentation resistance typically amounting to 50 percent over a 3 to 6 month period (1). This change in loadbearing properties has often been attributed to "fatigue softening" associated with repetitive indentation of the polymeric matrix, although laboratory tests simulating this mode of loading have generally led to smaller changes in indentation resistance than those observed in practice (5). Moreover, the loss of hardness caused by repetitive loading in laboratory testing is oversved to occur early in the life of cushions and mattresses and not after some weeks or months of continued use. It may be hypothesized that the difference between such studies and actual experience of wheelchair cushion use is attributable to several additional influences which can act upon foam properties but that are not present during conventional laboratory testing. These additional hypothetcal influences include:

1. The presence of a humid environment;
2. Exposure of foam cushions to ultraviolet light;
3. Prolonged compression of cushions as distinct from continual repetitive flexing; and
4. Inherent aging processes within the polymeric matrix itself.

The results of this study suggest that most polyurethane foams used for seating applications are inherently unstable in conditions of environmental exposure and are likely to undergo substantial degradation of loadbearing properties after several months of service regardless of the frequency or severity of use. Our data suggest that during the aging of polyurethane foams, two distinct processes occur that strongly influence the physical properties of these materials. The first process involves relatively rapid hardening of the polymeric matrix over the first few days of environmental exposure. This effect may be attributed to the chemical degradation of plasticizing agents which have been added to the foam to impart the softness of certain low-hardness grades. The second process involves the long-term softening and degradation of the foams which is observed over several months of aging. These changes are consistent with oxidation or chemical degradation of the polyurethane matrix leading to reduced molecular weight of the polymer. This process is probably accelerated through the presence of ultraviolet light or ozone—although the fact that cushion covers do not prolong cushion life suggests that ultraviolet radiation may not significantly indluence this process in the foams examined in this study. That issue can only be fully resolved by aging test pieces in complete darkness, a condition that was not examined in this work.

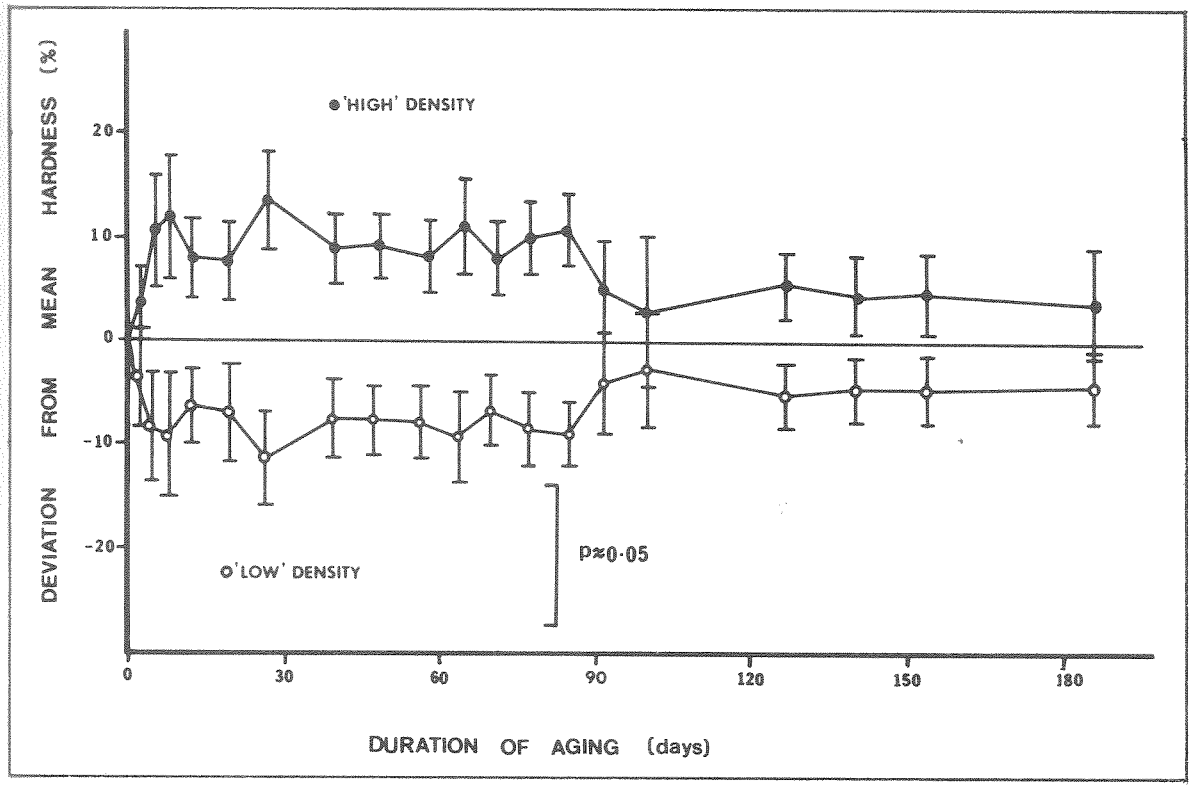

FIGURE 6.
Deviation from mean indentation resistance values associated with test pieces of "low" and "high" density.

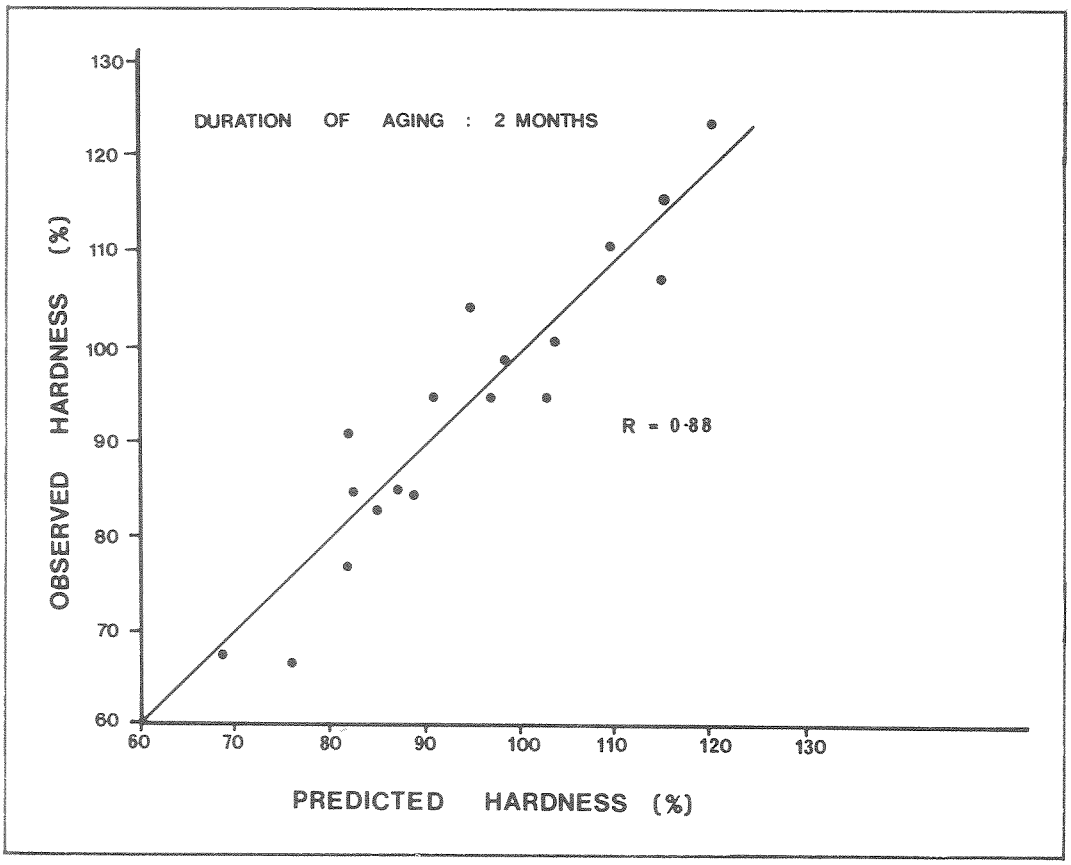

FIGURE 7.
Indentation resistance values of all test pieces after 2 months of aging, as predicted using the statistical correlation equation, and compared against observed experimental values.

The data presented in this report demonstrates a strong correlation between the initial properties of polyurethane foams and their response to environmental aging. This suggests that the impact of aging upon foam cushions over a large proportion of cushion life may be greatly reduced through correct foam selection. The regression analyses performed in this study predict that, through selection of polyurethane foams of optimum indentation resistance and density, the hardness changes accompanying aging may be reduced by up to 50 percent. Previous studies have demonstrated that the softening of foams during repetitive flexing is very sensitive to matrix density, with denser matrices suffering the smallest hardness losses. If it is hypothesized that the service performance of

foam wheelchair cushions reflects the combined effects of softening due to repetitive loading and environmental aging, then the service life of wheelchair cushions will be extended primarily through selection of foams of maximum practicable density in combination with relatively low hardness.

An alternative approach may be the adoption of processes to mechanically or environmentally pre-age foam cushions before use. This may allow the use of foams of greater density and hardness than has been customary in wheelchair cushions in the past, while still minimizing long-term deterioration and the disturbing incidence of skin ulceration to which that phenomenon leads.

CONCLUSIONS

During environmental exposure, polyurethane foams undergo substantial changes in indentation resistance, resulting in a significant loss of initial supportive properties. Although these changes may be minimized through selection of foams of higher density and reduced hardness, it is not presently clear what the relative influences of environmental variables (temperature, humidity, and ultraviolet exposure) are upon the aging of foam products. Those influences can only be isolated through a controlled study of aging upon the properties of polyurethanes. In such a study each environmental variable would have to be varied independently.

The relevance of environmental exposure to the service conditions experienced by wheelchair cushions also requires thorough investigation.

Measurement of hardness changes of real wheelchair cushions during service would enable the relevance of aging tests and test predictors to be estimated. It would also demonstrate the relative importance of variables characterizing polyurethane foams in determining superior performance over extended periods of use. Such work may also indicate that properties unrelated to static aging (e.g., compression set) also significantly affect service performance ■

REFERENCES

1. Marchant RP: Comparison of polyurethane and latex foams for furniture. J. Cellular Plastics, pp 85-89, 1982.
2. Noble PC: The Prevention of Pressure Sores in Persons with Spinal Cord Injuries. World Rehabilitation Fund, Intl. Exchange of Information on Rehabilitation, Monograph No. 11, 1981.
3. McFadyen FM and Stoner DL: Polyurethane wheelchair cushions: retention of supportive properties. Arch Phys Med Rehabil 61(5):234-237, 1980.
4. Denne W and Molden F: Fatigue in Polyurethane Foam. Oxford Orthopaedic Engineering Center, Annual Report 1978, pp 46-49.
5. Garber SL, Krouskop TA, and Noble PC: The Effectiveness of Preventive Management in Reducing the Occurrence of Pressure Sores. Proc 5th Ann Conf Rehabilitation Engineering, 1982, p 85.