TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY

Department of Materials and Environmental Technology

DEVELOPING THE TESTING RIG AND DETERMINING THE PERMANENT DEFORMATION OF POLYURETHANE FOAMS

POROLOONIDE JÄÄKDEFORMATSIOONI MÄÄRAMINE JA KATSESTENDI ARENDAMINE

MASTER'S THESIS

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AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.

No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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THESIS TASK

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Study programme: KVEM12/15 Technology of Wood, Plastic and Textiles

main speciality: Wood Technology

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1. Developing new testing rig for furniture
2. Testing different types of upholstery furniture seating foams

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Literature analysis	14.10.16
2.	Find different durability tests for foams	4.12.16
3.	Find suppliers for testing rigs for PUR foams	6.02.17
4.	Find suppliers for testing rigs for PUR foams in Europe	17.02.17
5.	Get offers from suppliers for testing rig	3.03.17
6.	Find mechanical companies in Estonia to supply a testing rig	17.03.17
7.	Develop a testing rig with a mechanical company	2.06.17
8.	Start testing PUR foams for deformation recovery	6.10.17
9.	Develop an improvement for existing testing rig	3.10.17
10.	Install improvements to existing testing rig	5.01.18
11.	Finish testing PUR foams	4.05.18

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PREFACE

The purpose of this master’s thesis is to develop a testing rig for upholstery furniture and to test polyurethane foams used in upholstery furniture for their final deformation. This was done researching foams mechanical properties, and by analyzing various standards specifically devised for upholstered furniture. In order to find a suitable solution for a testing rig, required aspects are listed and evaluated. Later, specialized producers are contacted in order for a quotation to be made. For even detailed needs, a model of was developed to be used as a universal testing rig. An alternative solution is also considered, which was implemented.

The research used 11 different foam models, which included standard foams, high resilience foams, and two-layered foams. Upon completion, data was analyzed to find links between the foams mechanical properties. Although there was little to no connection between foam hardness and final deformation, a link between density and deformation was much clearer.

I would like to thank my supervisor for their guidance during this process. Also a big gratitude to the specialists from SMC Pneumatics Estonia OÜ for providing us with (electro-)mechanical knowledge.

Keywords: polyurethane foam, foam deformation, upholstery, master’s thesis.

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1 INTRODUCTION

Polyurethane (PU) foam is a material engineered for energy absorption and have usage in many different fields including cushioning and packaging. The mechanical behavior of PU foams has attracted attention from engineers and researchers [1].

Foams are both versatile and crucial substance and are nowadays used in many different products. From the point of view of human physiology, sitting for more than couple hours is not good for both the nervous and muscle-skeletal systems.

The mechanical properties of PU foams are largely dependent on foam producer, as used substrates and production technology decide on intrinsic structure and foam density. The data on fatigue properties of PU foams are generally lacking [2].

Previously the Laboratory of Wood Technology, in Tallinn University of Technology used a Hegewald & Peschke Universal Testing Rig, which can be used for testing seating furniture, upholstery, and tables. The need for a new testing rig came from the short work range of the rig, and also due to the need to speed up testing if there's more than one specimen in queue.

Studying polyurethane foam ability to retain its thickness in upholstered furniture is important to producers for developing foams, which can last its life of use without sagging and customers coming back to shops for warranty.

However since no foam of the same type is exactly identical in its structure and properties, it is challenging to present a consentient statement for mechanical properties of polyurethane foams. In this thesis, 11 different types of PU foams will be tested for its permanent deformation after exaggerated conditions of seating on an upholstered furniture.

This aim of this thesis is divided into two parts. First task is to develop the testing rig for testing PUR foams based on European standards. The second task is to test the PUR foams used in upholstery furniture industry, provided by Vita Baltic International. Both of the tasks results are to be analyzed and a suitable testing rig will be established.

The first chapter of this thesis is about the literature analysis of PUR foams and testing methods. Chapter 2 evaluates various testing rigs and shows a new, developed model. Chapters 3 and 4 are describing the testing methods and analyzing the results.

2 LITERATURE REVIEW

Foams are both versatile and crucial substance and are nowadays used in many different products including safety equipment, sound deadening, shipping and packaging, mattresses, automotive interiors, insulation and thermal protection, transportation, furniture industry [3], both with springs and without springs [4]. Fatigue of polyurethane (PUR) foams is tested by ISO 3385:2014 standard [5] and it is used to predict how the initial cushioning characteristics of foam will deteriorate over time of use [6]. Other popular foam testing standards are ASTM D3574 and ISO 2439 [7].

Hyperelastic polyurethane foams are produced with the use of cross-linkers, catalysts and foaming agents. It is important that after curing the block, a mechanical opening of the pores takes place, which provide the level of flexibility of the foam [4].

From the point of view of human physiology, sitting for more than couple hours is not good for both the nervous and muscle-skeletal systems. Sitting can cause higher loads in the lumbar spine than standing, about 40% more. Wrong distribution of body weight can especially cause pains of the cardiovascular system (Fig. 1.1), resulting in inflammation of the venous system of lower limbs. [8]

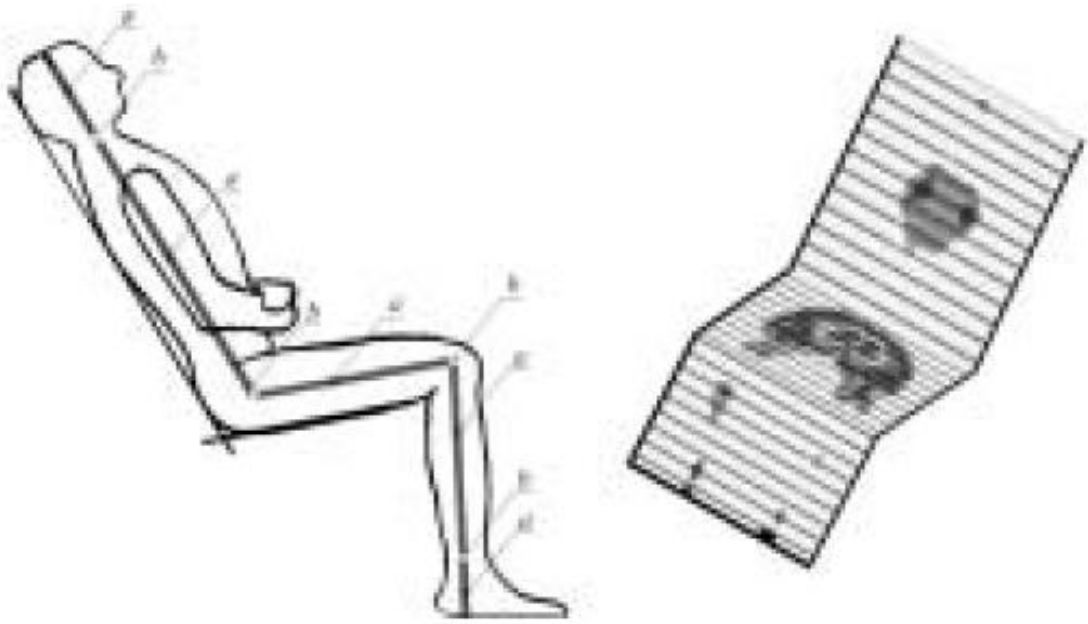


Figure 2.1 Man-seat system: a) centers of gravity of individual body parts, b) distribution of stresses on the seat surface [8]

Designers often delusively decide on a design and technology of making a seat without complying with the essential requirements of ergonomics and functionality. Therefore it is beneficial to gather credible information about the stiffness of seat cushions depending on the applied use and material solutions. [4]

2.1 Polyurethane foams and properties

Polyurethanes are any type of polymer containing a urethane linkage (-NH-CO-O-). Polyurethanes are generated by reacting an isocyanate ($R\text{-}(N{=}C{=}O)_n$) with a polyol, which contains two or more hydroxyl groups per molecule ($R'\text{-}(OH)_n$). The reaction is activated in the presence of a catalyst or by activation with ultraviolet light [9].

Isocyanates are highly reactive materials, which makes them useful in making polymers but also requires special care in handling and use. Toluene diisocyanate (TDI) is, by volume, the most important of isocyanate functional group, as it is used to adjust the properties of PUR foams. Polyols are polymers in itself and have on average two or more hydroxyl groups per molecule. The polyols used to make polyurethanes are not pristine compounds as they are often mixtures of similar molecules with different molecular weights and mixtures of molecules that contain different numbers of hydroxyl groups. To increase the load-bearing property of open-celled foams, polyols can be modified with fillers [10].

The properties of a polyurethane are greatly influenced by the types of isocyanates and polyols applied to make it. Polyol types determine the polyurethane foam properties, giving long, flexible segments, and give soft, elastic polymer. High amounts of crosslinking give tough or rigid polymers. Long chains and low crosslinking give a polymer that is very flexible, short chains with lots of crosslinks produce a hard polymer while long chains and intermediate crosslinking give a polymer useful for making foam [10].

One of the most desirable aspects of polyurethanes is their ability to be turned into foam. Making a foam requires the formation of a gas at the same time as the urethane polymerization is occurring. The gas can be carbon dioxide, either generated by reacting isocyanate with water or added as a gas [11].

High-density microcellular foams can be formed without adding blowing agents by mechanically agitating or nucleating the polyol component prior to use. Surfactants are used in polyurethane foams to emulsify the liquids, control cell size, and balance the cell structure to prevent collapse and surface defects. Rigid foam surfactants are used to produce very fine cells and a very high closed cell content. Flexible foam surfactants are designed to stabilize the reaction mass while at the same time maximizing open cell content to prevent the foam from shrinking [11].

There are two main reactions important in the production of flexible polyurethane foams: the blow reaction and the gelation reaction. To the manufacturer, balancing proportion of these two reactions provides the open-celled morphology in the foam that is highly important to physical properties. If the gelation, or cross-linking, reaction occurs too quickly, a tight close-celled foam may result. If the blow, or gas-producing, reaction occurs too quickly, the cells may open before the polymer has enough strength to uphold the cellular structure, resulting in collapse of the foam [11].

Depending on the composition, PUR foams can be classified as rigid or flexible foams. Rigid foams are widely used in applications such as building insulation, appliances, transportation and packaging. Rigid, closed-cell PUR foam has among the highest resistance to heat flow values of any commercially available insulation. Flexible foams are used as furniture, transportation, bedding, carpet underlay, textile, shock and sound attenuation [12].

2.1.1 Tear resistance

Tear strength is a much larger problem than tensile strength while handling the foam within the factory. Tear failures on foams in-use are relatively rare and are for most part connected with shear forces such as squirming or shearing the seating pillow across the front rail or shearing the top of an armrest with the hands while getting out of a chair [13].

While hardness is an important aspect in cushioning, tensile and tear strength are important while the foam is being stretched while handling or in use. Tear strength it the force needed to continue tearing a foam and is measured as force per linear centimeter (p.l.c.) of the cut. [14]

Foams are frequently drilled or punched to receive button straps, and tear failure around the holes are unavoidable with foams displaying tear strengths much less than 0.175 n/mm, unless the foam is protected in some form [13].

Shear forces during the shipment of upholstered products can also create tears with low tear strength foams. In many cases, the foam tears can be related to fatigue softening, but not just to poor handling. As polyurethane foam data sheets show, quantitative proof of the link between low tear strength and fatigue softening does not exist. However, there is enough data that shows information about the feasible effects of low tear strength on fatigue softening [13].

The total tear strength is the sum of the strengths of adjacent cell walls. If the tear strength is low, each of the cell walls has low resistance to tearing. This can result in not enough cell-wall strength while impact loading during sitting or concentrated loading of shear forces. At fist this kind of wall tearing may occur only to some of the cell walls, but with continued shear loading or impact loading, the change will be more monumental within the foam, affecting the load bearing properties. This type of softening is irreversible [13].

Proportionate changes in tear strength can indicate problems in foam formulation monitoring, changes in the chemicals used or changes within a run. Tear strength should be observed carefully [13].

Tear strength is measured using the method specified in ASTM D-3574. Sufficient tear strengths begin at approximately 1.0 pounds per lineal inch (p.l.i.). As the tear strength increases below 1.0 pounds per lineal inch, production handling problems are unavoidable [13].

2.1.2 Foams durability

The modern open-celled foam has become an every increasingly complex arrangement due to the need for a wide variety of functions. The physical properties of seating materials must maintain its high values both under static and dynamic conditions. In a static seating condition, foam provides a soft, flexible surface to the touch and provides apportioned pressure support when an occupant is seated. During a dynamic condition, the ability to reduce or protect the person from frequencies over 6 Hz, is important. [15]

Another equally important aspect of PUR foam is its ability to provide consistent performance during the time of use of an upholstered furniture piece. This is achieved by the foams ability to recover its properties when no load is applied. As this performance is highly important, many test procedures have been created to quantify long-term durability. Two of the best examples are Urethane Foam Dynamic Fatigue test [16], and Constant force pounding test [17]. At exaggerated conditions chosen to reproduce the effects of a foams lifetime, characterization of the PUR foam fatigue behavior has become more relevant to indicate foam properties change with dynamic cycle [15].

2.1.3 Foam durability testing

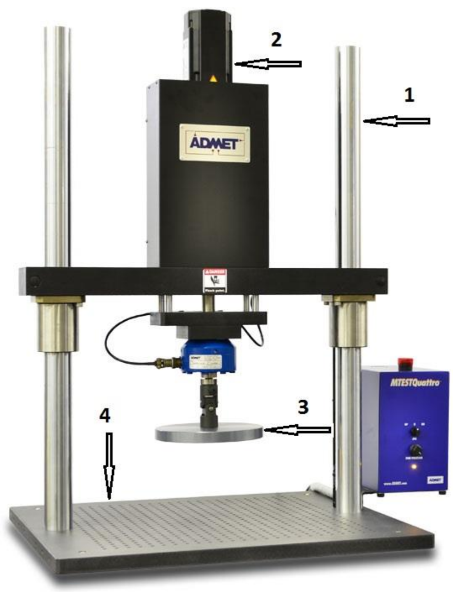
To provide safety, durability and comfort for customers, seat pillow manufacturers depend on the firmness of their seat cushions. Manufacturers use ISO and ASTM standards as testing foundations to ensure high-quality products [18].

The International Standard ISO 3385:2014 specifies a method for the determination of loss in thickness and loss in hardness of flexible cellular materials intended for use in load-bearing applications such as upholstery. Note that ISO 3385:2014 is not intended to function as a detailed engineering design specification for fatigue apparatus. [5]

The principle of ISO 3385 is repeated indentation of a test piece by and indentor smaller in are than the test piece, the maximum load reached during each cycle being kept within specified limits [5].

Required apparatus for this standard is pounding test machine (Fig. 1.2) with the following components:

- Plane platen, for supporting the test piece, suitably perforated in order to allow air to escape from the test piece.
- Indentor, having an overall diameter of 250 mm ± 1 mm, provided with a device for applying a maximum force of 750 N ± 20 N during the loading cycle. The indentor will be rigidly fixed to its guide. The machine shall be capable of oscillating the indentor towards the test piece in a vertical direction at a rate of (70 ± 5) strokes per minute. The indentor shall be linked to a re-settable counting device which displays the number of compression cycles performed during the test.
- Indentor drive mechanism, able to apply the maximum force of 750 N ± 20 N for no more than 10 % of the total duration of each cycle. [5]

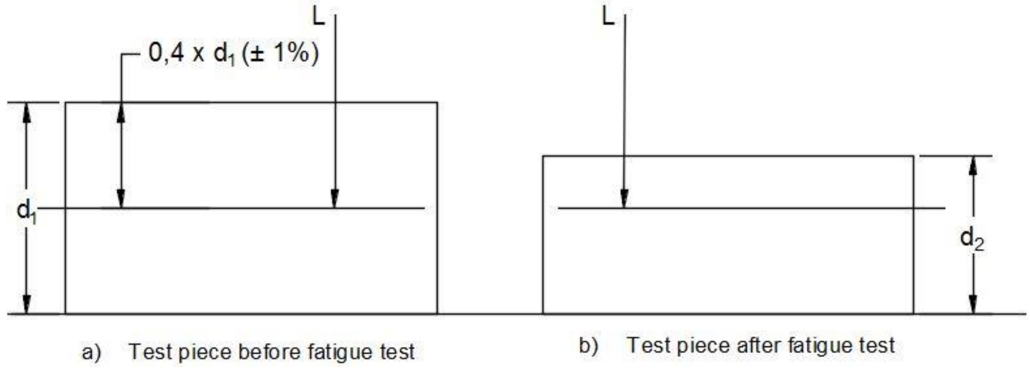


Key:

- 1 load frame
- 2 actuator
- 3 indentor
- 4 support platen

Figure 1.2.2 Example of machine with fully automatic adjustment – Example of one commercially available apparatus. ADMET eXpert 5952F [19]

Test piece shall be placed under the indentor with the speed set provide an indentation frequency of (70 ± 5) strokes per minute with the peak load of 750 N ± 20 N.Machine is ran for 80 000 continuous load cycles then removed from the machine and allowed to rest for 10 ± 0,5 min, before performing fresh measurements on the fatigued area.



Key

- L indentation level
- d_1 thickness of the test piece before fatigue test, expressed in millimeters
- d_2 thickness of the test piece after fatigue test, expressed in millimeters

Figure 1.2.3 Schematic representation of hardness re-test procedure

Expression of results are expressed in loss of thickness (formula 1), loss in hardness (formula 2) and percentage hardness loss (formula 3):

The percentage loss in thickness, Δd (%), is given using Formula (1):

$$\Delta d\ (\%) = 100\ \times \frac{d_1 - d_2}{d_1} \qquad (1)$$

where

d_1 - is the original thickness;

d_2 - is the final thickness.

The loss in hardness, ΔH (N), is given using Formula (2):

$$\Delta H\ (N) = \ H_1 - \ H_2 \qquad (2)$$

where

H_1 - is the original hardness, N;

H_2 - is the final hardness, N.

The percentage hardness loss, ΔH (%) is given using Formula (3):

$$\Delta H\ (\%) = 100\ \times \frac{(H_1 - H_2)}{H_1} \qquad (3)$$

where

H_1 - is the original hardness, N;

H_2 - is the final hardness, N.

Foam testing is often concentrated on Indentation Force Deflection (IFD or ILD) which determines the load bearing capacity, stiffness and firmness of a specified thickness of a foam specimen [3] [18].

Temperature control in any type of polymer testing is important, because of how sensitive the results are. Due to high surface area and low diffusion distances of an open-cell PUR foams, humidity can quickly affect the properties of the foam [20].

Due to a lack of open-cell PUR foam chemistry and mechanical properties in some articles, it is difficult to link water absorption to the foam microstructure [21].

2.2 Digital image correlation

Lu [22] has conducted series of work characterized and modeled the compressive mechanical response of a specific rigid closed-cell PU, PMDI (polymeric methylene diphenyl diisocyanate) foam, with a nominal density of 320 kg/m^3. Numerous experiments of various loading conditions were conducted to study the effects of temperature and strain rate on the mechanical behavior of the foam specimens.

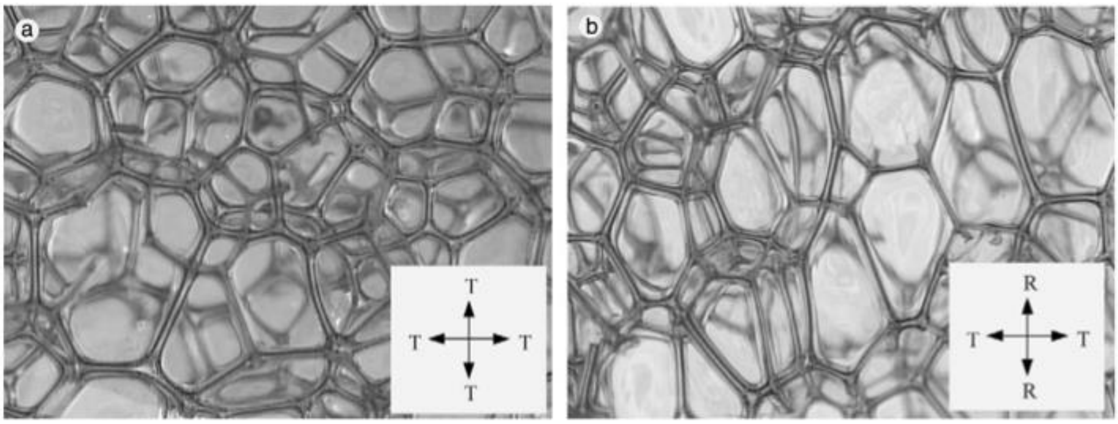


Figure 1.2.4 Microscopic views of polyurethane foam in the a) rise and b) transverse directions [23]

In the foam experiments, the typical strain gage technique is not applicable due to the compliance and very large deformation of the foam specimen. The digital image correlation (DIC) technique has proven successful when applied to soft materials and large deformations. The DIC technique is a full-field surface deformation measurement technique that mathematically compares a subset of a digital image from a reference configuration with a digital image from a deformed configuration [1].

Researchers [24] originally proposed and developed this technique, which has become and accepted method by the experimental mechanics community for measuring the surface displacement with subpixel resolution. First, fray scale random speckle patterns were generated on the specimen surfaces. The digital images were obtained from the specimens before and after the deformation. The images were then used to calculate the displacement and strain distributions of the specimen surface. The DIC technique not only can measure a wide range of strains, from sub-millistrain up to 500% but also is applicable to various sizes of specimens.

In the latest researches [25], the static mechanical properties of PUR foam were investigated via compression and interrupted loading and reloading. In the full-field characterization of mechanical behavior of polyurethane foams study the 3D-DIC system was used. In the tests, deformation associated with compression in the foam rise direction was not uniform within the specimen.

Examining PUR foams via compression in different directions and speeds show that the response is anisotropic, with the foam rise direction being stiffer and stronger. Strain softening occurs in this direction and compression yields localized deformation. Experimental results show that the Young's modulus and yield stress in the transverse direction are about half their values in the rise direction, while the yield strain is slightly larger [25]. The differences in response for the two directions show that the mechanical properties of polyurethane foam are direction dependent and arise from microstructural anisotropy [23].

3 DEVELOPING THE TESTING RIG

Tallinn University of Technology (TTU), Department of Materials and Environmental Technology, Laboratory of Wood Technology uses Hegewald & Peschke universal furniture test rig, which tests chairs, tables, seat back, arm rests and seat furniture and upholstery in accordance to EN 527, EN 1335, EN 1729, DIN 4551, BIMFA X5, and BSI/BS 5659. The load is applied by compressed air and the load is adjustable depending on the test parameters.

The universal testing machine can generate extension/compression rates of up to 20 cm/s and is therefore appropriate for applying quasi-static and low strain rate deformation.
TTU Laboratory of Wood Technology wished a more capable testing rig. This can be achieved by purchasing a new testing rig, or by purchasing additional pistons for the existing testing rig, due to being variably ready to equip with any number of load-controlled pneumatic test axes.

3.1 Requirements for testing rig

Due to large variety of testing samples dimensions, structure, and test types needed to be done, the testing rig is required to have certain features that are stated in table 2.2. Each parameter is evaluated according to the requirements to the needs.

Table 3.1 Requirements for testing rig

Features	**Required**	**Recom-mended**
1. Function		
Capability to test a variety of (upholstered) furniture	**X**	
2. Technical aspects		
Testing rig uses compressed air		**X**
Capability to hold a two-seated sofa	**X**	
Capability to test samples on horizontal plane (furniture back rests)	**X**	
Capability to apply minimum 1000 N force on vertical axis	**X**	
Capability to apply minimum 750 N force on horizontal axis	**X**	
Programmable Logic Controller (PLC) is controlled via touchscreen		**X**
Cylinders capability to work separately		**X**
Cylinders capability to move linearly	**X**	
3. Handling		
Service time – in compliance to regular maintenance 10…15 years	**X**	
4. Expenses		
Total cost under € 10 000		**X**

3.2 Available testing rigs on market

There are several companies that produce and sell testing rigs for furniture and upholstery. During the work, inquiries from 5 companies have been applied for, three of them produce specific testing rigs for a large variety of standardized tests, and two of them develop custom-made equipment.

3.2.1 Hegewald & Peschke

Hegewald & Peschke provides a large variety of upholstery testing machines, such as Alternating bending test rig PLC – and back rest; test rig for car seats; alternating bending test rig PLC – Seats. Hegewald & Peschke develops machinery specially designed for testing soft elastic foams. Hegewald & Peschke Inspekt S 5kN has a working area of 800 mm x 800 mm, which grants the ability to test not only sample pieces but also finished products. The test machines can also be used to carry out low-frequency, cyclical loading, relief and relaxation tests. Inspekt S 5kN with central loading can be used to perform ISO 2439: Flexible cellular polymeric materials – Determination of hardness (indentation technique); ISO 3386: Polymeric materials, cellular flexible – Determination of stress-strain characteristics in compression; DIN 53572: Testing of flexible cellular materials – Determination of compression after constant strain. [26]

Hegewald & Peschke offered a test stand for long-term tests on foamed materials (fig. 2.1). This testing device has been designed for long-term tests on foamed materials according to DIN EN ISO 3385: determination of fatigue due to constant impact loading of polymeric flexible foams. The flexible height-adjustment of the specimen between 20 and 90 mm allows for the test of different kinds of foam specimens. The support platen dimensions are 400 x 400 mm and is perforated with 6 mm holes. Due to its low weight of 35 kg, the test device can be moved with a suitable under construction.

Figure 3.1 Test stand for long-term tests on foamed materials by Hegewald & Peschke

The testing device consists of: load frame, made of light-weight metal profiles, PLC with cycle times and number that can be set arbitrarily and load setting up to 5 kN, pneumatic cylinder 63 x 100 with valve unit, load pad with the diameter of 250 mm and edge radius R=25 mm.
The price offer for this device has been evaluated to €9931.00.

3.2.2 ADMET

Admet has been producing testing machines for over 25 years [27]. Admet has a Dynamic Testing Systems series called eXpert 5900 series which includes 3 models: 5951, 5952, 5955. Specifications for each models are indicated in table 2.2. Admet eXpert 5900 Series Dynamic Testing Systems are suited for performing dynamic and static fatigue tests on a large range of materials and accessories. eXpert 5900 Series Dynamic Testing Systems can be used to perform ASTM D3574: Test methods for flexible cellular materials – constant force pound test. [28]

Table 3.2 Properties of ADMET eXpert 5900 Series Dynamic Testing Systems (Peschke)

Model	Unit	5951	5952	5955
Continuous force	kN	2,5	5	10
Dynamic force (3 sec)	kN	4	8	14
Maximum speed	mm/min	20 320	15 240	15 240
Actuator stroke	Mm	152	152	152
Position resolution	µm	2,54	1,27	1,27
Maximum power	VA	1760	2800	3600
Single phase voltage	Hz	50, 60	50, 60	50, 60

ADMET has offered a 5952F Foam Testing System (fig. 1.2), which has been designed to perform tensile and compression tests at both standard and fatigue rates of speed. This multifunctional system was designed to perform as many foam tests as possible including: ASTM D3574 tensile

strength, elongation, tear, indentation force deflection (IFD), compression force deflection (CFD), hysteresis, constant force pounding (CFP), recovery time tests (up to 600´´ per minute). ADMET 5952F Dynamic load capacity is 4,5 kN, maximum stroke 254 mm with the maximum speed of 15,240 mm/min.
The price offer for this device has been estimated between 40,000 to 50,000 USD, depending on grips, fixtures, services and accessories.

3.2.3 Zwick

Zwick has offered their Dynamic fatigue test bench for soft elastic foams (fig 2.2) consisting of: electromechanical actuator (Fmax ± 1 kN), TestControl controller, TestXpest software and load frame (inner dimensions 875 x 600 x 680 mm). Maximum test speed for this machine is 500 mm/s, maximum standard piston stroke is 180 mm.
The price for this machine is evaluated for €52,644.00, and as it is a product from Zwick project department, the production will take about 5 months.

Figure 3.2 Dynamic fatigue test bench 5 kN

3.2.4 Accessories for testing rigs

Hegewald & Peschke provides a measuring station for determining of geometry and ergonomics of seating furniture before and after a long-term tests according to EN 1335, also EN 1728, EN 1729, EN 581-2-3, EN 13761, DIN 68878 and BIFMA X5.1. It has a pneumatic lifting cylinder unit for simple positioning of the seat loading bad. Optional accessory for this station is a laser extensometer with stand for determining distances and differences on seating furniture.

3.3 Development of the testing rig

During the development phase many options were considered, both for exclusively for soft cell foams, and for furniture pieces. During this time we were able to establish many more specifications for our needs.

After the conclusions, that ready-made machinery may be too expensive, a decision was made to contact SMC Pneumatics Estonia, who are the local experts in pneumatic equipment.

SMC has made us two different personal offers, neither of them is yet what is really needed. The first offer (fig. 2.3) consist of a device designed specifically for cyclic PUR foam tests. It consists of a frame that holds an electric motor, and a platen on which a specimen with specific dimensions will be placed. The motor is capable of pounding the specimen with changeable weights up to a force of 750 N and a frequency of 70 strokes per minute. We discontinued this idea due to requirement for spacious foundation to hold the frame in place with all the vibration generated.

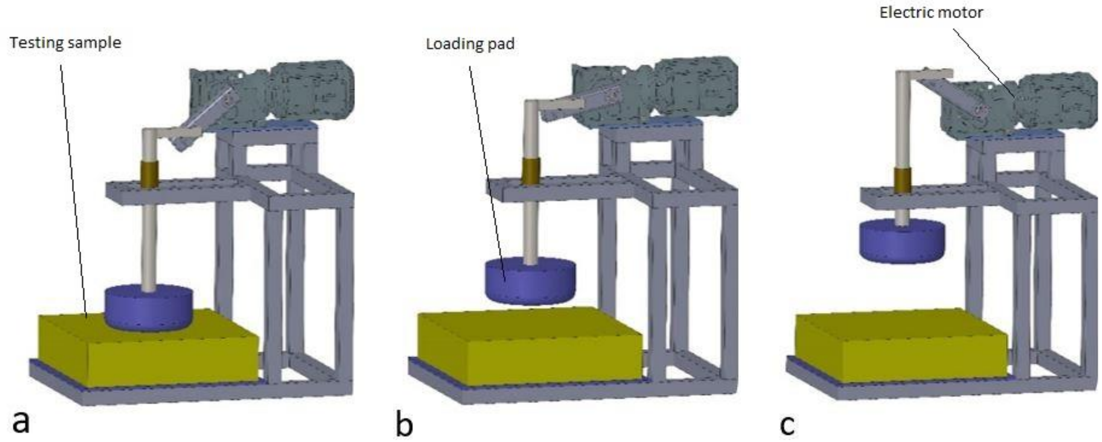


Figure 3.3 Mechanical pounder for PUR foams. a) force is applied, b) force is released, c) next cycle is ready

The second offering (fig. 2.4) was more pleasing for the Laboratory of Wood Technology, as it is made for full furniture pieces. Since this model is made for full-sized furniture pieces, a major disadvantage is the lack of horizontal cylinders needed for testing backrests. Also this version includes only one vertical cylinder, which is powered by electric motor. The presence of base frame is also considered as disadvantage.

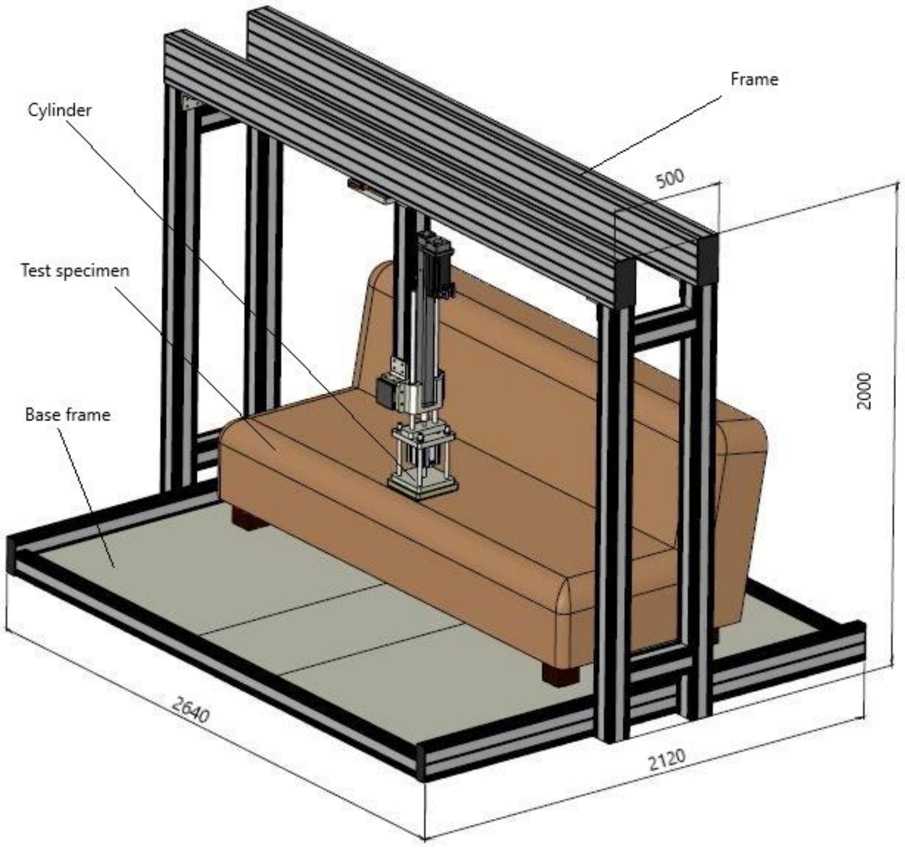


Figure 3.4 Testing system for full-sized furniture pieces

The third offering (fig. 2.5) was more customized version of previous model. This model consists of a frame made out of aluminum profiles and the frame is fixable onto the floor with anchor bolts. The system is controlled by programmable logic controller (PLC), in which the settings can be set via 10” touch-screen monitor. The console of horizontal cylinders is telescopic, which makes it adjustable vertically. It also has ability to change the angle of cylinders. The two main cylinders are mounted on linear guide rails and are adjustable within the whole length of the console. The main cylinders can work individually and at the same time. This testing more universal than the previous ones, as it enables testing two seating pillows at a time, allows testing seating furniture back rests, is wide and tall enough to test large and tall specimen.
In Table 2.3, the price list of each component of said offering is listed.

Table 3.3 Price list for universal testing rig, made by SMC Pneumatics Estonia

Item description	**Price, €**
Aluminum profiles, 100x200, 100x100, 50x100, 80x160, 160x160, 120x120	4960
Aluminum EN AW-7075, EN AW-6082, processing, transportation	850
Accessories for aluminum, bolt, nuts, caps, telescope accessories, R/V fixture plates	980
Linear guide accessories, guide bars, carriage, brakes	1730
Fixtures, bolts, nuts, washers, anchors	190
Adapters for cylinders	300
Air system components, cylinders, valves, pressure controller, gages, throttle, hose-pipes, etc.	4800
Electrical components, touch-screen, PLC, panel, cables, electrical chains, switches, indicators, connectors, etc.	5300
Programming	2000
Engineering design	3500
Manufacturing	12690
Total price (VAT not included)	**37300**

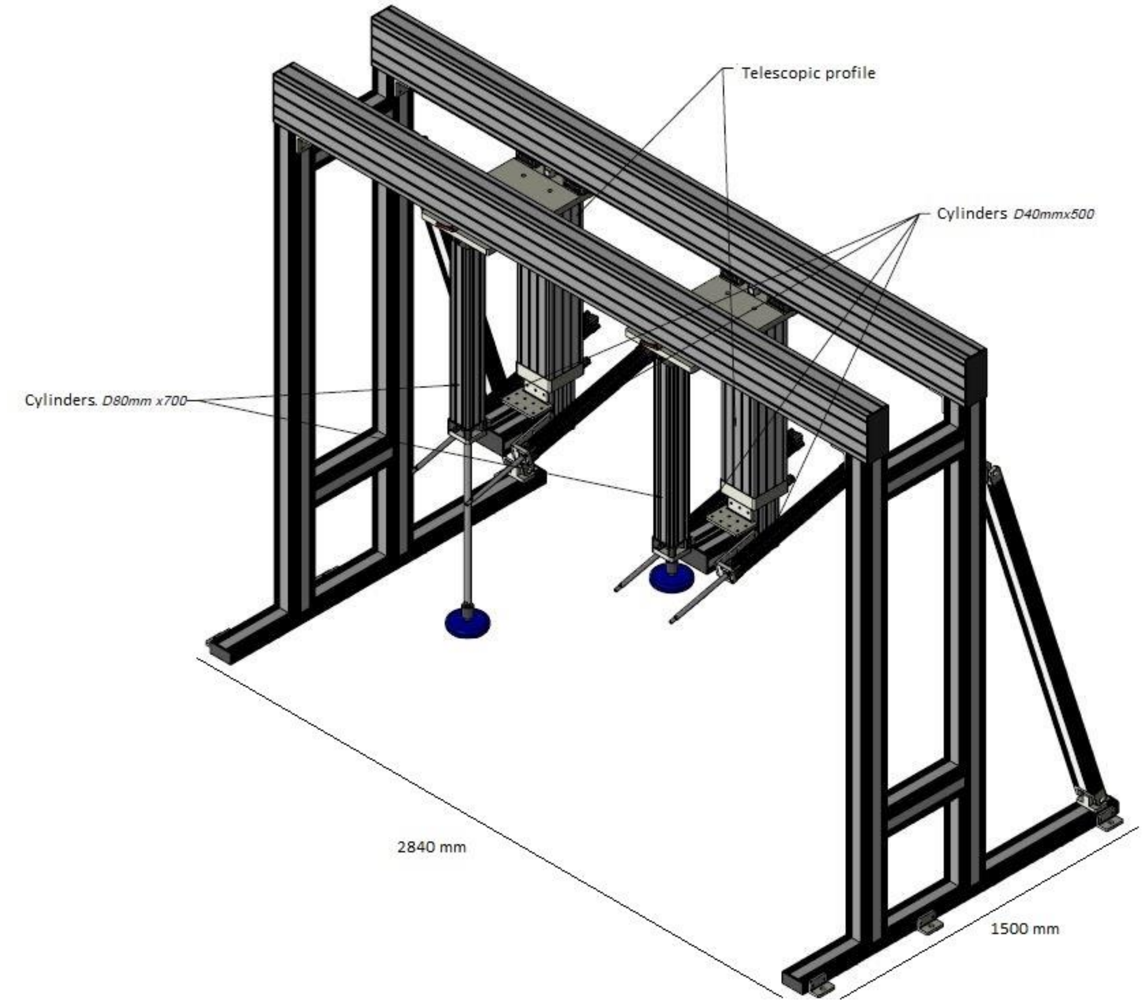


Figure 3.5 Testing system for full-sized furniture pieces

3.3.1 Comparing the models

In the following table (table 2.3) comparison between existing testing rigs and developed models of testing rigs is brought out. All of the ready-made testing rigs had some major disadvantages, mostly limited usage, high cost and long delivery time. SMC developed the best model for our need, but the cost was a critical point, that's why it was decided to develop an improvement to the existing testing rig.

	Properties					
Model	**Application range**	**Force, (N)**	**Force source**	**Frequency, (Hz)**	**Support platen dimensions, (mm)**	**Cost, (€)**
H&P	Foams	5000	Pneumatic	70	400 x 400	9931.00
Admet	Foams, pillows	4500	Pneumatic	N/A	N/A	40 000 – 50 000
Zwick	Foams, pillows	1000	Electro-mechanic	N/A	875 x 600	52 644.00
SMC	Universal	2500 / 700	Pneumatic	Customizable	1840 x 1500	37 300.00

Table 3.4 Evaluation of testing rigs

Evaluated parameter	**Parameter value**	**H&P**	**Admet**	**Zwick**	**SMC**
Universality	3	1	2	2	3
Force source	3	3	3	2	3
Support platen dimensions	3	1	2	2	3
Controlling	3	2	1	2	3
Cost	3	3	1	1	2
Total		**30**	**27**	**27**	**42**

The different solutions were graded according to the 3 point grading scale (table 2.4). After evaluating substantial parameters of offered testing rigs, the most optimal version appeared to be the model made by SMC Pneumatics Group, which matches it as it was custom developed.

3.3.2 Implemented development

An additional and much quicker solution is to purchase a profile to increase the working range of the existing two vertical cylinders. The idea is to purchase an 80x80L profile with the length of 2300 mm, and required components, to increase the working range nearly two times. As of the end of November, profiles 80x80x2300 and 80x80x300, brackets 80x80 were ordered (price list will be seen in table 2.4). This addition can be installed quickly to continue working as soon as possible. Also two wooden bottom shaped loading pads were ordered from Centre of Competence for Wood Processing and Furniture Manufacturing (TSENTER) (figures 3.7 and 3.8).

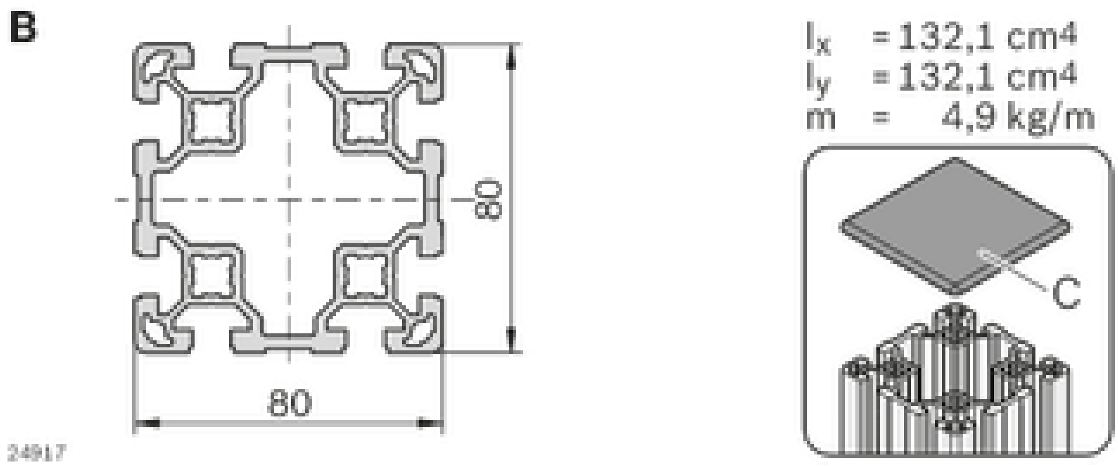


Figure 3.6 Cross-section view of the 80x80 profile [29]

Table 3.5 Price list of profiles purchased from Teamster Drive Systems

Item name	**Unit**	**Quantity**	**Price**	**Total**
Strut profile 80X80L, L=2300 mm	Pc	1	118,14	118,14
Strut profile 80X80L, L=300 mm	Pc	1	19,54	19,54
Gusset 80x80 Set brackets	Pc	2	10,95	21,90
Transport	Pc	1	15,00	15,00
Total				174,58
Total + VAT, €				**209,50**

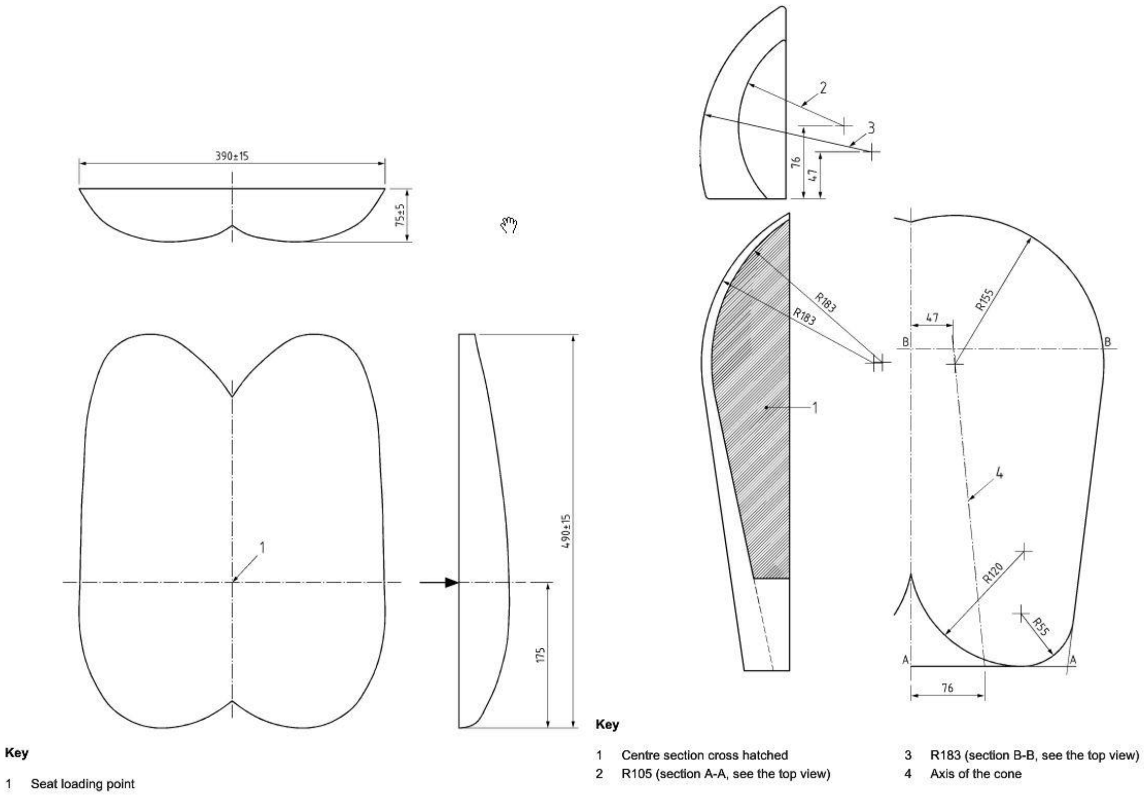


Figure 3.7 Seat loading pad, overall dimensions and seat loading pad geometry [30]

Figure 3.8 Wooden bottom shaped loading pad

Figure 3.9 Attached profile to existing testing rig (marked with red)

3.4 Workshop placement

Because of the size of the testing rig (size of the testing system by SMC is 2500 x 2120 mm), there will be the need for placement plan of the furniture testing lab. In the figure (Appendix 1) stationary machinery is depicted with required work zones. We can see that there's enough room for the testing rig.

4 MATERIALS AND METHODS

Tests are carried out by using ten sets of foams provided by Vita Baltic. All tests are carried out in Tallinn University of Technology, Department of Materials and Environmental Technology, Laboratory of Wood Technology, using a universal furniture test stand (fig. 3.2). The foams are placed on a sofa provided by Neiser Grupp AS.

4.1 Testing samples

In this thesis, durability of different types of polyurethane seating foams are tested. All foams are provided by company Vita Baltic International. Vita Baltic International produces foam blanks of a wide range of applications for various industries. According to UAB "Vita Baltic International", if properly selected and used, standard polyurethane foam will maintain its main characteristics and comfort level for up to 2 years, High elasticity polyurethane foams for up to 4 years.

All PUR foams used in tests are listed in table 3.1 to 3.3. There are 11 pairs of samples, making a total of 22 samples, consisting standard foams (VB) and high resilience foams (HR).

Hardness shows how much force is needed to compress a material up to required thickness. One of the method to measure hardness of a foam is by using Indentation Load Deflection, ILD-hardness, which measures the pressure that is required to load the mattress core till 40% compared to its original thickness. The other method is by using CLD-hardness (compression Load Deflection), which is the counter pressure in Pascal when 40% of the foam is pressed in. Compression set of a material is the permanent deformation remaining when a force that was applied to it is removed. [31]

Table 4.1 VB foam characteristics

Foam type	Relative density (net), kg/m³	Hardness (ILD 40%), N	Hardness (CLD 40%), kPa	Compression set (50%, 22 h, 70 ºC), %, max	Uses
VB3830	36-39	96 - 144	2,7 – 3,4	4	Armrest, backrest, seat, mattresses, pillows
VB3040	26,6-30,8	127,5 - 177	3,2 – 4,4	5	Armrest, noise insulation
VB2540	23,75-27,5	127,5-177	3,2-4,4	5	Seat,
VB3020	28-31	60-90	1,5-2,3	8	Seat, armrest
VB2532	23-26	104-156	2,6-3,8	5	Seat, backrest

Table 4.2 HR foam characteristics

Foam type	Relative density (net), kg/m³	Hardness (ILD 40%), N	Hardness (CLD 40%), kPa	Compression set (50%, 22 h, 70 ºC), %, max	Uses
HR3737	35-38	125 - 155	3,0 – 3,8	6	Seat, back
HR3532	33,25-38,5	98,4-139	2,7-3,4	5,5	Seat, backrest

Combined PUR foams used in this thesis contains a 30 mm thick upper layer and approximately 130 mm thick bottom layer. The purpose of such combination is that the top layer is meant to soften, while the bottom layer is supposed to be more resilient to compression.

Table 4.3 Combined foam characteristics

Foam type	Relative density (net), kg/m³	Hardness (ILD 40%), N	Hardness (CLD 40%), kPa	Compression set (50%, 22 h, 70 ºC), %, max	Uses
VB3423 / VB3030	32-35 / 28-31	85-115 / 110-140	2-2,8 / 2,7-3,4	5 / 5	Seats
HR3010 / HR3532	28,5-33 / 33,25-38,5	30-60 / 98,4-139	0,9-1,6 / 2,7-3,4	6 / 5,5	Seats
VB3423 / HR3532	32-35 / 33,25-38,5	85-115 / 98,4-139	2-2,8 / 2,7-3,4	5 / 5	Seats
HR3020 / VB3040	28-31 / 26,6-30,8	60-90 / 127,5 - 177	1,5-2,3 / 3,2 – 4,4	8 / 5	Seats

4.2 Testing methods

All tests are carried out in Tallinn University of Technology, Department of Materials and Environmental Technology, Laboratory of Wood Technology, using Hegewald & Peschke universal furniture test stand (fig. 3.2). The foams are placed on a sofa "Pittsburg", provided by Neiser Grupp AS.

Figure 4.1 Mechanical Hegewald & Peschke furniture test stand

Testing were done according to the standard EVS-EN 16139:2013 test method 6.8, which refers to standard EVS-EN 1728:2012. There are two test samples of each patch of foams, totaling of 20 test samples. The tests were carried out according to the "L1" type of use, which states that the specimen are used in areas in which seating is intended for mixed use. The testing required 100 000 cycles, which is approximately 4 days, 15 hours, 6 minutes, 40 seconds. Temperature and relative humidity of the workroom and the room containing were kept at constant values.

Table 4.4 Foam cyclic loading testing plan

Testing name	**Loading (N)**	**One loading cycle (s)**	**Recovery time (s)**	**Time of one cycle (s)**	**Number of cycles**
Loading to the seating foam	1000	2	2	4	100 000

Table 4.5 Time plan to cyclic loading

Testing name	100 000 cycles time in seconds	100 000 cycles time in hours	100 000 cycles time in days
Cyclic loading to the seating foam	400 000	111,1	4,5

Table 4.6 Foams deformation measuring times after the end of last cycle (minutes)

0	30	60	360	1440	10080

4.2.1 Description of dynamic testing

All samples must be conditioned in room temperature and relative humidity. During these tests, foam samples are unpacked and held in said conditions for a week.
Before testing, the distance between the laser distance measurer holder and the floor was measured. The distance between the holder and the floor is controlled before each test to ensure constant settings.

Centre point will be measured and marked on each foam sample. As 5 points are needed, other 4 are placed 5 cm away from the center point, in four directions (fig. 4.5). These points will show the pillow thickness parameters to show the deformation.

Distance from the laser holder to each of those 5 points will be measured. That distance is subtracted from the distance from the laser holder to the floor.
After the measuring, the foam sample will be placed on the sofa and the testing rig will be switched on.

After 100 000 cycles the first measurement will be done immediately, continued with specified time periods stated in table 4.5.

Leica Disto D2 (fig. 3.3) is an indoor laser distance measurer with Bluetooth technology and a range up to 100 m. This laser distance meter has a memory of 10 last measurements taken, with accuracy ± 1.5 mm. [32]

Figure 4.2 Leica Disto D2 laser distance measurer (Geosystems)

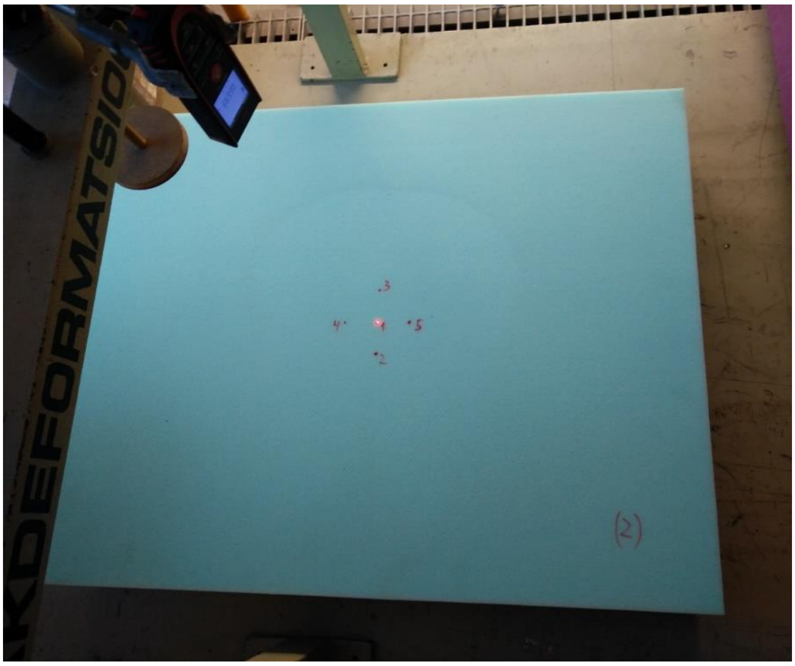


Figure 4.3 Placement of points on foam

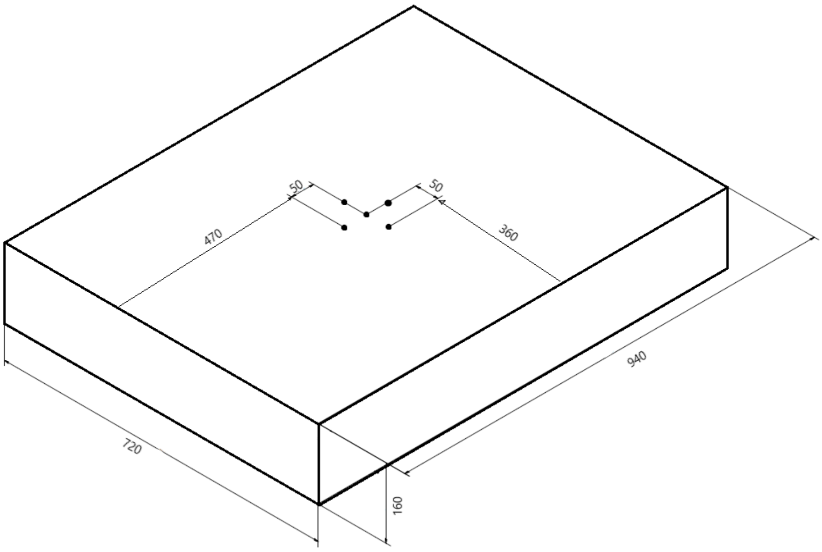


Figure 4.4 Single layered foam with measuring points

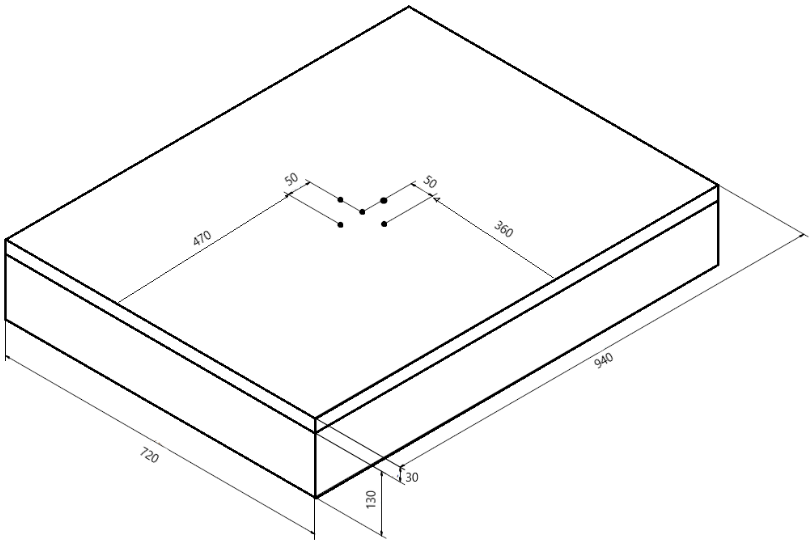


Figure 4.5 Two-layered foam with measuring points

4.2.2 Description of static testing

An experimental static load test was carried out. The test consists of loading 5 pairs of samples with static load for 24 hours, then let to rest for 24 hours, after which comes 7 days static load. One sample of each pair was held in indoor conditions for 5 weeks, while the other sample of each pair was exposed to outdoor conditions for 5 weeks during winter time.

The load applied onto the center of the foam was 80 kg. Measuring were done immediately after removing the load, then after 30 minutes and after 24 hours.

5 RESULTS AND DISCUSSION

Laser distance measurer Leica Disto D2 measure accuracy may affect test result accuracy. Laser accuracy at maximum range is ± 1,5 mm. Distances were measured with 0,1 mm precision. Laser position could have influenced measuring, as the device can slightly move while pressing the button. Also depending on the cell size of the foam, the laser could have been on the edge or on the bottom of the open cell of the foam.

Average temperature during the testing time was 22 °C and the average relative humidity was 30%. Temperature and relative humidity can affect deformation recovery rate and final recovery.

In chapters 4.1 to 4.4 will be the analysis of dynamic load test results.

5.1 VB foams

There was a total of 5 pairs of standard (VB) foams. The dynamic test results show no correlation between a foam having a higher hardness value and lower final deformation (VB3040 and VB 3020, or VB2540 and VB2532). However having higher density does have an effect on final deformation being lower (VB3040 and VB2540).

5.1.1 VB3830 foam

The final average deformation of sample #1 is 0,028% of the initial thickness, average final deformation of sample #2 is 0,072% of the initial thickness. Second samples average final deformation is 150% (0,96 mm) greater than of the first samples thickness.

Table 5.1 VB3830 foam samples deformation recovery in time

Sample #1							
Time, (minutes)	Thickness at measuring points (mm)					Average thickness, (mm)	Average deformation, (mm)
	1	2	3	4	5		
Initial	138,5	139,5	138,5	138,5	139,5	138,9	0
0	137,6	137,4	137,6	137,4	137,4	137,48	1,42
30	138,3	137,8	138,4	138	137,8	138,06	0,84
60	138,5	138,1	138,2	138,6	138,2	138,32	0,58
360	138,7	137,9	138,3	138,6	138,4	138,38	0,52
1440	138,7	138,6	138,7	138,8	138,5	138,66	0,24
10080	138,9	138,5	139	139,1	138,8	138,86	0,04
Sample #2							
Time, (minutes)	Thickness at measuring points (mm)					Average thickness, (mm)	Average deformation, (mm)
	1	2	3	4	5		
Initial	138,6	139,1	138,7	139,2	138,7	138,86	0
0	137,7	138,1	137	137,3	137,1	137,44	1,42
30	138,1	138,1	137,2	137,6	138,6	137,92	0,98
60	138,2	138,3	137,9	138,3	138,8	138,3	0,6
360	138,4	138,4	137,8	138,2	139	138,36	0,54
1440	138,6	138,4	138,1	138,5	138,5	138,42	0,48
10080	138,6	138,5	139	139,1	138,8	138,8	0,1
Average final deformation							**0,055**

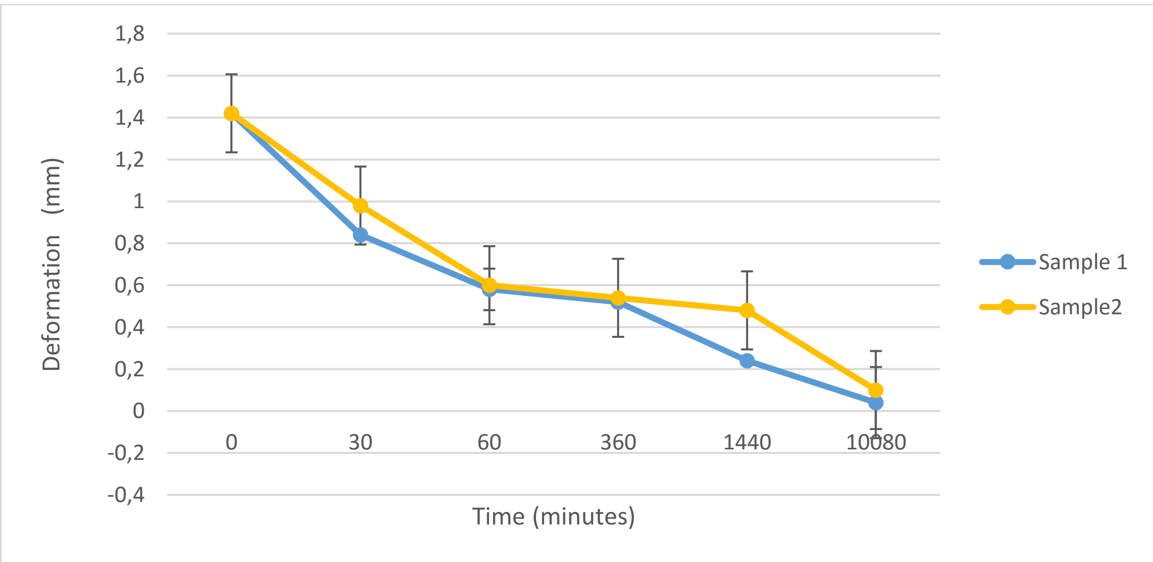


Figure 5.1 VB3830 foam samples deformation recovery in time

5.1.2 VB3040 foam

The final average deformation of sample #1 is 0,38% of the initial thickness, average final deformation of sample #2 is 0,29% of the initial thickness. Second samples average final deformation is 90.38% (0,5 mm) smaller than of the first samples thickness.

VB3040 foam samples had 160% higher final average deformation than VB 3020, although having two times higher foam hardness, 127,5-177 N and 60-90 N respectively.

Table 5.2 VB3040 foam samples deformation recovery in time

Sample #1							
Time, (minutes)	**Thickness at measuring points (mm)**					**Average thickness, (mm)**	**Average deformation, (mm)**
	1	**2**	**3**	**4**	**5**		
Initial	136,8	136,8	137,1	136,8	136,8	136,86	0
0	134,8	135,4	134,8	134,8	135,2	135	1,86
30	135,5	135,8	135,4	135,4	135,7	135,56	1,3
60	135,9	136	135,5	135,7	135,6	135,74	1,12
360	136,1	136	135,8	135,7	135,8	135,88	0,98
1440	136,1	136,1	136,1	136,1	136,1	136,1	0,76
10080	136,5	136,5	136,1	136,1	136,5	136,34	0,52
Sample #2							
Time, (minutes)	**Thickness at measuring points (mm)**					**Average thickness, (mm)**	**Average deformation, (mm)**
	1	**2**	**3**	**4**	**5**		
Initial	136	136,4	136,2	136,2	136,2	136,2	0
0	134,9	135,6	135,1	134,8	135,1	135,1	1,1
30	135,7	135,9	135,6	135,1	135,7	135,6	0,6
60	135,9	136,1	135,3	135,4	135,9	135,72	0,48
360	136,3	136	135,7	135,5	136,3	135,96	0,24
1440	136	136,5	135,9	135,7	136	136,02	0,18
10080	135,9	136,3	136,2	136,3	136,2	136,18	0,02
Average final deformation							**0,395**

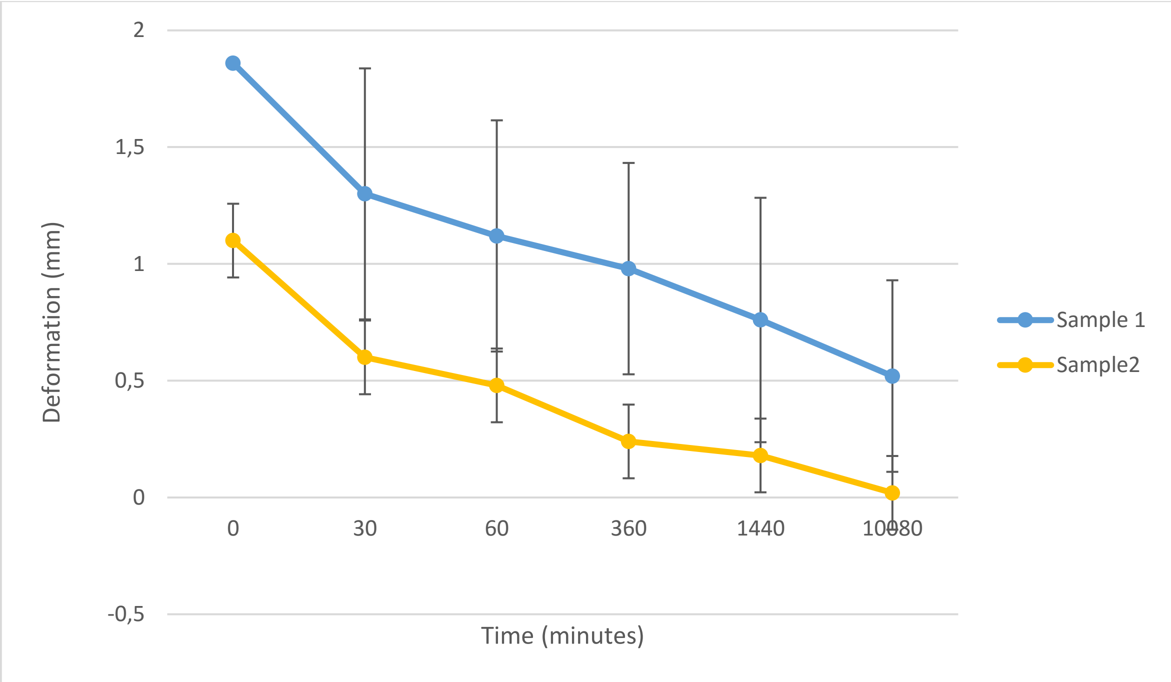


Figure 5.2 VB3040 foam samples deformation recovery in time

5.1.3 VB2540 foam

The final average deformation of sample #1 is 0,80% of the initial thickness, average final deformation of sample #2 is 1.15% of the initial thickness. Second samples average final deformation is 44% (0,44 mm) greater than of the first samples thickness.

VB2540 foam has 127,5-177 N hardness compared to 104-156 N of VB2532, but has 178,8% higher deformation than VB2532. VB2540 has 127,6% higher final deformation than VB3040, having densities of 23,75-27,5 kg/m^3 and 26,6-30,8 kg/m^3respectively.

Table 5.3 VB2540 foam samples deformation recovery in time

Sample #1							
Time, (minutes)	**Thickness at measuring points (mm)**					**Average thickness, (mm)**	**Average deformation, (mm)**
	1	**2**	**3**	**4**	**5**		
Initial	124,4	124,2	124,7	124,9	124,8	124,6	0
0	119,4	120	119,7	120,5	119,1	119,74	4,86
30	121,7	122	121,5	122,5	121,1	121,76	2,84
60	122,2	122,3	121,9	122,9	121,5	122,16	2,44
360	122,6	122,6	122,4	123	122,5	122,62	1,98
1440	122,7	123,1	123,5	123,7	123,1	123,22	1,38
10080	123,3	123,7	123,6	123,9	123,5	123,6	1
Sample #2							
Time, (minutes)	**Thickness at measuring points (mm)**					**Average thickness, (mm)**	**Average deformation, (mm)**
	1	**2**	**3**	**4**	**5**		
Initial	126,1	125,5	126,1	126,1	125,6	125,88	0
0	121	121,1	119,3	120,9	120,3	120,52	5,36
30	123	123,2	122	122,9	121,7	122,56	3,32
60	122,8	123	122,8	123,1	122,6	122,86	3,02
360	123,7	124,3	123,8	124,4	123,5	123,94	1,94
1440	124,2	124,4	124,1	124,7	123,8	124,24	1,64
10080	124,9	124,4	124	124,6	124,3	124,44	1,44
Average final deformation							**1,11**

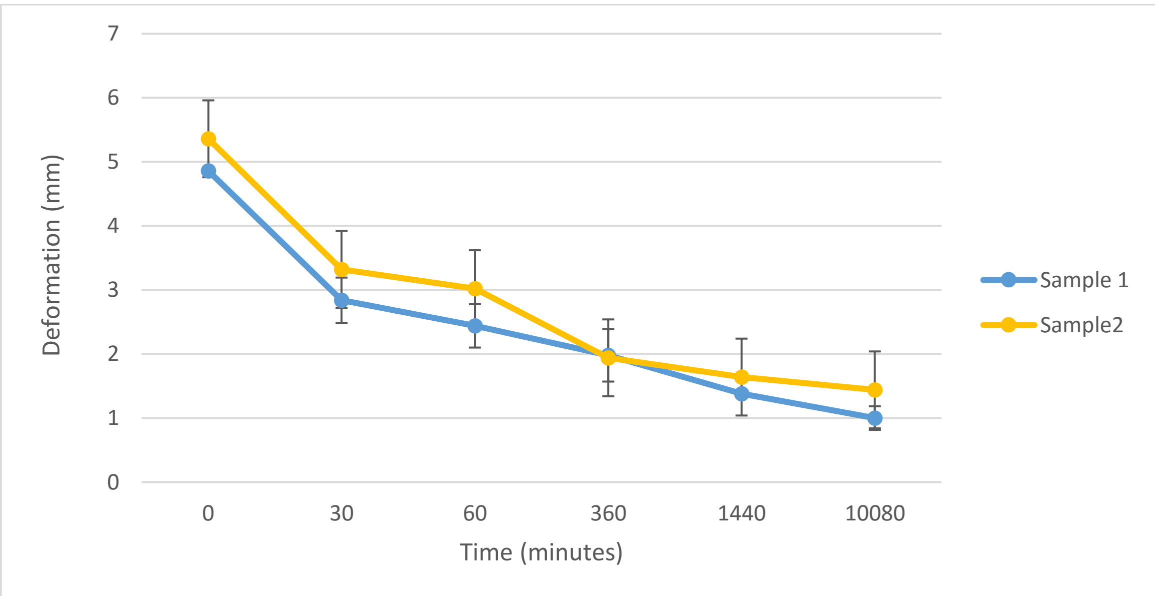


Figure 5.3 VB2540 foam samples deformation recovery in time

5.1.4 VB3020 foam

The final average deformation of sample #1 is 0,35% of the initial thickness, average final deformation of sample #2 is 0.35% of the initial thickness. Second samples average final deformation is 65,12% (0,56 mm) smaller than of the first samples thickness.

VB3020 foam samples had 160% lower final average deformation than VB3040, although having half the foam hardness, 127,5-177 N and 60-90 N respectively.

Table 5.4 VB3020 foam samples deformation recovery in time

Sample #1							
Time, (minutes)	**Thickness at measuring points (mm)**					**Average thickness, (mm)**	**Average deformation, (mm)**
	1	**2**	**3**	**4**	**5**		
Initial	130,8	131	131	130,8	130,6	130,84	0
0	129,1	128,9	128,7	129,1	128,1	128,78	2,06
30	129,6	129,5	129,3	129,7	129,1	129,44	1,4
60	129,8	129,6	129,2	129,7	128,8	129,42	1,42
360	130,1	130,1	129,6	130,3	129,8	129,98	0,86
1440	129,8	130,3	129,7	130,1	129,5	129,88	0,96
10080	130,5	130,7	130,2	130,3	130,2	130,38	0,46
Sample #2							
Time, (minutes)	**Thickness at measuring points (mm)**					**Average thickness, (mm)**	**Average deformation, (mm)**
	1	**2**	**3**	**4**	**5**		
Initial	131	131,3	131,1	131,4	131,4	131,24	0
0	130,1	130,8	129,7	130,2	130,4	130,24	1
30	130,6	131,1	130,1	130,7	131,1	130,72	0,52
60	131	131,5	130,2	131,1	131,5	131,06	0,18
360	130,9	131,3	130,8	131,5	131,5	131,2	0,04
1440	131,2	132	131	132	131,5	131,54	-0,3
10080	132,5	131,8	131,1	131,6	131,5	131,7	-0,46
Average final deformation							0

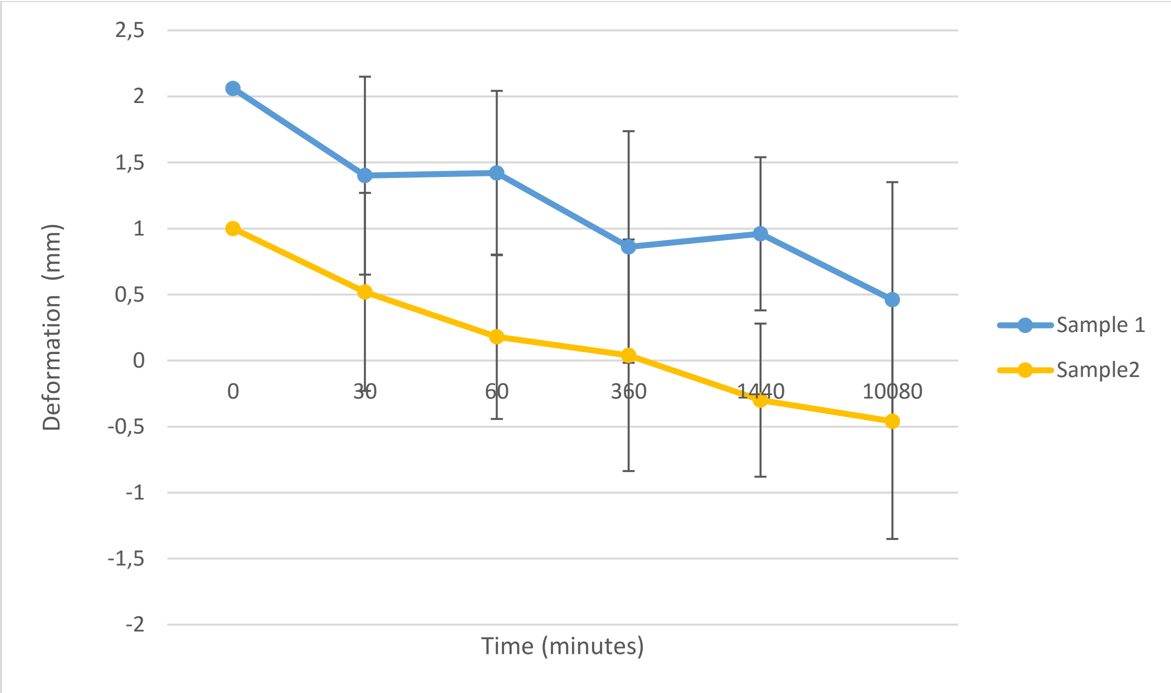


Figure 5.4 VB3020 foam samples deformation recovery in time

5.1.5 VB2532 foam

The final average deformation of sample #1 is 0,70% of the initial thickness, average final deformation of sample #2 is 1,16% of the initial thickness. Second samples average final deformation is 65,12% (0,56 mm) smaller than of the first samples thickness.

VB2532 foam has hardness value of 104-156 N, while VB2540 foam has 127,5-177 N, having lower hardness, but also 178,8% lower deformation than VB2540.

Table 5.5 VB2532 foam samples deformation recovery in time

Sample #1							
Time, (minutes)	**Thickness at measuring points (mm)**					**Average thickness, (mm)**	**Average defor-mation, (mm)**
	1	**2**	**3**	**4**	**5**		
Initial	123	123,6	123,3	123,2	123,5	123,32	0
0	121,3	122,2	120,3	121,4	121,1	121,26	2,06
30	122,8	123,4	121,6	123,2	122,4	122,68	0,64
60	122,7	123,5	122,4	123,1	123,1	122,96	0,36
360	123,3	123,7	123	123,5	122,9	123,28	0,04
1440	124,8	124,5	124,1	124,5	124,4	124,46	-1,14
10080	124,5	124,5	123,5	124	124,4	124,18	-0,86
Sample #2							
Time, (minutes)	**Thickness at measuring points (mm)**					**Average thickness, (mm)**	**Average defor-mation, (mm)**
	1	**2**	**3**	**4**	**5**		
Initial	122,5	123,2	123	122,5	123,1	122,86	0
0	121,4	122,6	120,2	121,3	120,8	121,26	1,6
30	122,9	122,9	121,4	122,4	121,8	122,28	0,58
60	122,3	123	122,1	121,5	122,5	122,28	0,58
360	123,1	123,1	122,5	123,7	123,3	123,14	-0,28
1440	124,4	124,4	123,9	123,5	124,1	124,06	-1,2
10080	124,2	125,6	123,5	123,7	124,4	124,28	-1,42
Average final deformation							**-1**

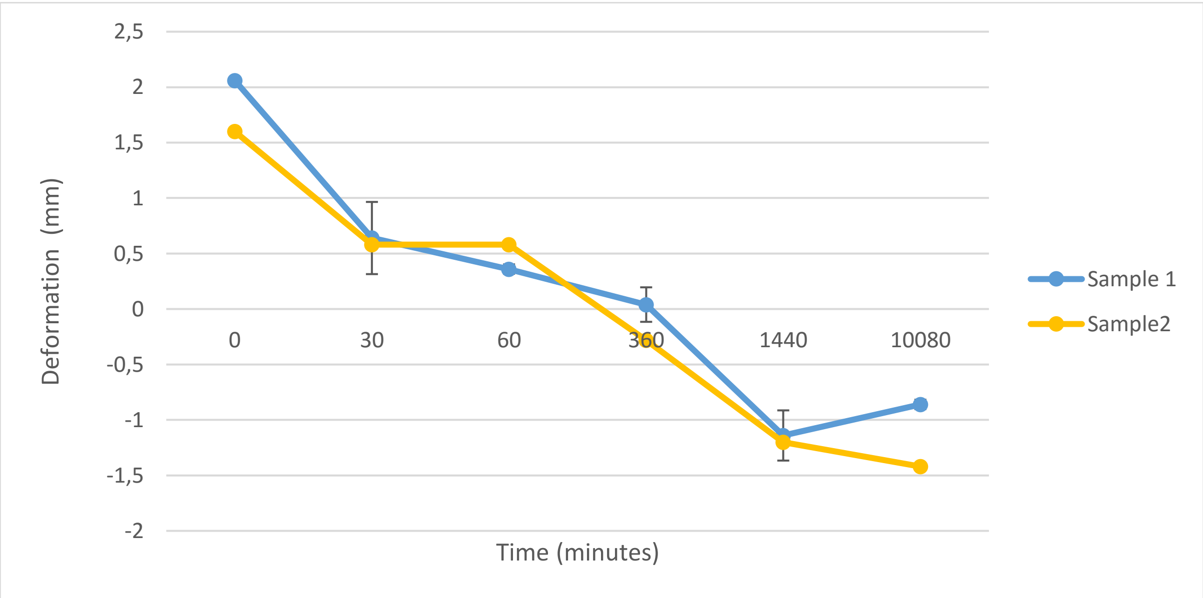


Figure 5.5 VB2532 foam samples deformation recovery in time

5.2 HR foams

As there was only two different high resilience foam sample models, a sufficient comparison can't be made. This data will be, however, useful for future comparison of high resilience foams.

5.2.1 HR3532 foam

The final average deformation of sample #1 is 0,29 of the initial thickness, average final deformation of sample #2 is 0,38% of the initial thickness. Second samples average final deformation is 27% (0,1 mm) greater than of the first samples thickness.

Table 5.6 HR3532 foam samples deformation recovery in time

Sample #1							
Time, (minutes)	**Thickness at measuring points (mm)**					**Average thickness, (mm)**	**Average deformation, (mm)**
	1	**2**	**3**	**4**	**5**		
Initial	122,1	122,4	122,5	123,1	121,6	122,34	0
0	116,3	117,9	116,4	116,6	116,3	116,7	5,64
30	120,8	120,2	118,7	119,6	118	119,46	2,88
60	118,8	120,5	119,3	119,8	118,7	119,42	2,92
360	120,4	120,7	120,4	120,9	120,3	120,54	1,8
1440	121	122	121,3	121,6	120,7	121,32	1,02
10080	122	122,2	122,1	122,2	121,4	121,98	0,36
Sample #2							
Time, (minutes)	**Thickness at measuring points (mm)**					**Average thickness, (mm)**	**Average deformation, (mm)**
	1	**2**	**3**	**4**	**5**		
Initial	122,4	122,4	122,6	122,8	122,9	122,62	0
0	117,2	117	116,7	117,3	117,7	117,18	5,44
30	118,3	118	119,1	118,6	118,6	118,52	4,1
60	117,8	120,2	118,1	118,5	118,3	118,58	4,04
360	120,5	120,7	119,9	120,1	120	120,24	2,38
1440	120,5	121,1	120,8	120,9	120,9	120,84	1,78
10080	122,2	122	121,7	122,5	122,4	122,16	0,46
Average final deformation							**0,385**

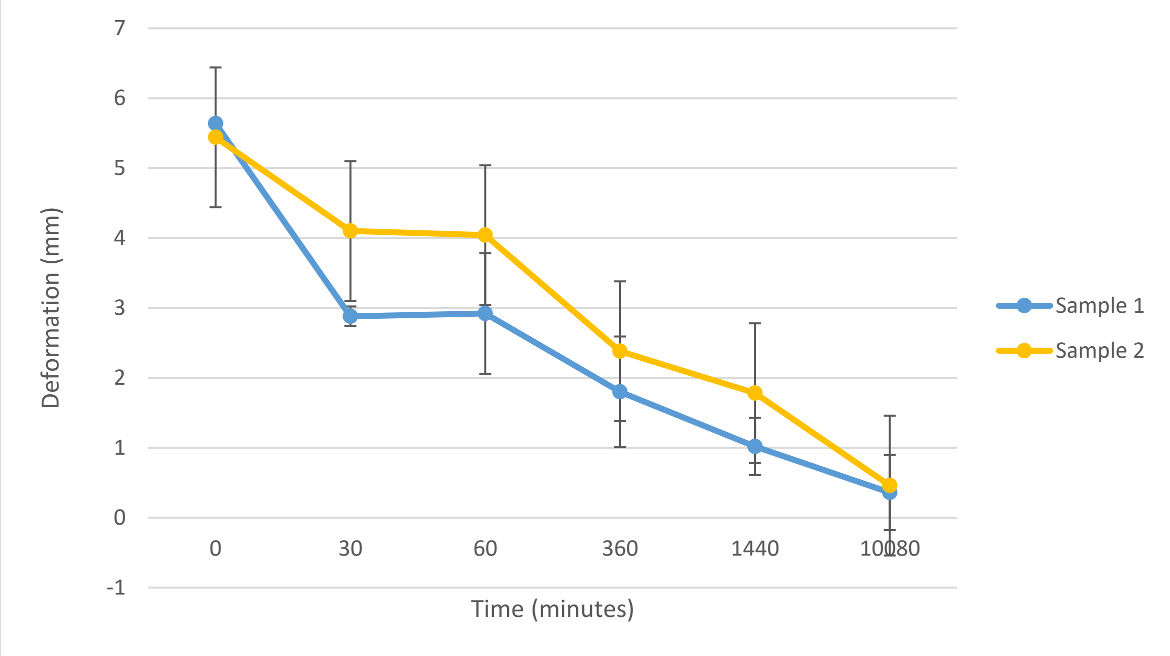


Figure 5.6 HR3532 foam samples deformation recovery in time

5.2.2 HR3737 foam

The final average deformation of sample #1 is 0,31% of the initial thickness, average final deformation of sample #2 is 0,46% of the initial thickness. Second samples average final deformation is 50% (0,2 mm) greater than of the first samples thickness. The 2 mm difference between samples of the same type of foams may come from unpacking and settling time.

Table 5.7 HR3737 foam samples deformation recovery in time

Sample #1							
Time, (minutes)	**Thickness at measuring points (mm)**					**Average thickness, (mm)**	**Average deformation, (mm)**
	1	**2**	**3**	**4**	**5**		
Initial	127,5	128,5	128,5	129,5	128,5	128,5	0
0	124,5	125,5	124,5	125,5	124,5	124,9	3,6
30	125,5	127,5	125,5	126,5	126,5	126,3	2,2
60	125,5	126,5	126,5	126,5	126,5	126,3	2,2
360	126	127	126,5	127,5	127	126,8	1,7
1440	126,5	127,5	126,5	128,5	127,5	127,3	1,2
10080	127,5	128,5	127,5	128,5	128,5	128,1	0,4
Sample #2							
Time, (minutes)	**Thickness at measuring points (mm)**					**Average thickness, (mm)**	**Average deformation, (mm)**
	1	**2**	**3**	**4**	**5**		
Initial	130,5	130,5	130,5	130,5	130,5	130,5	0
0	126,5	127,5	126,5	126,5	126,5	126,7	3,8
30	128,5	127,5	127,5	127,5	127,5	127,7	2,8
60	129,5	128,5	128,5	128,5	128,5	128,7	1,8
360	130,5	128,5	128,5	129,5	129,5	129,3	1,2
1440	131,5	128,5	129,5	129,5	129,5	129,7	0,8
10080	129,9	130,5	129,6	129,5	130	129,9	0,6
Average final deformation							**0,5**

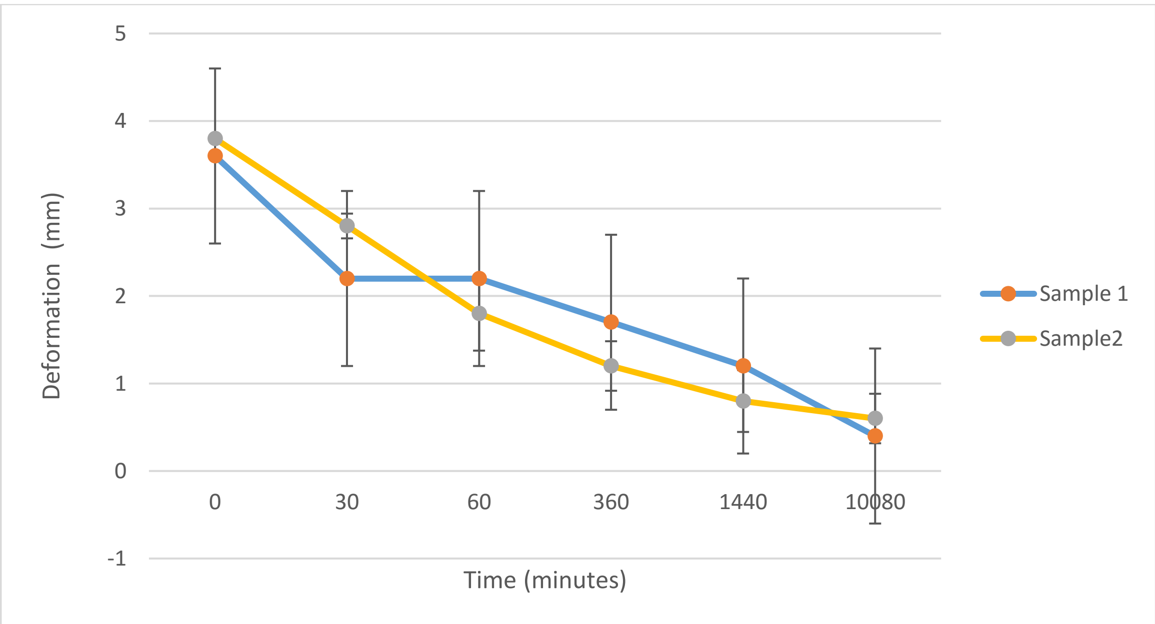


Figure 5.7 HR3737 foam samples deformation recovery in time

5.3 Combined foams

Due to the specimens having two layers, a comparison between individual foam types cannot be given. This data however will be useful when comparing single layered foams to combined foams in the next section.

5.3.1 VB3423 / VB3030 foam

The final average deformation of sample #1 is 0.11% of the initial thickness, average final deformation of sample #2 is 1,08% of the initial thickness. Second samples average final deformation is 914,29% (1.28 mm) smaller than of the first samples thickness.

Table 5.8 VB3423 / VB3030 foam samples deformation recovery in time

Sample #1							
Time, (minutes)	**Thickness at measuring points (mm)**					**Average thickness, (mm)**	**Average deformation, (mm)**
	1	**2**	**3**	**4**	**5**		
Initial	129,5	129,6	129,4	129,7	129,7	129,58	0
0	128,1	128,8	128,1	128,7	128,1	128,36	1,22
30	129,1	128,6	128,6	129,5	129,5	129,06	0,52
60	128,8	129,3	128,8	129,4	129,8	129,22	0,36
360	128,9	128,7	129	129,5	129,6	129,14	0,44
1440	128,5	129,7	129,4	129,3	129,6	129,3	0,28
10080	129,4	129,1	129,5	130,2	130,4	129,72	-0,14
Sample #2							
Time, (minutes)	**Thickness at measuring points (mm)**					**Average thickness, (mm)**	**Average deformation, (mm)**
	1	**2**	**3**	**4**	**5**		
Initial	131	131,2	131,4	131,3	131,4	131,26	0
0	130,1	129,7	129	129,5	129,2	129,5	1,6
30	130,1	130,3	129,6	130,1	129,6	129,94	0,58
60	130,8	130,6	129,9	130,4	129,8	130,3	0,58
360	130,9	130,2	130,1	130,2	129,8	130,24	-0,28
1440	131	130,9	129,5	130,8	130,7	130,58	-1,2
10080	131,4	131,1	130,7	131,3	131,1	131,12	-1,42
Average final deformation							**-0,07**

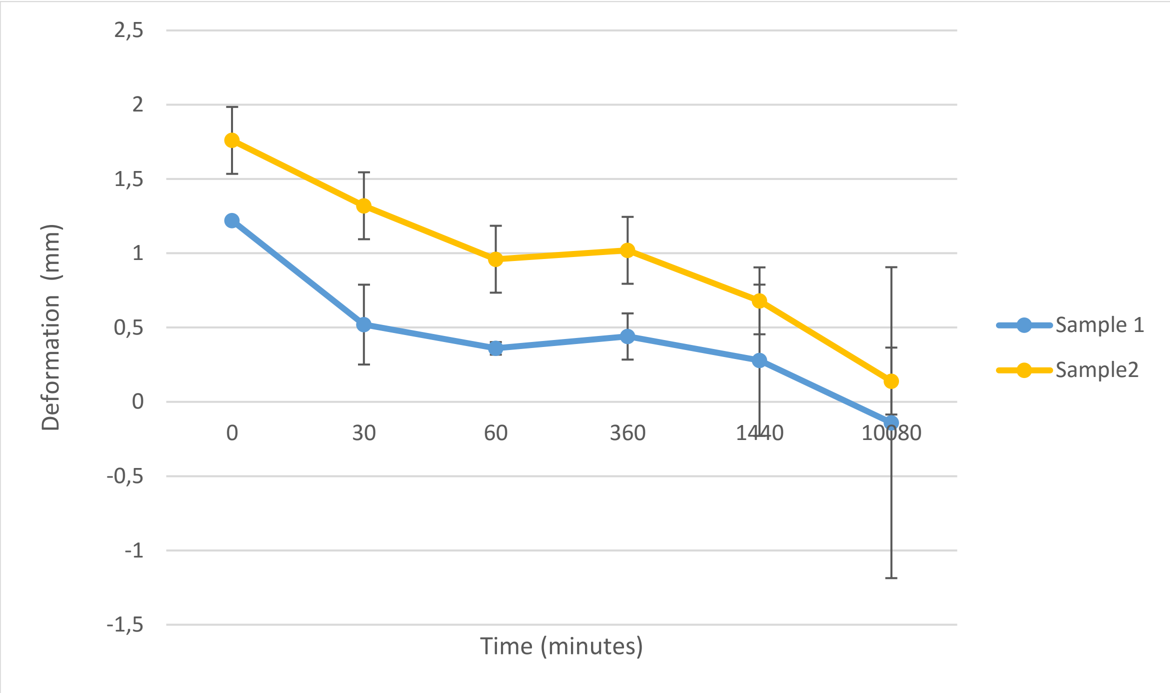


Figure 5.8 VB3423 / VB3030 foam samples deformation recovery in time

5.3.2 HR3010 / HR3532 foam

HR3010 combined with HR3532 foam samples had the highest initial deformation (5,85 mm) and the highest final average deformation (1,42 mm).

The final average deformation of sample #1 is 1,31% of the initial thickness, average final deformation of sample #2 is 0,75% of the initial thickness. Second samples average final deformation is 42,86% (0,72 mm) smaller than of the first samples thickness.

Table 5.9 HR3010 / HR3532 foam samples deformation recovery in time

Sample #1							
Time, (minutes)	Thickness at measuring points (mm)					Average thickness, (mm)	Average deformation, (mm)
	1	2	3	4	5		
Initial	129,1	128,7	127,8	127,2	126,7	127,9	0
0	120,3	123	120,7	120,9	121,1	121,2	6,7
30	124,3	124,1	123,5	122,8	122,9	123,52	4,38
60	123,2	125,5	124,3	122,9	124,8	124,14	3,76
360	124,3	123,6	124,6	124,5	125,3	124,46	3,44
1440	126,5	127	125,5	125,2	124,9	125,82	2,08
10080	126,6	128	125,7	125,3	125,5	126,22	1,68
Sample #2							
Time, (minutes)	Thickness at measuring points (mm)					Average thickness, (mm)	Average deformation, (mm)
	1	2	3	4	5		
Initial	127,5	128,6	128,1	127,7	128,7	128,12	0
0	123,6	123,7	121,6	123	123,7	123,12	5
30	124,8	125,5	125,4	124,5	125,1	125,06	3,06
60	123,5	126,2	124,7	124,5	124,3	124,64	3,48
360	124,9	126,5	124,6	125,5	126,8	125,66	2,46
1440	125,8	126,5	125,1	126,3	126,3	126	2,12
10080	125,9	127,4	127,3	127,5	127,7	127,16	0,96
Average final deformation							**1,5**

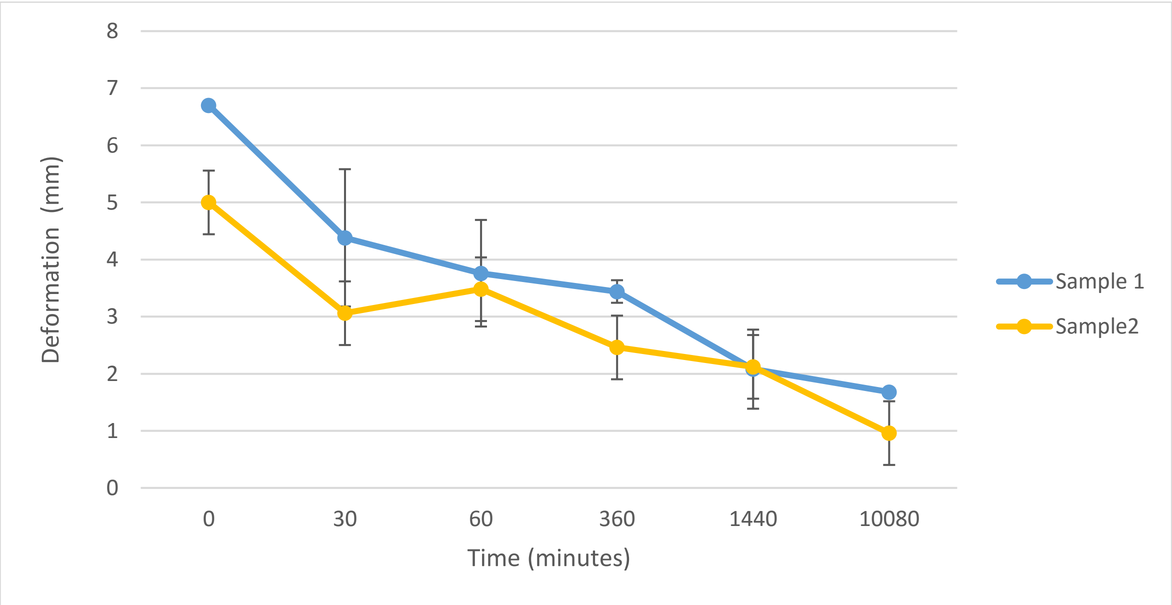


Figure 5.9 HR3010 / HR3532 foam samples deformation recovery in time

5.3.3 VB3423 / HR3532 foam

The final average deformation of sample #1 is 0,36% of the initial thickness, average final deformation of sample #2 is 0,6% of the initial thickness. Second samples average final deformation is 65,22% (0,3 mm) smaller than of the first samples thickness.

Table 5.10 VB3423 / HR3532 foam samples deformation recovery in time

Sample #1							
Time, (minutes)	**Thickness at measuring points (mm)**					**Average thickness, (mm)**	**Average deformation, (mm)**
	1	**2**	**3**	**4**	**5**		
Initial	127	127,8	127,6	127,6	128	127,6	0
0	122,1	124,3	122,2	122,7	123	122,86	4,74
30	124,7	126,2	125,3	125,4	125,1	125,34	2,26
60	125,5	126,3	125,7	125,9	125,3	125,74	1,86
360	126,3	127,4	126,2	127	127,1	126,8	0,8
1440	126,8	127,8	127,3	127,6	127,5	127,4	0,2
10080	127,9	128,4	128	128	128	128,06	-0,46
Sample #2							
Time, (minutes)	**Thickness at measuring points (mm)**					**Average thickness, (mm)**	**Average deformation, (mm)**
	1	**2**	**3**	**4**	**5**		
Initial	126,5	126,8	126,8	126,9	126,7	126,74	0
0	122,6	124,1	121,1	123,2	123	122,8	3,94
30	124,5	125,4	124,1	124,6	124,5	124,62	2,12
60	125,2	126	124,7	126	125,2	125,42	1,32
360	126	126,4	125,5	126,1	126,5	126,1	0,64
1440	126,9	127,2	126,6	127,2	126,8	126,94	-0,2
10080	127,1	127,7	127,1	128	127,6	127,5	-0,76
Average final deformation							**-0,535**

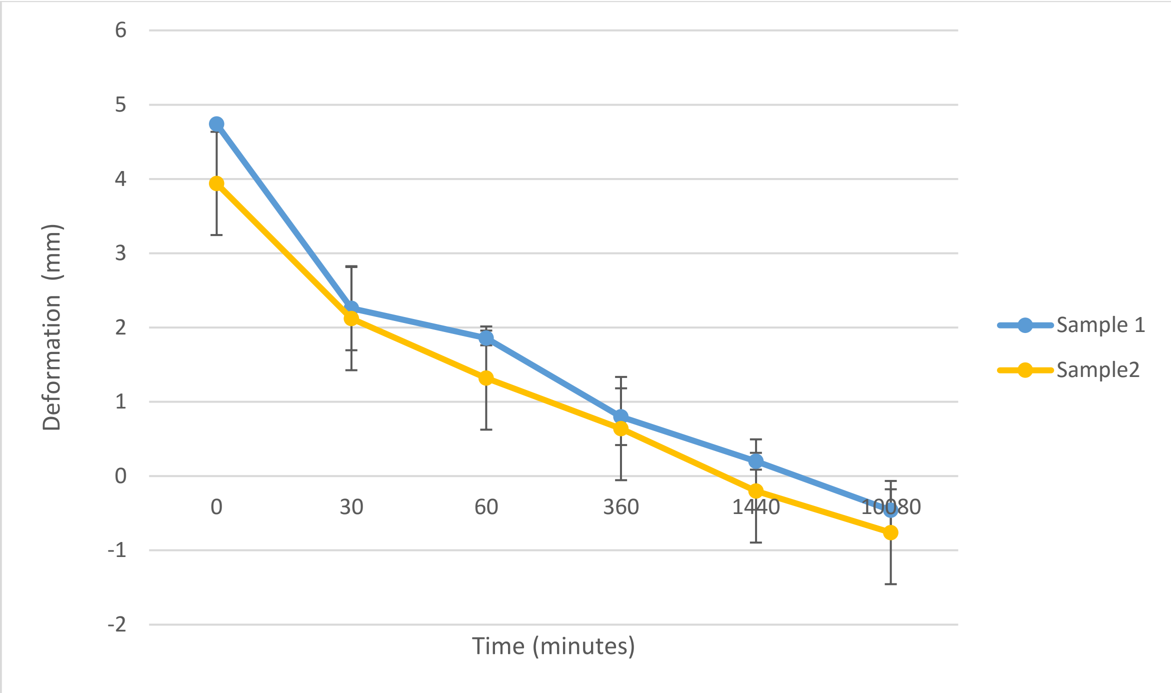


Figure 5.10 VB3423 / HR3532 foam samples deformation recovery in time

5.3.4 HR3020 / VB3040 foam

The final average deformation of sample #1 is 0,57% of the initial thickness, average final deformation of sample #2 is 0,23% of the initial thickness. Second samples average final deformation is 29,73% (0,3 mm) higher than of the first samples thickness.

Table 5.11 HR3020 / VB3040 foam samples deformation recovery in time

Sample #1							
Time, (minutes)	**Thickness at measuring points (mm)**					**Average thickness, (mm)**	**Average deformation, (mm)**
	1	**2**	**3**	**4**	**5**		
Initial	130,5	130,8	131,4	131,4	130,8	130,98	0
0	128,3	129,7	128,5	129,2	129,2	128,98	2
30	129,4	130,2	129,8	130,4	130,4	130,04	0,94
60	129,8	130,5	130,2	130,8	130,5	130,36	0,62
360	130,1	131,1	130,4	130,5	129,8	130,38	0,6
1440	130,1	130,9	130,4	130,8	130,8	130,6	0,38
10080	131,5	132	131,9	131,6	131,6	131,72	-0,74
Sample #2							
Time, (minutes)	**Thickness at measuring points (mm)**					**Average thickness, (mm)**	**Average deformation, (mm)**
	1	**2**	**3**	**4**	**5**		
Initial	132,7	132,2	133,3	132,5	133	132,74	0
0	130,6	130,7	130,3	130,2	130,4	130,44	2,3
30	131,4	131,6	131,2	131	130,9	131,22	1,52
60	131,3	131,1	131,1	131	131,2	131,14	1,6
360	131,8	131,4	131,7	131,6	131,9	131,68	1,06
1440	131,9	131,5	132,2	131,5	132,1	131,84	0,9
10080	132,9	133,1	133,1	132,7	133,4	133,04	-0,3
Average final deformation							**-0,52**

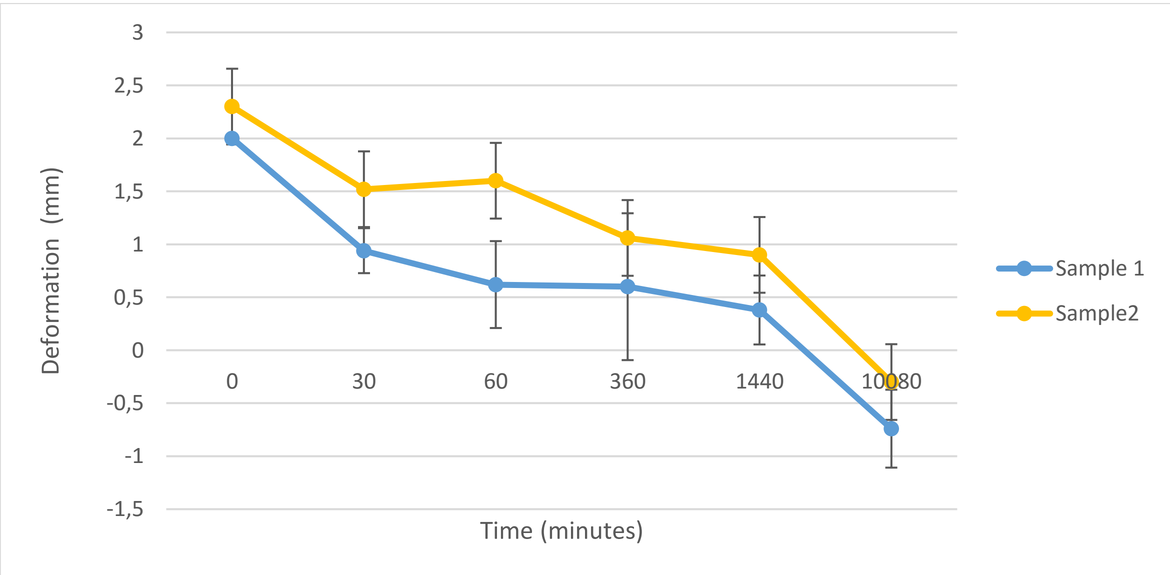


Figure 5.11 HR3020 / VB3040 foam samples deformation recovery in time

5.4 Comparison of foam test results

It is important to note that deformation values depend on numerous chemical and structural contents, some foam samples with lower densities can have higher ILD than foams with higher densities. Because of that, the two parameter values should be looked at independently.

Previous researches [33] [34] show that HR foams are crushed to increase the open cell content to influence the foam mechanical properties. This shows up in the results data, as the high resilience foams had much higher initial deformation values than standard foams, but restores rapidly to almost the same level as standard foams. This is because of the higher elasticity of the high resilience foams. Higher density commonly shows the higher ability to retain its original properties, and ILD mostly relates to comfort [35].

In the graph below, we can see that most of the foam samples had final average deformation well below 1 mm. However VB3423 / HR3532 and VB2540 had final deformation of respectively 1,32 mm and 1,22 mm.

Table 5.12 Seating pillow foam samples deformation recovery in time

	Average deformation in time, (min, mm)					
Sample	**0**	**30**	**60**	**360**	**1440**	**10080**
HR3737	3,7	2,5	2	1,45	1	0,5
VB3830	1,42	0,91	0,59	0,53	0,36	0,07
VB3040	1,48	0,95	0,8	0,61	0,47	0,27
HR3532	5,54	3,49	3,48	2,09	1,4	0,41
VB2540	5,11	3,08	2,73	1,96	1,51	1,22
VB3020	1,53	0,96	0,8	0,25	0,22	0,03
VB2532	1,83	0,61	0,47	0,45	0,33	0
VB3423 / VB3030	1,41	0,55	0,47	0,08	-0,46	-0,78
HR3010 / HR3532	5,85	3,72	3,62	2,95	2,1	1,32
VB3423 / HR3532	4,34	2,19	1,59	0,72	0	-0,61
HR3020 / VB3040	2,15	1,23	1,11	0,83	0,64	-0,52

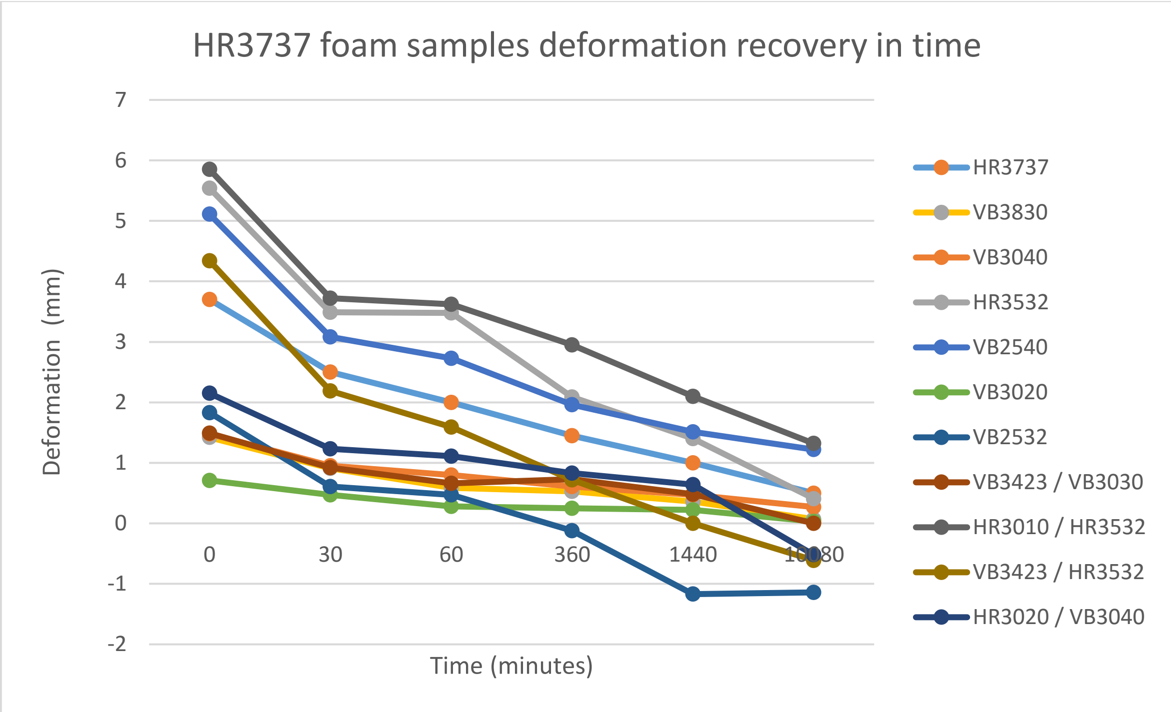


Figure 5.12 Seating pillow foam samples deformation recovery in time

Results showed no correlation between high resilience (HR) foams and standard foams (VB) having higher and lower deformation respectively. The tests however also showed that high resilience foams had higher initial and final deformation than standard foam.

If a HR foam is combined with a VB foam, the final deformation drops remarkably. This is seen in the samples HR3010 / HR3532 having final deformation of 1,32 mm, and VB3423 / HR3532 having final deformation of -0,61 mm, which makes a 192.2% difference.

As the results show, two foams of the same density and the same hardness, VB3532 and HR3532, it can be seen that the HR foam has 88,2% (3.71 mm) higher initial deformation and 187,2% (1.02 mm) higher final deformation.

5.5 Static load test

As the test results show, the foam samples held indoors had much higher average deformation in time, than the ones kept outdoors. The foams were kept in outdoor storage house from 09.02.2018 till 16.03.2018 and during that time period weather data was collected from Tallinn Harku Aerology

Station. The average air temperature during that time was -6 °C and average relative air humidity was 81,7%.

The difference between the foams kept outdoor conditions compared to the samples kept indoor conditions were as high as 1,19 mm (VB3040) and as low as 0,14 mm (VB3830). The results show that VB3040 foam samples had the highest deformation difference, 190,4%, while VB3839 foam had the lowest difference of 41,2%

Table 5.13 Foam deformation recovery after static load test

	Average deformation in time, (min, mm)						
Sample	**0**	**30**	**1440**	**0**	**30**	**1440**	**Difference, (%)**
HR3737 (in)	3,7	2,5	2	1,45	1	0,5	150,9
HR3737(out)	1,42	0,91	0,59	0,53	0,36	0,07	
VB3830 (in)	1,48	0,95	0,8	0,61	0,47	0,27	41,2
VB3830 (out)	5,54	3,49	3,48	2,09	1,4	0,41	
VB3040 (in)	5,11	3,08	2,73	1,96	1,51	1,22	190,4
VB3040 (out)	0,71	0,47	0,28	0,25	0,22	0,03	
HR3532 (in)	1,83	0,61	0,47	-0,12	-1,17	-1,14	37,5
HR3532 (out)	1,41	0,55	0,47	0,08	-0,46	-0,78	

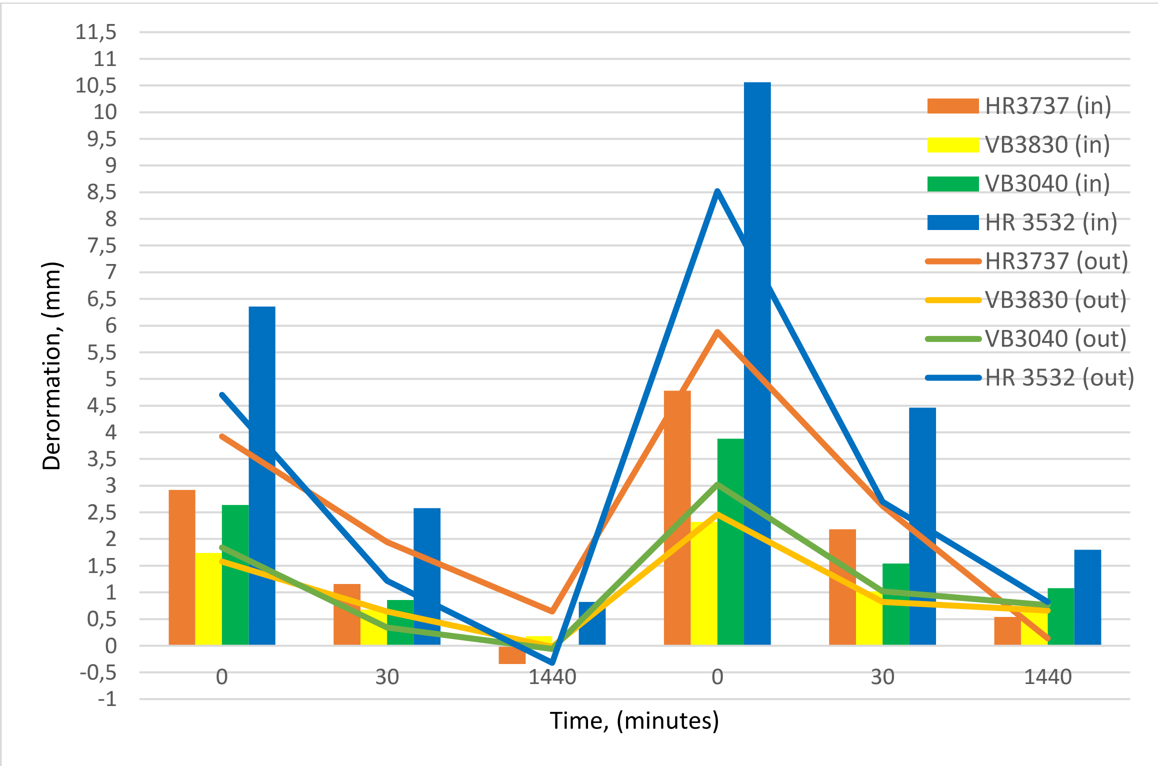


Figure 5.13 Foam deformation recovery after static load test

SUMMARY

The aim of this master's thesis was to develop a testing rig for testing upholstery furniture, and to test polyurethane foam samples for their final deformation. During this thesis, an overview of polyurethane foams and its usage in upholstery, including the principal PUR foams testing methods were investigated.

Upholstery foams have three important aspects to be considered. First is the foam being loaded under static seating condition, so it's important to provide distributed pressure point to an occupant. Second is dynamic loading conditions, which show how foam withstands thousands of seating cycles during its lifetime. The third important aspect is its ability to serve consistent performance during its lifetime.

In this thesis, different foam durability tests were investigated. Testing is essential to produce foams that are able to withstand years of use. Two best examples for foam durability tests are Urethane Foam Dynamic Fatigue test and Constant Force Pounding test. Within this thesis, a few alternative testing rigs and accessories for existing Hegewald & Peschke universal furniture test rig was searched. Several offers were requested from companies that specifically produce testing rigs for various tests.

SMC has offered a personal solution for the Laboratory of Wood Technology, which is a custom made model, for the needs of our department. However, due to the personal offer being high-priced, and alternative solution was made. Laboratory of Wood Technology has purchased an 80x80x2300 profile to mount the existing two vertical cylinders on. This provides a longer working range which in turn enables testing two foam samples at once, reducing time cost.

The second part of the thesis was to investigate different types of seating foams provided by Vita Baltic International with 11 models of their foam samples. 5 of them standard foams, 2 of them high resilience foams, 4 of them double-layered foams. All models have two samples.

The results showed no correlation between high resilience foams having lower deformation than standard foams. A link between higher sample density and lower deformation was found, as higher density shows the ability to keep its original properties. The test results showed that most of the

foam samples had final average deformation well below 1 mm. However VB3423 / HR3532 and VB2540 had the highest final deformation of 1,32 mm and 1,22 mm respectively.

As an experiment, a 7 days static load test was made for foam sample pairs, one of the pairs being held at indoor conditions, the other held at outdoor conditions prior to applying the load. The results showed that the samples previously kept at outdoor conditions had considerably lower final deformation, with the differences from as low as 37,5% (HR3532) to as high as 190,4% (VB3040).

Overall it can be said that the testing rig was improved and the polyurethane foams were tested and analyzed to find links between foam deformation and density. In the future research, more foam samples of the same densities and hardness' should be tested, as well as to be held at a more controlled climate conditions, i.e. climate chamber.

KOKKUVÕTE

Selle magistritöö eesmärk oli arendada mööblikatsestend, ja katsetada polüuretaanvahtude deformatsiooni. Lõputöö käigus tehti kirjanduslik ülevaade polüuretaanvahtudest ja selle kasutusest pehmemööblitööstuses. Sealhulgas sai uuritud peamiseid PUR-vahtude testimise meetodeid.

Pehmemööbli jaoks mõeldud vahtplastidel tuleb arvestada kolme olulise aspektiga. Esiteks rakendatakse vahule staatiline koormus, mistõttu on oluline pakkuda istujatele jagunenud toetuspinda. Teiseks on dünaamilised koormustingimused, mis näitavad, kuidas vaht eluea jooksul talub tuhandeid istekohti. Kolmas oluline aspekt on võime kasutusea jooksul samalaadseid mehaanilisi omadusi säilitada.

Selle magistritöö käigus uuriti erinevate polüuretaanvahtude vastupidavust. Vahu vastupidavuse katsetamine on oluline, toota vahtplaste, mis suudavad aastaid kasutada. Kaks parimat näidet vahtplastist testide kohta on Foam Dynamic Fatigue test ja Constant Force Pounding test. Selle lõputöö raames otsiti olemasoleva Hegewald & Peschke universaalse mööblikatsestendi asemele uut katseseadet. Taotleti mitmeid pakkumisi firmadelt, kes toodavad spetsiaalselt mitmesuguste testide jaoks testimise seadmeid.

SMC Pneumatics Estonia pakkus puidutehnoloogia labori vajadustele individuaalset lahendust, mis on kohandatud mudel. Kuid kuna ka selle pakkumise hind oli kõrge, tuli välja mõelda alternatiivne lahendus. Puidutehnoloogialabor on ostnud 80x80x2300 profiili, millele olemasolevad kaks vertikaalse silindrit paigaldada. See tagab pikema tööpiirkonna, mis omakorda võimaldab testida kahte vahu katsekeha korraga, vähendades ajakulusid.

Töö teine osa koosneb Vita Baltic Internationali pakutud 11 vahtplasti mudelit katsetamist. 5 neist on standardsed vahud, neist 2 on kõrge vastupidavusega vahud, neist 4 on kahekihilised vahud. Kõikidel mudelitel on kaks näidist.

Tulemused ei näidanud seost, et kõrgemate vastupidavusega vahtudel oleksid väiksemad deformatsioonid kui standardsetel vahtudel. Leiti seos kõrge tiheduse ja madalama deformatsiooni vahel, kõrgem tihedus näitab vahu võimet taastada oma esialgsed parameetrid. Katsetulemused näitavad, et enamikel katsekehadel jäi jääkdeformatsioon alla 1 mm piiri. Kuigi VB3423 / HR3532 ja VB2540 katsekehadel olid jääkdeformatsioonid vastavalt 1,32 mm ja 1,22 mm.

Eksperimentaalse katsena viidi läbi vahtplasti mudeli paaridele 7-päevane staatiline koormuskatse, ühte katsekeha paarist hoiti isetingimustes, teist hoiti välistingimustes enne koorma paigaldamist. Tulemused näitasid, et eelnevalt välistingimustes hoitud katsekehadel olid oluliselt väiksemad deformatsioon, deformatsiooni erinevused jäid 37,5% kuni 190,4% vahele.

Kokkuvõtteks võib öelda, et testimisseadme võimekust arendati ning polüuretaanvahud testiti ja analüüsiti, et leida seos vahu deformatsiooni ja tiheduse vahel. Tulevaste uurimuste käigus tuleks katsetada rohkem samade tiheduste ja kõvadusega polüuretaanvahte ja neid hoida kontrollitud tingimustes, näiteks kliimakambris.

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APPENDICES

Appendix 1 Placement plan of the furniture testing lab