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THE EFFECT OF OVERALL DENSITY ON THE MECHANICAL PROPERTIES OF FLEXIBLE POLYURETHANE FOAM

OYETUNJI O. R. & HAMMED B. M

Department of Mechanical Engineering, Ladoke Akintola University of Technology, Ogbomoso

ABSTRACT

The comfortable mattress is said to be an essential ingredient in a good night sleep, but we have little understanding of the desirable properties (especially, the mechanical properties) of a quality mattress and as a result, when allowed to test mattresses in a typical showroom, individuals choose a mattress that does not minimize overnight motion and maximize perceived sleep quality. Many of the symptoms people suffer from are being caused, in part; by the way they sit, stand and sleep. In order to have a good understanding of how to choose the appropriate mattress, both for seating or bending application, which will help solve these problems, a vibrant knowledge of the major indicator of mattress quality is of paramount importance and this is the purpose of this research work.

A series of laboratory tests were carried out on four samples of flexible polyurethane foams of zero, four, seven and fourteen years of usages and of different manufacturers (to allow for variation of density) to determine the relationship between the foam's overall density and other mechanical properties of the foams such as the support factor, compression modulus, resilience, tensile strength, etc , all of which are the major indicators of the quality and performance of any flexible polyurethane foam.

The results obtained for these laboratory tests showed significant variation in the values of support factor, compressibility modulus, resilience, tensile strength, percentage elongation and hardness factor with respect to variation in the foams' densities. These factors improve as the foam's density increases, except for the compression set and hardness factor which were found to decrease, indicating they are not function of foam's density.

A study of the trend of variation of these factors with density shows that the major determinant factor of flexible polyurethane foam's quality is its density and not necessarily its age.

KEYWORDS: Mattress, Overall Density, Mechanical Properties, Polyurethane Foam

INTRODUCTION

A mattress, sometimes referred to as foam can simply be defined as a manufactured product to sleep or lie on, consisting of resilient materials and covered with an outer fabric or ticking. The first mattress consists of a pile of leaves, grass or possibly straw, with animal skins over it. Up till the early 2000s, beds were normally upholstered with a single fabric – covering all surfaces of the mattress and ticking, or for inexpensive bed sets, a covered with up to six different fabrics [3].

Generally, four kinds of mattresses are produced in the Western world: foam mattress e.g. polyurethane, latex mattresses e.g. synthetic latex, spring mattresses e.g. bi-conical spring mattress and fluid-based beds e.g. water beds. Next to these varieties, natural materials e.g. kapok or straw are also produced to a lesser degree in other parts of the world. The flexible polyurethane foam mattress has been found to gain more recognition in both furniture and bedding applications.

Although, quite a number of factors affects the quality of a flexible polyurethane foam which is usually determined in terms of its durability, comfort and support which foam can offer; of all these factors, the foam's density has been identified to be the major indicator of the foam's quality as all other mechanical properties such as support modulus, compression set, tensile strength, sag factor, resilience, elongation, e. t. c also improve as density increases.

Aside being used for sleeping, mattress commonly provides an area for multiple disparate daily activities. Adults sleep an average of about 8 hours a day; 5 year olds sleep an average of 11 hours [4]. Some consumers spend much longer than this in bed due to age, injury, or illness. People vary widely in the amount of sleep that they need. A growing body of literature indicates the effects of sleep on health, ability to function, and quality of life [5-13]. A comfortable mattress is commonly assumed to be an essential ingredient in a good night's sleep [14].

The broad aim of this research work is to investigate the effect of overall density on the mechanical properties of a flexible polyurethane foam or mattress.

DETERMINATION OF FOAM QUALITY

Quality measurements of flexible polyurethane foams are widely reported in literature according to ISO5999-2007 standards [15-20]. Specifications of the cushioning properties include the degree of firmness or softness, weight, resilience and durability. In order to ensure uniformity in the assessment of the quality of flexible polyurethane foams, Polyurethane Foam Association (PFA) adopted the American Society of Testing Materials (ASTM) procedure ASTM D 3574-86 Test (Standard Methods of Testing Flexible Cellular Materials – Slab, Bonded, and Molded polyurethane foams) for characterizing the quality of foam samples. Based on ASTM D 3574-86 B1 procedure, quality assessment of foam samples is generally on the following properties:

- Density
- Indentation Force Deflection (Hardness Index)
- Resiliency/Elasticity (Degree of springiness)
- Compression
- Tensile Strength and Elongation

Detailed descriptions of how each of the above tests is carried out are presented in the method.

According to the International Standard Organization (ISO), a typical polyurethane product that conforms to the specified standards shown in Table 1 below is reported to have a lifespan of between 3 to 15 years depending on the end use and frequency of usage.

Table 1: Physical and Mechanical Properties Requirements by International Standard Organization (ISO)

Properties	Minimum Value	Maximum Value
Density (kg/m^3)	12	40
Compression Set (%) *50% Indentation* *70% Indentation*	 1 1	 10 15
Elongation (%)	100	350
Hardness Index (kN) *70% IFD*	 70	220
Tensile Strength (kN/m^3)	70	240
Support Factor (ratio)		1.6:1 3.0:1

Source: (Oertel, 1993)

Effects of Density on Mattress Performance and Quality

Density is a key flexible polyurethane foam specification. It is an important indicator of foam performance with regard to comfort, support and durability. It is also an indicator of the relative economics of the foam (i.e. the cost of a foam with higher polymer or overall density, though having a better quality, will be higher than that with a lower density). Foam density is not the same as its weight; it is actually a measurement of mass per unit volume, usually measured in pounds per cubic foot (pcf) or in metric terms, kilogram per cubic meter (kg/m^3). Density is a function of the chemistry used to produce the foam, of additives used to increase density (as fillers or to improve the luxurious appearance of the foam), and of any additives used to improve the combustion resistance properties of the foam.

The foam's property is majorly a function of the density of the "virgin" or unfilled foam. This is also called polymer density. If the foam contains no additives or fillers, the polymer density is the same as the overall foam density. When additives or fillers are used in producing the foam, the foam overall density will be higher than the polymer density. Obviously, the denser the foam, or the more material used to produce it, the more material there is in the cushion to provide support for weight.

Density also translates into foam durability. Again, the more polymer material used to produce the foam, the better foam tends to retain its original properties. As a general rule, the higher the density (of the polymer or overall foam) the greater the support Foam density is independent of foam firmness.

Flexible polyurethane foam is available in a broad range of densities, ranging from as low as 0.8 pcf to as high as 8 pcf (see Figure 1). Most foam applications utilize foam in the range of 0.9 to 2.5 pcf density range (pcf = pounds per cubic foot).

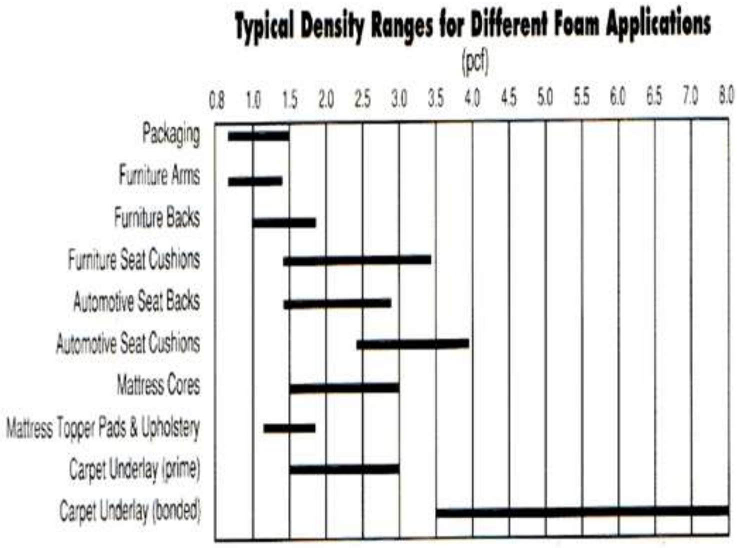

Figure 1: Recommended Density Ranges of Polyurethane Foams for Different Applications By Polyurethane Foam Association (PFA)

Source: INTOUCH® Bulletin by PFA (Volume 1, March 1991)

Mattress Maintenance and Care

For a mattress to satisfactorily perform its desired functions and meet up with its durability requirement, the following maintenance tips need to be adequately taken note of:

- The mattress should be placed atop a firm base to prevent sagging.
- A new mattress should be rotated once a month for the first six months and once every 2-3 months after that.
- Double sided or two sided mattresses should be alternately flipped and rotated; manufacturers suggest that one rotate (spin) the box springs or foundation twice a year.
- Folding and bending of the mattress should be avoided if possible, as should heavy wear in one spot and excessive weight on the handles.
- Mattresses should not be soaked, lest mildew develop inside the upholstery; instead, they can be cleaned with a vacuum or with mild surface cleanser and a slightly damp cloth. A mattress protector can help prevent stains and soiling of the ticking.
- Queen and larger size mattress sets should be supported by a 5- or 6-leg frame. A queen size mattress is 60 inches wide and requires more support than smaller sizes.

MATERIALS AND APPARATUS

The materials used in this research work consist majorly of four samples of flexible polyurethane foams which were of 0, 4, 7 and 14 years and essentially of different manufacturers. The following are the list of testing machines (apparatus) used in carrying out various tests on the foam samples:

- Digital weighing balance
- Resilience testing machine (Rebounder)

- Compression machine (with oven)
- Indentation Hardness testing machine (with a set of Computer for display of result)
- Tensile and Percentage Elongation testing machine.

Method

Procurement of Materials

Among the four samples of foams used for this research work, three (used) were purchased from their respective users while the new one (of zero years) was purchased from the foam industry (Yinka- Oba Foam, Ilesha) where the laboratory tests were carried out.

Preparation of the Test Samples

The test samples after being taken to the material testing laboratory of a company, were allowed to recover from their initial compressions due to the ropes used in tighten them, this lasted for about an hour so that they can gain full recovery. Having recovered fully well, the samples were moved down to the cutting section to be sized to the required dimensions for the various tests.

Experimental Procedures

A detailed description of each of the laboratory tests carried out on the each of the four flexible polyurethane foam samples is presented below:

Density (Measurement)

This is a measure of the weight of the foam relative to the space it occupies. It gives a numerical expression of the contents to air ratio of the foam which consequently affects almost all of the other parameters used in specifying the foam's quality. On a general note, the higher the density, the better foam will be. (8)

Procedure

- Measure the dimensions (i.e. length, breadth and height) of the test piece and convert all measured values to meters (m). The product of these dimensions gives the sample's volume in cubic meter (m^3).
- Measure the weight of the test piece using weighing balance and convert the measured value to kilogram (kg).
- Divide the sample weight by its volume to get the desired density in kg/m^3.

$$\text{Density } (kg/m^3) = \frac{W}{(L \times B \times H)} \quad (1)$$

W= Weight (kg)

L= Length (m)

B= Breath (m)

H= Height (m)

Indentation Force Deflection

The indentation hardness test is a measure of both the foam's hardness factor (which is used in determining the degree of firmness or softness of the foam) and the foam's support factor (which indicates the foam's load bearing property). In real term, the hardness index is the force required to depress a circular plate (by 40%) into the foam.

Procedure

- Cut the test sample (foam) to suitable size, usually a dimension of 380mm x 380mm x 50mm is recommended by the manufacturer of the hardness testing machine.
- Position the test piece on the support plate that is perforated for airflow.
- Carry out a preloading exercise on the test piece until the initial readings on the machine are reset to zero value, this is done by gently loading and unloading the machine.
- The indentation is then carried out in three stages, all at 100mm/min; **stage one**, usually regarded as "Method A" compresses the test piece to 40% of the original height, maintains this position for 30sec. before unloading and the required force is automatically determined, which is a measure of the foam's material index; **stage two**, which is usually referred to as "Method B" is the most commonly used as it is the one that gives both the hardness factor and load quotient which are of interest. This method carries out the indention in three steps; firstly by compressing the test piece to 25% of its original height and determines the required force, during the second step, the compression force is increased such that the compression rate also increases to 40%, the force required is also determined and lastly during the third step compresses the test piece to 65% while the required force, all in Newton, N is also determined.
- The hardness Index or firmness corresponds to the 40% IFD. The Compression Modulus or Support Factor, which represents the foam's load bearing capacity, is usually calculated as the ratio of the 65% IFD to the 25% IFD. This ratio is further reduced to the simplest form, the denominator being one. According to International Standard Organization (ISO) this ratio must not be less than 1.6:1 if the foam is to be suitable for use as cushion. The **stage three**, which is regarded as "Method C" only gives the foam's *instantaneous hardness index* by compressing the test piece to 40% of its original height and immediately unloads.

Resilience/Elasticity

This test is used to determine the degree of springiness or elasticity of the foam. The value obtained from this test shows the ability of the foam to rebound after being squeezed.

Procedure

- Cut the test piece to a dimension of 100mm x 100mm x 50mm.
- Place the test piece on the marked out space on the machine sample holder and screw up this holder until it is in close contact with the tubular height measuring scale of the machine, which is calibrated in millimeters (mm) through a total height of 460mm.
- A circular steel ball of small diameter is then dropped with the aid of a magnet holder through the opening at the upper end of the measuring scale and the height through which the ball spring up as it drops on the test piece is automatically determined and displayed on the machine's monitoring unit. This is repeated for about nine times

and the average height is automatically computed by the machine.

- Divide the machine's total height (460mm) by the average height to get the desired percentage resilience as follows:

$$\text{Resilience (\%)} = \frac{Ah \times 100}{Th} \quad (2)$$

Ah= Average height (mm)

Th= Total height (mm)

Compression

The value obtained from this test is a measure of the ability of the foam to recover after the applied load is removed i.e. when the user gets out of the mattress. The compression set which can be defined as the difference between the initial thickness and final thickness of the foam, expressed as a percentage is determined from this test.

Procedure

- Cut the test piece to a dimension of 50mm x 50mm x 25mm.
- Place the test piece in the provided compression device that consists of two plates having dimensions larger than that of the test piece.
- Compress the test piece to 50% of its original thickness and maintain this in an oven whose temperature is set at $70^{o}C$ for about 24 hours.
- After 24 hours, remove the test piece from the apparatus and place it on a surface of low thermal conductivity like wood for about 30 minutes, for it to recover before measuring its final thickness.
- The compression set is the calculated as follows:

$$\text{Compression set (\%)} = \frac{t_o - t_f \times 100}{t_o} \quad (3)$$

Where:

t_o = The original thickness of the test piece (mm)

t_f = The final thickness of the test piece after recovery (mm).

Tensile and Percentage Elongation

These tests give information about the elasticity of the foam and also indicate the strength of the foam under tension. By definition therefore, Tensile Strength is the maximum force required to break a test piece divided by its original cross sectional area. The elongation at break is the change in length of the test piece determined at the time of break and is expressed as a percentage of the original gauge length of the test piece.

Procedure

- Cut the test piece to a dimension of 155mm x 25mm x 13mm.
- Firm grip the test piece with the two holders on the tensile testing machine whose distance between centers is 55mm.
- The test piece is then pulled apart till it breaks and the Breaking force; F (N) is displayed on the machine's monitoring unit while the Change in length, L (mm) at break is measured with the aid of a ruler fixed to the side of the machine.
- The Tensile Strength and the Elongation expressed as percentage of the original length are calculated as follows:

$$\text{Tensile Strength } (N/m^2) = \frac{Bf \times 1000}{A} \quad (4)$$

Bf = Breaking force (N)

A = Cross sectional area (m^2)

N.B: *The multiplying factor of 1000 in the above equation is just a conversion factor and not a percentage.*

And

$$\text{Elongation } (\%) = \frac{L_b - L_o \times 100}{L_o} \quad (5)$$

Where:

L_o = the original length of the test piece (mm)

L_b = the final length of the test piece, at break (mm).

N.B: $L_b - L_o = \triangle L$.

RESULTS OF LABORATORY TESTS

The result of various laboratory tests carried out on four different samples of flexible polyurethane foams is as shown in the table 2 below:

Table 2: Results of Laboratory Tests Carried Out on Flexible Polyurethane Foam Samples

Tests 14.81 16.77	**Density of Mattress (kg/m^3)**			
	19.06 33.02		**19.06**	**33.02**
Support factor (ratio) 1.6:1 1.8:1	2.0:1 2.6:1			2.6:1
Resilience (%) 32.57 35.87	39.78 43.50		39.78	43.50
Compression *Set* (%) 8.70 7.41	6.52 4.44		6.52	4.44
Tensile Strength (N/m^2) 122.38 124.22	162.08 174.21		162.08	174.21
Elongation (%) 122.73 138.78 Hardness index (N) 129.59 149.26	183.60 331.82 115.76 132.02		183.60 115.76	331.82 132.02

NOTE: The foam samples used were of different ages their ages were 0 (i.e. new), 4, 7 and 14years respectively.

Graphs of Each of the Properties against Density

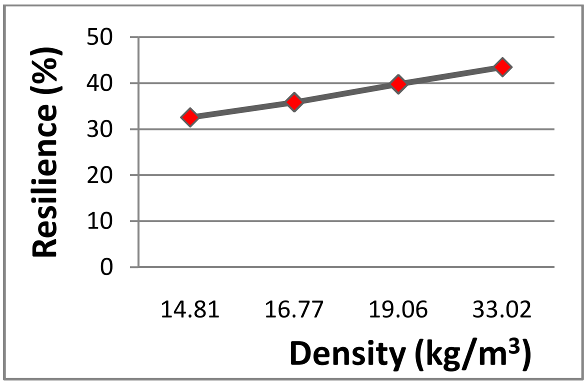

Figure 2: Graph of Resilience (%) against Density

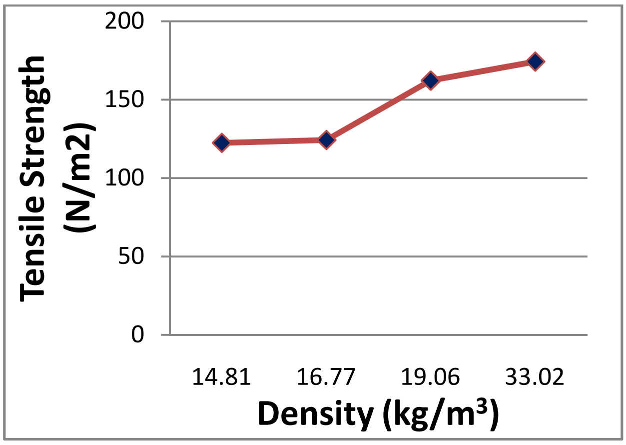

Figure 3: Graph of Support Factor/Compression Modulus against Density

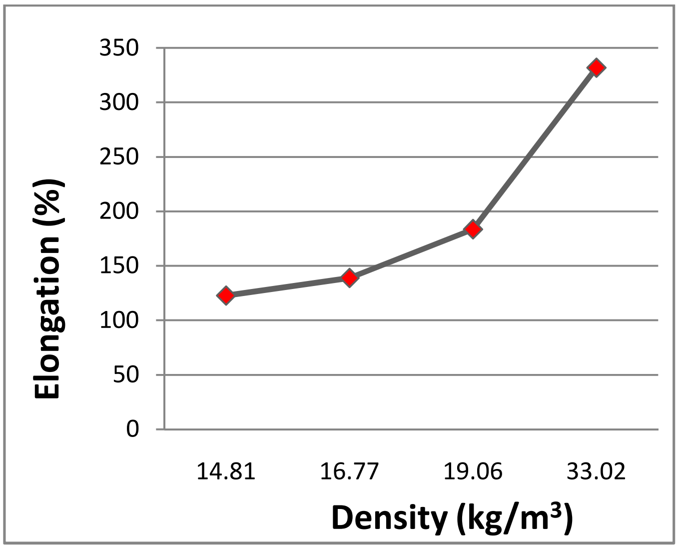

Figure 4: Graph of Tensile Strength against Density

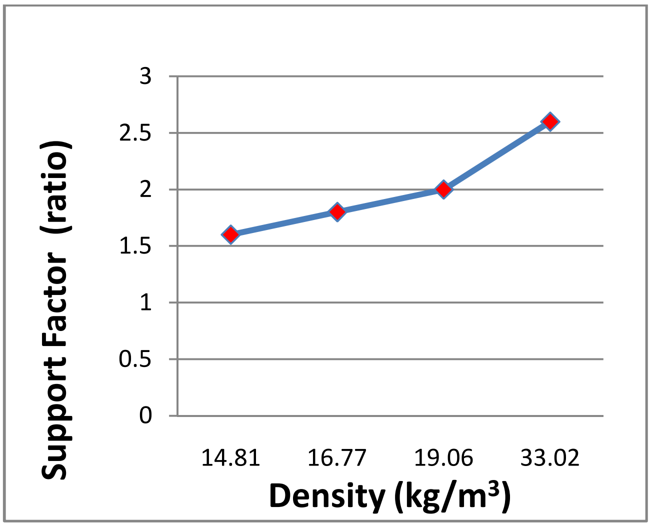

Figure 5: Graph of Percentage Elongation against Density

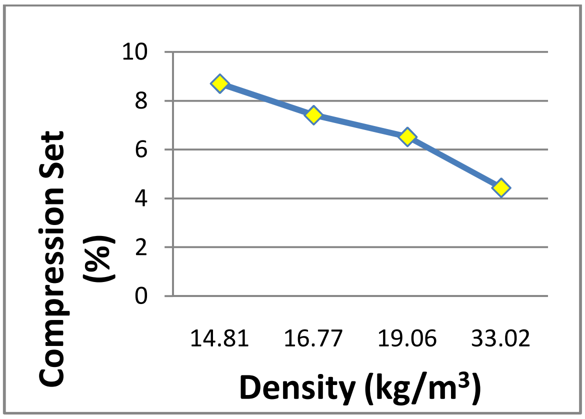

Figure 6: Graph of Compression Set against Density

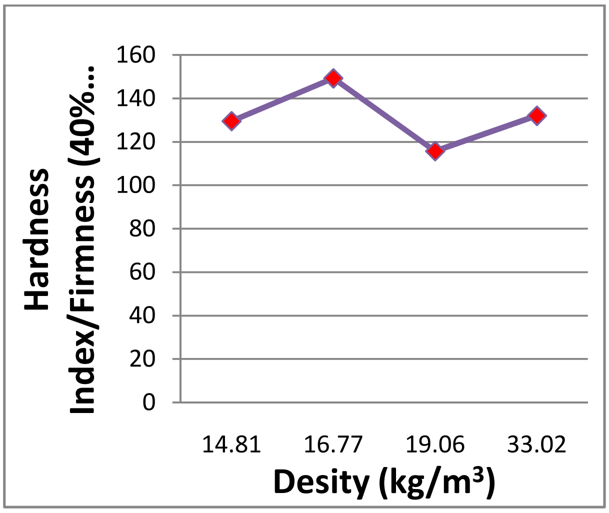

Figure 7: Graph of Hardness Index/Firmness (40% IFD) against Density

Discussion of the Results and Graphs

From the results presented in Table 2, it is evident that those properties of the foam which are reflectors of the foam's quality, especially the Compression Modulus, Support Factor, Resilience and Tensile Strength are largely predicted and affected by the foam's density and not necessarily functions of the age of foam – as this could be observed from the fact that the oldest of the foam samples (i.e. the one of 14 years) had the best quality in terms of its Support Factor, Tensile Strength, Resilience and Percentage Elongation being the highest and even the value of its Compression Set being the lowest of them all is also an indication of better quality (Since the Compression Set, in percentage, is a measure of the foam's tendency to lose height during usage and must be at minimum before a mattress can be rated as being of good quality).

The Compression Set of 4.44% (of the high density foam, 33.02kg/m^3) means that there is about 4.44 percent tendency that the 14 years old foam will lose height during use. This is a considerable improvement when compared to with the more relatively new foam (4 years), but of lower density (14.81kg/m^3) whose tendency to lose height during use is as high as 8.7%.

The graphs in Figures 2, 3, 4, and 5 showed that the Resilience, Support Factor, Tensile Strength and Percentage Elongation, all increase (i.e. improve) as the foam's density increases. This means that in order to improve the foam's performance and quality which are majorly determined by these factors, the overall density of any foam should be increased. The differences in the shapes of these graphs however suggest that the rate of change in each of these factors with respect to change in the foam's density differ.

The perfectly straight line graph obtained for the Resilience (Figure 2) indicates that no matter the level of change (increase or decrease) in the foam's density, the foam's resiliency or elastic property will continue to change (increasing or decreasing) uniformly.

The graphs for the Support factor, Tensile Strength and Percentage Elongation (Figure3 and Figure 4) having their shapes somewhat zigzag showed that the amount of improvements in the foam's quality (measured in terms of these factors) that will be brought about by change (increase) in the foam's density are will be proportional to the change in the density i.e. "the higher the magnitude of the change in the foam's density, the higher the change in these factors, and vice versa"

On the contrary, the Compression Set's graph observed to be the only one with a negative slope, is a major indication that an inverse relationship exists between this parameter (Compression Set) and the foam's density, meaning that "an increase in the foam's density will bring about a decrease in the value of the Compression Set, and vice versa". This is in agreement with what existing literatures revealed about this particular property of flexible polyurethane foam.

Finally, the entirely different shape (somewhat sinusoidal) obtained for the foam' firmness proved that the Firmness's property of the foam is neither a function of the foam's density nor its age, but rather a function of the foam's production chemistry and fillers/additives. Denser foam can be made soft while less dense foam is made hard, therefore there is nothing likes "firm density" or "soft density".

CONCLUSIONS

From the results obtained for the various laboratory tests carried out on the various samples of polyurethane foam, it can be concluded from this research work that:

- The density of flexible polyurethane foam, measured in pounds per cubic foot (pcf) or kilogram per cubic meter (kg/m^3), is a key factor for determining flexible polyurethane foam performance and quality.

- Foam density is independent of foam firmness.
- Density relates to the comfort, support and durability properties of the foam.
- The ability of foam to provide support can be measured and specified. This measurement is called compression modulus or support factor. Compression modulus is a ratio of foam's load bearing abilities.
- Two key factors affect foam support. The first is foam density; the higher the density, typically the better the ability of the foam to provide support. The second is foam chemistry and manufacturing process which affects the strength of the foam cell structure. Foams with high compression modulus (greater than 2.0) are often called "high performance" foams.
- Support is perhaps the most important function of flexible polyurethane foam. Foam's ability to provide support has a direct effect on other key properties such as comfort and durability.
- Finally, the foam's quality and performance are independent of its age but rather solely dependent of the foam's overall or polymer density.

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NOMENCLATURE

L_o: The original length of the test piece (mm)

L_b: The final length of the test piece, at break (mm)

ΔL: Change in length (mm)

t_o: The original thickness of the test piece (mm) t_f : the final thickness of the test piece after recovery (mm)

F: Breaking force (N) ρ: density (kg/m^3)

%: percentage elongation

REFERENCES

1. Howard, B. J. and Wong, J. (2001). Sleeping disorders, *Pediatrics in Review*, 22, 327-341.
2. Alapin, I., Fichten, C. S., Libman, E., Creti, L., Bailes, S., & Wright, J., (2001). How is good and poor sleep in older adults and college students related to daytime sleepiness, fatigue and ability to concentrate? *Journal of Psychosomatic Research*, 49(5), 381–390.
3. Centers for Disease Control and Prevention (CDC). (2007). Sleep and sleep disorders: Sleep hygiene tips. Available at http://www.cdc.gov/sleep /hygiene.htm
4. Elmenhorst, E. M., Elmenhorst, D., Luks, N., Maass, H., Vejvoda, M., & Samel, A. (2008). Partial sleep deprivation: Impact on the architecture and quality of sleep. *Sleep Medicine, 8*, 840-850.
5. Hamilton, N. A., Gallagher, M. W., Preacher, K. J., Stevens, N., Nelson, C. A., Karlson, C., & McCurdy,

D.(2007). Insomnia and well being. *Journal of Consulting & Clinical Psychology, 75*, 939–946.

6. Hanel, S. E., Dartman, T., & Shishoo, R. (1996). Measuring methods for comfort rating of seats and beds. *International Journal of Industrial Ergonomics, 20*, 163–172.
7. National Institutes of Health (NIH), National Center for Sleep Disorders Research. (2003b). *National sleep disorders research plan*. NIH Report No. 03-5209. Bethesda, MD: National Institute of Neurological Disorders and Stroke.
8. National Institutes of Health (NIH), National Institute of Neurological Disorders and Stroke. (2003a). *Brain basics: Understanding sleep.* Bethesda, MD: National Institute of Neurological Disorders and Stroke.
9. Roberts, R. E., Roberts, C. R., & Duong, H. T. (2008). Chronic insomnia and its negative consequences for health and functioning of adolescents: A 12-month prospective study. *Journal of Adolescent Health, 42*, 294–302.
10. Van Dongen, H. P., Maislin, G., Mullington, J. M., & Dinges, D. F. (2003). The cumulative cost of additional wakefulness: Dose-response effects on neurobehavioral functions and sleep physiology from chronic sleep restriction and total sleep deprivation. *Sleep, 2*, 117–12
11. Better Sleep Council, (2008b). Mattress buying guide. Available at http://www.bettersleep.org/Ease /shop.asp
12. Oertel, G. (1983). *Kunststoff 7: Polyurethane, 2nd Edition.* Carl Hanse Verlag, Munich. Vol 15, 2nd Edition, New York. Pp 58-62.
13. Macosko, C.W. (1994). Rheology: Principles, Measurements and Applications. Wiley, New York. Pp 425-427.
14. Herington, R. and Hocks, K. (1998). Flexible Polyurethane Foams, 2nd Edition. The Dow Chem. Co. pp 26-54.
15. Makanjuola, D. (1999). *Handbook of Flexible Foam Manufacture.* Temm Consulting Ltd., Nigeria.
16. UT (2000). Global Polyurethane Industry Directory 2001. Urethane Technology, Crain Communications, London.
17. Mills, N.J. (2007a). Polyurethane Foams: *Processing and Microstructure, Polymer Foams Handbook,* Pages 19-37.
18. Wikipedia Encyclopedia (2010) Mattress. www.wikipedia.org/wiki/mattress