TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY

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Performance of cushioning materials in packaging

Pakendi pehmendusmaterjalide efektiivsuse määramine

Master Thesis

Author applies for academic degree of Master of Science in Engineering

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Author's Declaration

I have written the Master’s thesis independently.
All works and major viewpoints of the other authors, data from other sources of literature and elsewhere used for writing this paper have been referenced.

Master's thesis is completed under .... supervision

“.......”....................201….. Author .... signature

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Supervisor …... signature.

Accepted for defence

.... chairman of defence commission

“.......”....................201… .

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Master's thesis task

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Student: Kaupo Leht, 143915MARM

Field of study Industrial engineering and Management

Supervisor: Meelis Pohlak, Senior Research Scientist

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Performance of cushioning materials in packaging

Tasks and timeframe for their completion:

Nr	Task description	Completion date
1	Review of the requirements the packaging and electronic device must stand against	14.03.2016
2	Review of the currently used solution and test standards	20.03.2016
3	Defining loads which take place during transportation	7.04.2016
4	Material testing and finding alternative design.	25.04.2016
5	Analyzing new solution	20.05.2016

Engineering and economic problems to be solved:
Mechanical static and dynamic loads testing to propose optimal foams for products support during transportation in economic and strength wise.

Defence application submitted to deanery not later than 20.05.2016 Deadline 20.05.2016

Student Kaupo Leht /signature/ ………..…………. date …..........………

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1. INTRODUCTION

This main task of the thesis is to analyze and define alternative packaging foam material for product support during transportation. It can be proposed the most suitable cushioning material for the regarded company. Firstly the thesis includes review of packaging test methods, standards and acceptance criteria for the company and the same analyses from literature perspective. Also the analyses of mechanical strength the typical product can withstand. The packaging design process is reviewed as well.

Also it is reviewed the before made test, which is then followed by material testing carried out by the author for the existing material and alternatives, which output is making much easier to have design brainstorming for possible solutions to concentrate, evaluate them and to have also the material evaluation matrix for those design options to choose the best alternative. After that is the new solution testing and also description of new solution. Once everything before mentioned is done, the brief process calculations of finding cycle time and line capability per month and through it also the economic calculations is done to see the difference between existing and new packaging cost, also including various materials cost for possible demand examples.

1.1 Background and problem

Objective is to suggest the alternative material solution for currently used packaging foam to have packaging cost reduction. Also to have possible more environmentally friendly material, then the green design is needed to consider. The plastic foams which are surrounding the product are making 54% of total packaging material cost for a company; also 80% of total cost comes from 25 packaging items.

Necessity is coming from possible novelty creation for the company, which is production firm, but like any other nowadays enterprises in current economic business environment it is searching for solutions towards cost efficiency. So from one aspect of being green helps to create better image and attract the future possible stakeholders in the field of sustainability which could lead to collaboration and helps in the way to save cost (bring money in), and create more value for the customers by advertising the attractive strategy and again result with the same thing where “green customer” at one point wants to buy a product from you.

But even if we are leaving out the “wanting to be green” part we can all agree on the obvious necessity to research cheaper alternative material solution.

From the material in terms of chemical, physical properties to the design solution role which sees cost savings in such aspects like the material can take less space during transportation thanks to design (resulting fuel and shipping reduction), avoid use of different types of material, raw material cost in terms of producing it, more parts per pallet resulting the lower cost in warehousing, reusable package etc. and still meet the necessary requirements for the Company.

Project is done within the collaboration of Company and TUT, in the spring of 2016.

1.2 Goals

The goals are as follows:

- Selection of alternative materials.
- Possible proposing of environmentally friendly material.
- Reducing the cost of fitments used by the Company.

The hypothesis is that the current solution requirements for the regarded fitments are not time relevant, so better material optimization (meaning weaker material in strength wise and less material usage) can be done and still meet the acceptance criteria, thus reducing the cost of packaging materials.

1.3 Methods

Reviewing the literature of packaging test methods, standards. Also reviewing what kind of dynamical, static conditions typical electronic product can withstand. Which is followed by the review of the packaging test methods. Then the review of the requirements from the company about which forces the product and the package itself has to stand up against, along with which standards are used inside the company plus what are the acceptance criteria's for the product and the package after test has been carried out. After the background review author carried out material strength testing of current material and alternatives by doing impact, compression and tensile testing. After that also carrying out packed product impact testing, then by the help of this testing will participate in design brainstorming and create evaluation matrix.

Used equipment for the testing of compression test is Instron 5866, for drop/impact test it is self-build rack, during impact testing is used acceleration sensors which are MEMS based capacitive 3-D (for both, impact of package and materials).

For tensile testing it is electromechanical tension testing machine with extensometer. All tests were carried out in TUT laboratories.

1.4 Summary of tasks

In background review among others are main tasks like literature review of requirements for the device and packaging, reviewing test standards, the current solution.

Once that is finished, then from testing part is defining important criteria's for loads taking place during transportation, also carrying out the material testing for materials (also for alternative solution) and packed product, after that is line capability calculation for current and new solution followed by packaging cost calculation and the finding of alternative material solution.

1.5 Packaging in general

Packaging is somewhat in many cases remaining behind the scenes, consumers don't actually notice it, but its functionality and importance is much greater than one would think it to be. There are many areas which need to have high and different requirements for packaging such as perishable foods, like fresh meat and fish which would be spoiled without correct packaging. Electronic equipment's (to which this thesis is also tied to), along with domestic appliances such as irons, microwave ovens etc., they all rely on packaging protection from damage occurring in the distribution chain. Also what packaging is doing is that it also influences the convenience use of a product. Not just that but it's the instrument in selling the product, by attracting the consumer. [15]

For understanding the packaging function and to make sure that they are adequately met, it is essential to define the product; its critical properties and value. This should always be the beginning point, without the product it has no reason to exist. The designer needs to work closely alongside the product developer to understand the product and what can cause it to transform to the point of becoming unacceptable. [15]

Containment

Here is bit description of each function necessary for the packaging to take into account. Firstly about containment, properly designed, constructed and seal proof package will provide total containment for the inside content, it will assure the prevention of dangerous leakage, or loosing of parts.

This all must be assured throughout the expected lifecycle of the product, which included multiple handling stages from the end of the packaging line to the use of the final consumer. [15]

In doing risk analysis. Firstly should be brainstormed the most potential threat spots, by that including all spots where it could fail, not just obvious ones, like nail spikes through package. Then brainstorm how and why the failure could occur at each of those points you previously wrote down.

After the potential cause factors are identified, it is time to ensure during the development stage that the required performance characteristics are designed, specified component and process specification's, and that control is in place to ensure those specifications are followed. [15]

Also during development phase of the package have to make sure that the likely conditions of use are taken into account, the needed requirement for this also dependent of the product (see chapter 1.13 of description of the product). [15]

Protection

By protection it is considered the prevention/reduction of damage to the product, and this throughout the all stages of its life. It included packaging and manufacturing operations, warehousing and handling, transportation to the merchant, store for sale, displaying etc. [15]

Deformation for the product in terms of damage can occur at any of those handling stages, although warehouse and distribution are the main environment where the damage happens, that is due to dropping (from pallets, transit, during order picking), vibration in vehicles, also compression wise (stacking) etc. See table 1 for typical hazard in the supply chain. Damage can also come from such factors like dust, birds, dirt etc. [15]

Table 1. Typical hazards in the supply chain, their causes and effects [15]

Hazard	Causes	Possible effects
Shock	Falls from conveyors, pallets, vehicles, possibly due to poor stacking; shunts due to irregular movement along conveyors; drops due to manual handling; impacts in transit due to driving over poor road surfaces	Breakage; deformation
Vibration	Vibration occurs naturally in all types of transport. In road transport the effects are enhanced over the rear axle of the vehicle, and by any imbalance in the load. Irregular road surfaces also increase vibration	Breakage; scuffing; product separation and/ or settlement; loosening of screw caps; garments falling from hangers
Compression – static	Stacking in storage, made worse by damp conditions	Breakage; crushing; load collapse
Compression – dynamic	Clamp truck pressure; severe vibration during transport	Breakage, crushing, stack resonance
Puncture	Poor quality pallets, bad handling practices	Breakage; product spoilage; load collapse
Changes in relative humidity	Loads left outside; goods stored in damp warehouses, or where climatic conditions are not controlled; goods shipped via and to different climates	Product spoilage, e.g. corrosion; packaging failure, e.g. damp corrugated board cases
Changes in temperature	As above	Product spoilage; drying out of paper/board materials;
Exposure to light	Retail display	Fading of product and/or pack; product spoilage, e.g. rancidity
Insects, rodents, birds, dust, dirt	Goods stored in warehouses not cleaned or treated for pest control, or where doors/windows are left open or badly fitting	Product spoilage due to poor hygiene; contamination of product and pack
Pilferage and tampering	Goods exposed to uncontrolled personnel access; display on shelf	Loss of products; damaged packs and products; contamination; counterfeit products

Evaluating the protection function

The protection level of the product is taken from the inherent severity of the product plus the pack protection must be equal to the likely danger/hazards happening during the transportation from the factory to consumer. [15]

Main steps to decide what type of packaging suits the best is more situated to packaging process, which is covered in chapter 1.10.

1.6 Company description

Production electronic company which is looking for alternative solution to support their products in distribution flow. Like any other manufacturing, it uses the production process to combine various material inputs and also immaterial (plans, know-how) into making the output for consumption, in this process will have output with value to the consumer. And like many modern companies it is making use of Lean manufacturing to reduce waste and Six Sigma methodology to remove variations in the process. [42]

1.7 Packaging as green solution

From packaging point of view, most of product packages are single-use, and they will turn to waste after they are used, and product life cycle of them is short, so this means consumption of large amount of resources. In the same time ecological environment has also been an unprecedented threat.

For example in China, the pollution waste only generated from the packages alone has become the fourth-largest source of pollution, this is followed by the water pollution, lake and ocean pollution, and air pollution. The protection of ecological environment by developing the green packaging and promoting sustainable economic development have become agreement in the world's packaging manufacturing in many industrialized countries. [51]

"Ecological package", also called as green package is defined as environmental friendly package which is fully made from natural plants, can be used multiple times, be degradable. [51]

Where can we be more environment friendlier?

The following helps to answers to this from main aspects like, material, volume, design and logistic wise. Minimizing the environment impact, it can be done by selecting appropriate materials, correct outer shield and transportation support. [35]

Another aspect is the focus of the volume. As already said, package has a life cycle like any other products; it has to be optimized for the volumes in the early phases and in later phases. [35]

From logistic perspective, the shortening of the total transport distance is possible by using locally produced packaging (as much as possible). Making prioritization in transportation ways, like using sea before air, optimizing the pallets usage in ships, planes, trucks.

This is possible by packing products together as much as possible. Using returnable package, for maximum re-usage as possible. [35]

To lower environment impact by:

1. Using as little material as possible by weight and volume
2. Replacing heavy materials with lighter ones
3. Analyzing the changes in transport logistics, product dimensions, product fragility level, and quickly adapting to these changes for the design.[21]

Design aspect

Crude oil has been raw material for plastics for long time. This issue is now raising as oil is limited resource. Nowadays bio-based and mixtures of different bio based plastics have becoming commercial. As it takes long time for oil based plastic to degrade, the problem with pollution still exists. All material is degradable but the time it takes to degrade varies enormously, see figure 1. [21]

The package time to degrade in nature depends much on sunlight, temperature, humidity, and related factors. Additives can make plastic biodegradable. The problem however is to control the breaking down of the plastic. To achieve really short time, the degrading should occur in facilitated with controlled humidity, temp. and microorganisms. [21]

So, to sum it up, minimizing environmental impact has three steps. 1. Minimize use of oil based plastics 2. Introducing bio based plastics 3. Introduce biodegradable plastics.

Figure 1. Average breakdown time [21]

The improper packaging and handling of dangerous goods are often the cause of the incidents. So, there are packaging instructions using methods in the respective regulations for each type of dangerous goods. Usually dangerous goods require that they be packed in UN-approved packaging. They use 'UN Specification marking", which indicates that the packaging has been successfully tested in accordance with the international standards. [6]

Company cost benefit

During the new package development engineers tend to overlook about the waste costs, and other important costs.

Good example is coming from logistics, even when suitable environment for it had been defined, this caused product damage. The over packing in this matter was the cause (for example with extra or higher density foams), which cause extra costs and won't solve the product damage problems. [35]

The selection of recycled materials should be expanded, which will not only reduce environmental pollution but also saves raw materials. [35]

Green material usage, not only to reduce environmental pollution, but also can replace some of the more expensive or lack resources in order to reuse. The strategy for sustainability is to consider three elements, economy, performance and environment. [35]

The largest cost in the packaging cost is the material cost, because of this organizations need reasonable procurement (material wise), to minimize the grade of material. [35]

Large scale logistic wise packaging is subject to handling, removal, storage and transportation, and speed up the links between operations which is helping to reduce packaging unit also to save packaging materials and cost. It can also help to protect cargo body, such as container bags usage, use of pallets, containers etc. [35]

Minimize the used material. In term of easily disassemble of the package, recycle, sorting, design should try to avoid using many different types of material and regarding the complex packaging they should be designed easily separated by the structure. [35]

1.8 Already existing package solution materials on the market

The environmental and packaging standards and regulations have defined requirements which can be possibly be passed by new environmental friendly materials. The applicable materials which can replace synthetic foams are continuously changing. Because the development and testing of these materials. The following table 2 is well illustrating the materials which will get higher focus in the field of packaging development. [35]

Table 2. Current and emerging bio-based plastics and their biodegradability [35]

Biodegradability	Fully fossil-based	Partially Bio-based	Fully bio-based
Fully biodegradable	- PBS - PBSL - PCL - PTMAT - etc...	- Stretch blends (with bio-degradable fossil-based copolymers) - PLA blends (with biodegradable fossil-based copolymers)	- TPS - Stretch blends (with bio-based and bio-degradable copolymers) - PLA - PHA - Cellulose acetate - Regenerated cellulose
Non- biodegradable	- PE - PP - PET - PVC - PUR - ABS - etc...	- Starch blends (with polyolefin) - PA 610 - PET from bio-based ethylene - PUR from bio-based polyol - etc...	- Bio-based PE - PA 11 - Bio-based PB

Biobased raw material

So, to understand the environment friendly foams better, its needed to clearly define them.

Biodegradable: capable to go through decomposition into carbon dioxide, water, methane, or biomass in where main dominant mechanism is microorganism's enzymatic action. Measurable in standardized tests. [35]

Compostable: Process of biology. Output is carbon dioxide, water, inorganic compound and biomass and leave no visually seen or toxic residue. [35]

Degradation: irrevocable process change of material structure, typical characterization is loss of properties (molecular weight, structure or mechanical strength). It's affected by environmental conditions and proceeds over period of time. [35]

Disintegrating: It's the crumbling into small fragments of packaging or packaging material, happening by a combination of degradation. [35]

1.9 Product process flow to customer

In the product process to customer is brought out the distribution from packaging perspective, see figure 2. [27]

Figure 2. Product value chain through packaging perspective [27]

The optimization of one part of the packaging system could lead to new problems in another problem of the system. Like fo example, the packaging material reduction for the consumer package can result in more waste of product or a need for a more packaging material in the retail package. [27]

The packaged product distribution could go in both ways, like seen in figure 3 damaged vs successful delivery. [46]

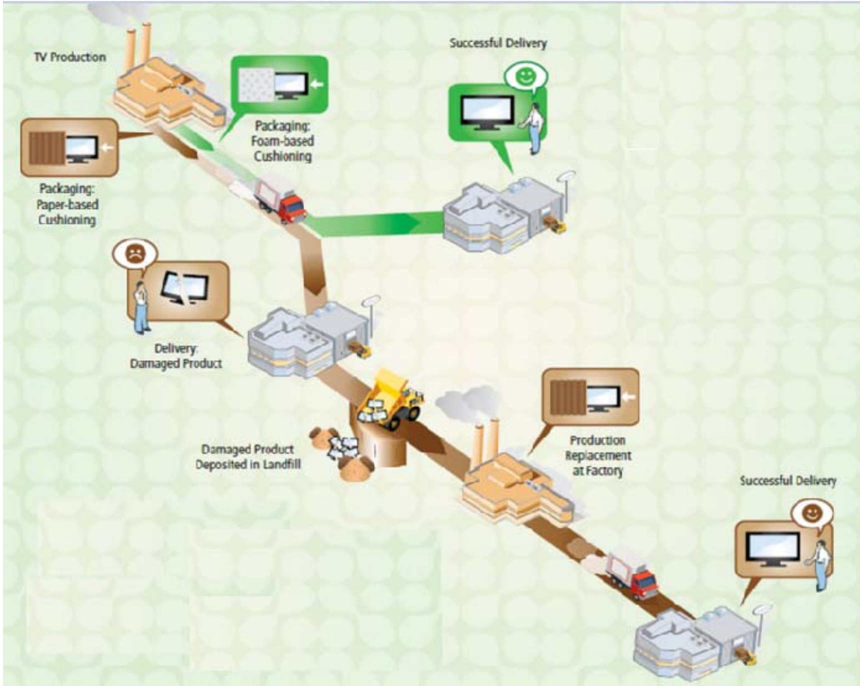


Figure 3. Unsuccessful delivery vs successful [46]

Fig. 4 shows the contents of the current box, where are shown the foam fitments that are under the focus of the thesis

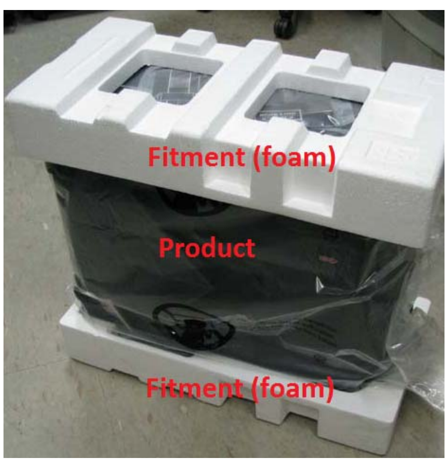


Figure 4. Product between foams [23]

1.10 Packaging design process

To understand packaging development process is to understand the key component- product. The data for this is achieved by making actual tests, or there may be comparison products which has proven performance which can be used as a guidance.

The aim is to have the product type (physical shape) and what conditions it can stand before it breaks (takes damage).

For example what kind of drop/shock impact it can stand, what vibration frequency, the temperature, humidity level etc. The value of the product is also to be considered as to define what kind of protection can be afforded. In this point also the legislation must be noted, like legislation of hazardous goods. [15]

Now heading to more into details, as this study of work describes/analyzes the fitment material, here also will start off by considering the cushioning the product requires. Its first step is to define how much mechanical shock the product can stand on its own. The most known terms for this are the fragility or g-factor. Fragility is usually express in units of g's, which is the indication of maximum deceleration the product can withstand without being damaged. The lower the number of g the more fragile a product is. Table 3 below helps to illustrate the fragility. [38]

Table 3. Approximate fragility of typical packaged articles [38]

Class	Typical Contents	Fragility
Extremely Fragile	Missile guidance systems, precision aligned test instruments	15-25 g's
Very Delicate	Mechanically shock-mounted instruments and electronic equipment (Shock mounts should be firmly secure prior to packaging. They are provided for in-service protection only.)	25-40 g's
Delicate	Aircraft accessories, electric typewriters, cash registers and other electronically operated office equipment	40-60 g's
Moderately Delicate	Television receivers, aircraft accessories	60-85 g's
Moderately Rugged	Laundry equipment, refirgerators, appliances	85-115 g's
Rugged	Machinery	115 g's and up

The fragility of a product is defined by making to it a series of gradually more severe shocks (decelerations) in order to find the lowest severity impact which damages the product. So, the highest g level which did not cause damage is known as product g-factor. [38]

It may be needed to make tests in different orientations, to determine fragility, because it is normally so that product has greater strength in one direction than another. [38]

Under designing means that the g factor is estimated too high, and in reality product doesn't survive as much shock as anticipated. On the opposite, if the factor is anticipated too low, and in reality the product can withstand even more shock then this means over design of the package which is unnecessarily expensive. [38]

Defining the environment

It need to be identified how the product is moved, stored, displayed and sold, as each of those stages has its own hazards. This includes the internal movements within the premise and externally, when the goods are outside of premise of the manufacturer. The globalization of manufacturing has resulted the more complex distribution chain. [15]

Once the product fragility is known, the designer will consider those handling and environment of the transportation the product will face.

One of the elements is drop height for the shock amount. Drop height is defined by the product weight which usually reflects how the product will be handled. [38]

The table 4 below illustrates the typical drop height for products. It may be used if information of the products handling in distribution chain is unknown. [38]

Table 4. Typical drop heights of the product [38]

Weight Range (kg)	Type of Handling	Drop Height (m)
0-4,5	1 person throwing	1
4,5-9	1 person carrying	0.9
9-22	1 person carrying	0,7
22-45	2 person carrying	0,6
45-113	Light equipment	0,5
113+	Heavy equipment handling	0,4

Once both, the product fragility and drop height have been determined the cushion curves can be used to select the best material type, thickness, density for each application. [7]

Cushion curves are made by dropping a series of known weights onto samples at a specified heights while measuring the shock amount absorbed by the foam. Then results are plotted on graph which illustrate foams cushioning curves. [7]

An example of ideal cushioning curve is shown below figure 5. It shows the performance of cushioning material. The horizontal axis shows static load range (in pound per square inch) that packed items might apply to material.

The vertical axis represents shock as the cushion is impacted. Curves are often made for several drop impacts (average 2-5 drops). [38]

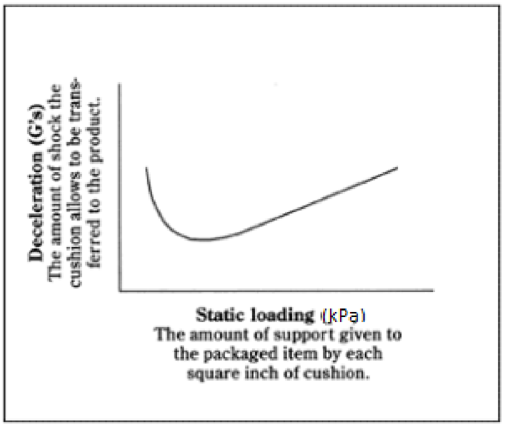


Figure 5. Ideal cushioning curve [38]

Considering also the vibration as one of the hazards. The probability to it to happen during transit is 100%. Each mode of transit type like rail, aircraft, truck and ships subject the package to different levels of vibration frequencies.

Each material has a range of vibration frequencies, some of which may amplify and transfer a more serious vibration to packaged product. See table 5 for typical vibration between in different carriers. [7]

Table 5. Typical resonance frequencies of carriers [7]

TRAIN/RAILROAD	2 - 10 Hz (suspension) 50 - 70 Hz (structural)	Moving rail car over rail tracks
TRUCK	2 - 10 Hz (suspension) 15 - 25 Hz (tires) 50 - 70 Hz (structural)	Normal highway travel
AIRCRAFT	2 - 10 Hz (propeller) 50 - 70 Hz (jet engine)	Aircraft structure during normal flight
SHIPBOARD	10 Hz (on deck) 100 Hz (structure/bulkheads)	Vibrations caused by normal shipboard travel due to the flow of water around the ship and from any imbalance and misalignment of the propeller drive shaft system.

To choose the material it is needed to know how big foam (cushion) area is necessary to support the product (through static loading calculation). Then the density of the foam needs to be defined as the property of the material, with the chosen material it's possible to determine ideal foam thickness by taking into account the product fragility factor and drop height. [8]

Best shown as an example in the following figure 6 as material was selected as polyurethane with density of 2lb/ft^3 (32 kg/m^3). [8]

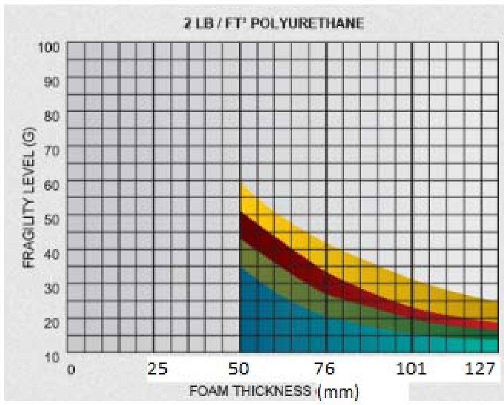


Figure 6. PUR thickness vs fragility [8]

1.11 Current package requirements

This section concentrates about requirements set for current package, considering also the standards. Then through it it's possible to know in which direction the new one has to be designed.

SAE of USA, JASO of Japan and IEC of EU, ETSI, there's also ASTM, and ISO, which will be talked later on. [43]

As the Company belongs to consumer electronic industry, then to it also applies those requirements set by consumer product standards and all relevant requirement especially imposed from before mentioned standards. In the packaging world there are many categories of requirements for packaging from such aspect like chemical, physical treatment (in storage, in handling and transport), climatic, also for the marking system (handle with care, stacking mark etc.). [43]

But in this work we will concentrate about physical treatments.

Previously was talked about the packaging design process and also in this chapter is the requirements set by various directives but also now following shortly the section of physical treatment in storage, handling, transportation. How the tests itself are carried out can be seen in 1.14 of previous work of testing- and also in chapter 2 to see authors own made tests.

So, to put it in short what the standards describe in making of tests: apparatus (example. compression device), test sample dimensions, quantity, repetition, procedure of step by step of what to do in which order, also about reporting.

The mainly used standards are American Society for Testing and Materials (ASTM) and International Organization for Standardization (ISO). [1] [26]

The common packaging test standards apply to the Company also.

As an examples are the following cushioning test standards:

ASTM D1621-00. Test method describing a procedure for the compressive properties of rigid cellular materials, namely expanded plastics. [45]

ISO 1856:2001. It specifies three methods for compression set determination of flexible cellular materials. [17]

For the whole package there are different standards, some examples:

ASTM D5276. This is procedure description of drop testing of loaded boxes, cylindrical containers etc. using the free fall method. [44]

ASTM D999. Vibration test method description. About filled shipping containers. To get to know the performance of a container during the transportation. [1]

Based on subchapter 1.10 we can say that Company products tolerate 40g impact on its own. And packed product can stand 50g (23ms).

1.12 Current material properties

Current materials, as it is oil based is not biodegradable. The material is EPP (expanded polypropylene) and EPE (expanded polyethylene), with density of EPE 30 kg/m^3 and EPP 35 kg/m^3

Following is the units in accordance of the SI (for the same material), see table 6 for EPP physical properties. [14]

Table 6. Typical physical properties of EPP [14]

Physical Properti	Test Method	Units	Tested Densities						
		g/ltr	20	30	40	50	60	80	100
Tensile Strength	ISO 1/98 DIN 53571	kPa	270	450	560	670	760	960	1150
Tensile Elongation	1.50 1798 DIN 53571	%	21	20	19	18	17	15	13
Compressive Strength	ISO 844								
25% Strain	DIN 53421	kPa	80	150	210	275	340	500	700
50% Strain	Test Speed	kPa	150	200	300	370	475	700	960
75% Strain	5 mm/min	kPa	350	460	600	800	1000	1600	2300
Compression Set 25% Strain - 22H - 23c	ISO 1856 C Stabilising 24H	%	13,5	12,5	12.0	12.0	11, 5	11,5	11,5
Stauchharte	ISO 3386 40% Stain	kPa	80	105	125	140	150	170	185
Burn Rate	FMVSS 302 1503795 Sample thickness 12.5mm/min	mm/min	100	80	60	50	40	30	25

Also now another source EPP properties table, see table 7. [13]

Table 7. The properties of EPP [13]

Product density	kg/m3	20	40	60	80	100	Test specification
Tensile strength	kPa	260	600	880	1020	1300	DIN EN ISO 1798
Elongation at break	%	19	17	15	12	10	DIN EN ISO 1798
Compressive forces							
25% deformation	kPa	80	220	430	500	780	DIN 53 421
50% deformation	kPa	150	390	560	930	1340	DIN 53 421
75% deformation	kPa	330	700	1050	2150	3370	DIN 53 421
Compression set 22 h/RT/24 h 25%	%	12	11	10	-	-	DIN EN ISO 1856
Compression hardness	kPa	50	200	400	-	-	DIN EN ISO 3386
Damping	-	2.8	2.7	2.6	-	-	from ISO 4651
Static surface loading 5% / 100 d	kPa	12	23	92	-	-	DIN 53 421
Thermal conductivity at 10 °C	W/(m * K)	0.039	0.041	0.042	0.043	0.045	DIN 52 612
Water absorption in 1 day	vol.-%	0.5-1.5	0.5-1.5	0.5-1.5	0.5-1.5	0.5-1.5	In accordance with DIN 53 428
Water absorption in 7 days	vol.-%	1.0-2.5	1.0-2.5	1.0-2.5	1.0-2.5	1.0-2.5	In accordance with DIN 53 428
Surface resistance (23°C / 50% rel. humidity)	Ω	5 * 1012	5 * 1012	5 * 1012	5 * 1012	5 * 1012	DIN/VDE 0303

And third comparison of EPP here, see table 8.

Table 8. EPP properties [10]

Property	Test method	Unit	Material density (MD) as ISO 845 [kg/m³] (Core density)				
			35	40	50	60	70
Tensile strength	DIN EN ISO 1798	[kPa]	530	600	740	880	1020
Elongation at break	DIN EN ISO 1798	[%]	34	33	30	27	25
Compressive stress at 10% strain at 25% strain at 50% strain	according to ISO 844	[kPa]	 150 180 280	 180 220 330	 240 290 440	 310 370 550	 390 460 670
Compression set (50%, 22 h, 23°C) 24 h after stress release	DIN EN ISO 1856 (Procedure C)	[%]	29	28	27	26	25
Dimensional stability at heat (Linear size alteration after 4 d, 110°C)	according to DIN ISO 2796	[%]	<2	<2	<2	<2	<2
Thermal conductivity	DIN 52612	[W·m⁻¹·K⁻¹]	0.037	0.038	0.039	0.040	0.041
Water absorption (1 day)	according to DIN 53428	[Vol.-%]	<1	<1	<1	<1	<1
Flammability sample thickness: 13 mm	FMVSS 302		← fulfilled at MD 30 [kg/m³] →				

Although author is testing the impact and compression of materials for current, if needed for other properties, the above tables show that other properties are quite similar between different sources, then by knowing the density of current material it can be said that other properties can be assumed to be in the same range as shown in the tables. This time it is brought out for EPP, as by product material usage its generating top cost, see chapter 4

1.13 Description of products for which the new solution is to be searched

Here not going too much into detail, it’s not even so necessary to have product details as in foam testing point of view, to give an idea of the shape of 4 products, there are the rough dimensions as following, product 1 and 2 (as same design) are 500 H x 470Wx 180 depth, product 3 is 700x 310 x 180, Product 4 is L 490x380Wx170H [mm]. Now, the weight which is important in how big is the impact how, much weight foam has to stand. They are as following: product 1,2 are 26 kg, product 3 is 22 kg and product 4 is 13 kg.

1.14 Previously done material testing

This chapter tells about previously done different material tests and analyzes for the foam (fitments). Bringing out some of the examples from each category as main necessary tests for design : drop test and compression.

Here we start off with the description of drop test done for material of EPE and EPP.

When the product fragility and drop height have been determined as explained in chapter 1.10 then it's possible to use cushion curves to select material type, density, and thickness for each application. [7]

More detailed cushioning performance in the following figure 7.(ibid.,9).

There is 25, 50 & 76 mm thickness for 20 g/l, EPE foam, from 610mm drop height. [7]

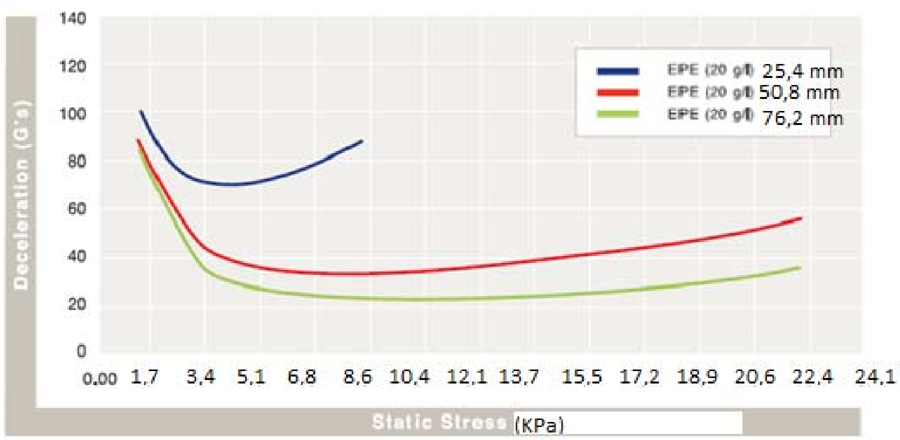


Figure 7. Impact test [7]

Then continue to define how much foam is required to support load of the part- static loading (KPa) while still absorbing the shock impact. The amount of support given to the packaged item by each mm of cushion. See figure 8 and 9. [7]

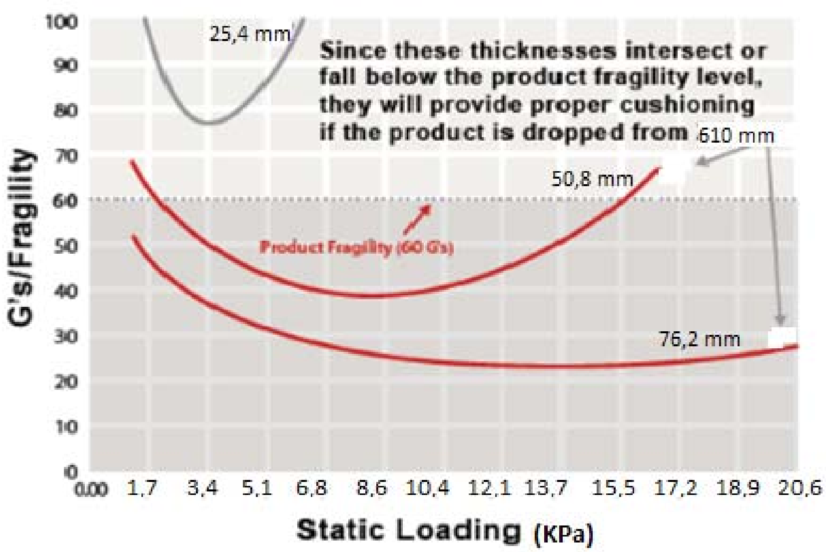


Figure 8. Mechanical static loading results [7]

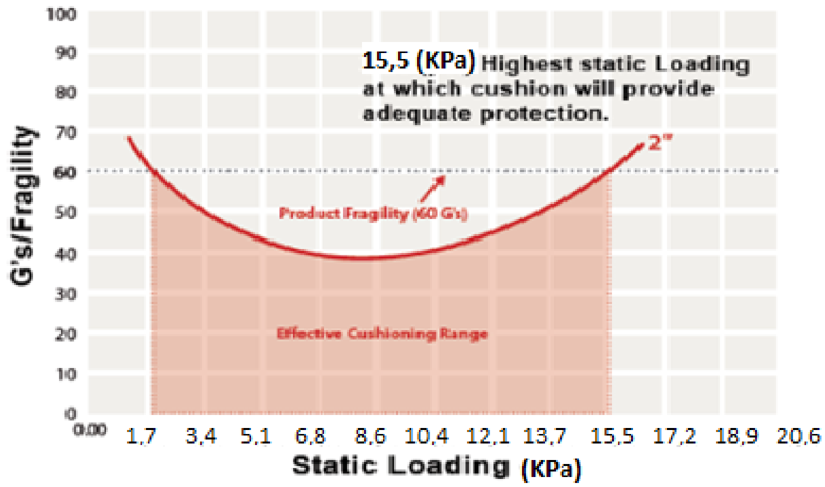


Figure 9. Effective cushioning area [7]

To go even more details to show how it's done. In the following figure 10 it's showing the apparatuses, test standard, size of the specimen etc. See figure 10. [19]

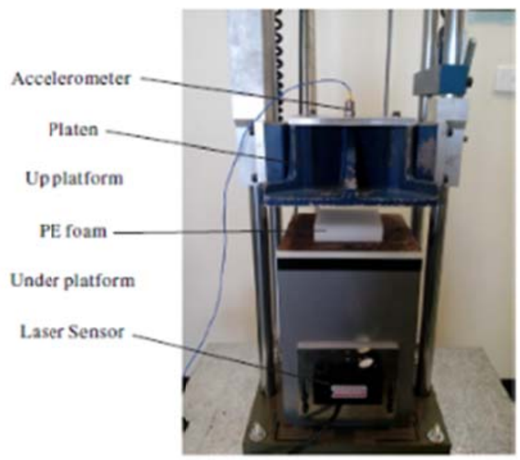


Figure 10. Compression test example [19]

Method to obtain cushion curves of a specific material is described in the American Society for Testing and Materials (ASTM) D1596. [19]
Above picture shows an accelerometer attached to the platen and a laser displacement sensor installed under the plater during the drop of the mass 7kg some height m (three height: 30, 60 and 90cm). The accelerometer measures the impact acceleration. The guides have pneumatic brakes to capture the platen when it rebound after the impact. The impact velocities from respective heights are 2.42, 3.43 and 4.20 m/s. Test is typically conducted five times. [19]

Figure11 is the acceleration and platen position of the cushion test with a drop height of 60 cm for PE foam of 25.4mm thickness and area of $0.01m^2$. [19]

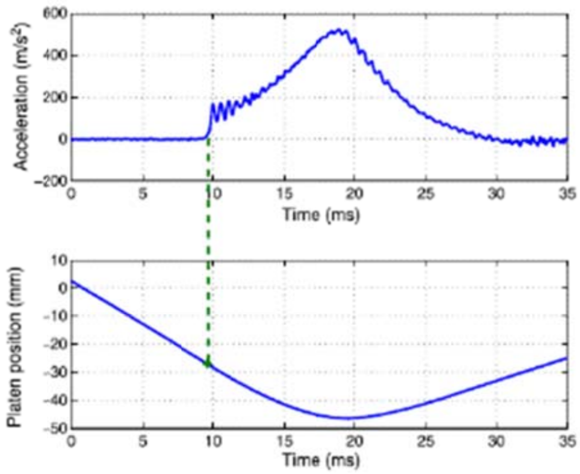


Figure 11. Acceleration results [19]

Continuing on with the compression test example. Taking from the same source, testing of the PE foam (thickness25,4mm and size: 100x100mm). [19]

Compression test had a servo hydraulic universal testing machine by Instron. Capable of crosshead speeds of up to 400mm/s. See figure 12, The cushioning material is between the parallel platens. [19]

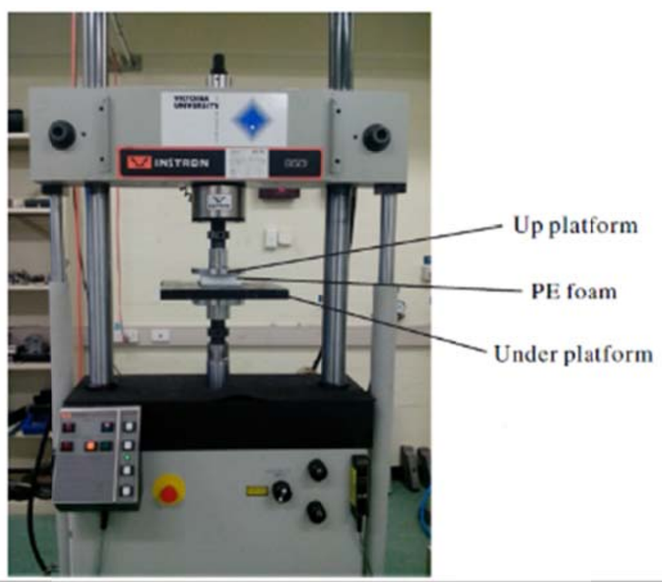


Figure 12. Compression test example [19]

Here, the test was conducted five times under the same condition. Crosshead speed of 0.1, 0.2, 0.5, 1, 2, 5, 10, 50, 200, 300 and 400 mm/s, respectively. [19]

During the compression the cushioning material goes through elasto-plastic deformation figure 13 can be seen the compressive stress with crosshead speed of 1 mm/s for PE foam, where strain represents deflection divided by the original thickness and multiplied by 100%, and stress represents the applied force divided by cushion area. [19]

Following the below figure 13 is shown the tilt at the beginning of the rising curve is showing almost elastic behavior, while the behavior is largely plastic for higher applied stress. [19]

Quite similar to other cushioning materials, like EPS, polyurethane, PE foams and even corrugated paperboard. [19]

Figure 13 The compressive stress properties of the compression test with a crosshead speed of 1 mm/s for PE foam of 25.4mm thickness and area of $0.01m^2$. [19]

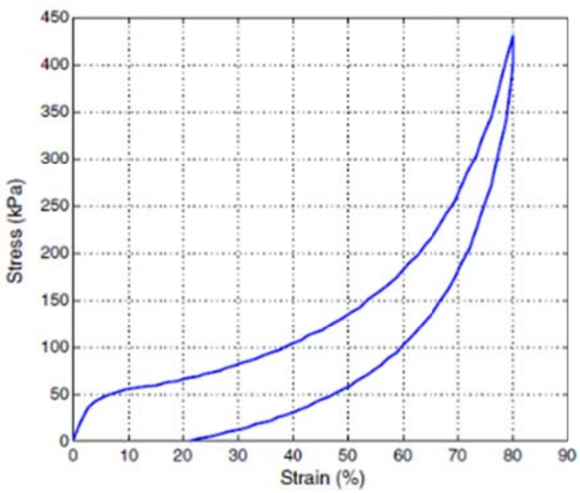


Figure 13. Compressive stress [19]

Before moving on to the next chapter it is little conclusion as of why the bare backgrounds review is not applicable to quickly find out the solution solely based on literature. The need for self-testing for this particular case/project is high as there are many variables which need to be taken account. As many companies who design the packaging solutions for customers are making various engineering tests regarding the design process perspective, as also brought out in this thesis it is mandatory to take into account such things like product weight, g-factor, specific characterization, also the way of transport and physics related threats during it. Also there are just too much variation of electronic devices (for example) in terms of design and in mass etc., also cushion mass, its thickness etc. per different materials that its coming down to be more easier to make those tests than to find the results from literature and to rely on them, moreover that literature is falling short when there is need to find information for packed product testing in terms of different drop height, cushion thickness, product weight etc. and all this exactly for this designed product in question.

2. MATERIAL STRENGTH TESTING

Author determined the dynamic cushioning performance through impact measurement by making drop test (other option for this case is pendulum test), drop tests was made to cushioning material and to packed product. Also was made the compression test. The test results are input to other project member PC simulation. [47]

2.1 Impact testing

Test equipment:

The apparatus consists of a flat based drop hammer (which is adjustable in height wise), mass with 23,3 kg, diameter of 20 cm, and having a surface larger than the test piece, and an anvil whose face is parallel to the base of the drop hammer. See figure 14 of author assembled test rack. And see appendix A.1. for dimensions of the test rack.

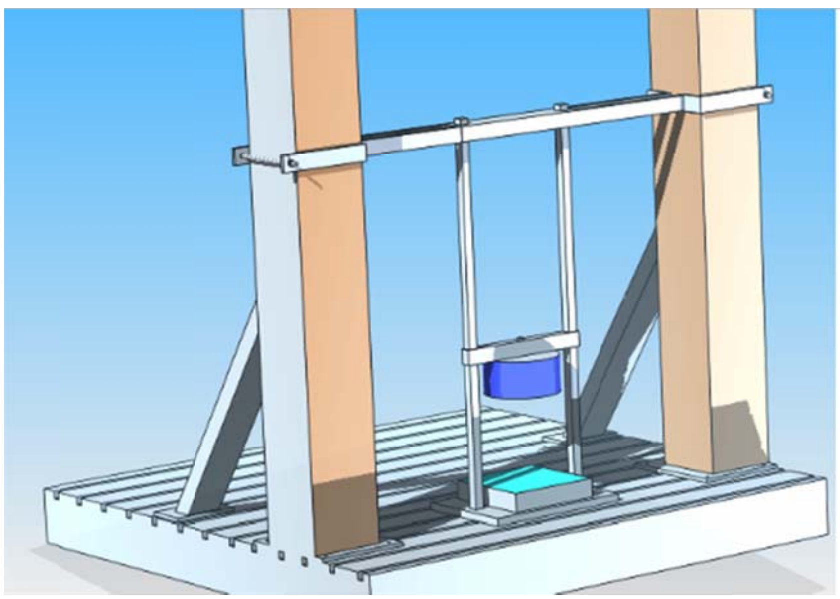


Figure 14. Impact tester

Following figure 15 shows transducer as they are mounted on top of the drop hammer (descending mass). During mounting was used hot glue gun, force transducer is able to measure up to 200g.

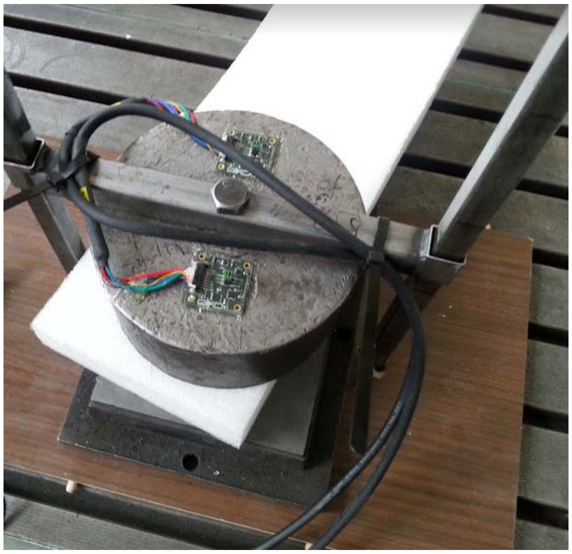


Figure 15. Drop hammer with anvil and two sensors

Transducer is sensor board based, 2 pieces of MEMS (Micro electro mechanic sensor) type sensors are on top of falling hammer. MEMS based capacitive 3-D acceleration sensor. Its connected to data box USB6259 with 16 bit and 1Ms/s data throughput, also with data processing software working with LAbView application for the PC for processing and visualization. The sensor dimension are 4mm, 4mm, 1.45mm. Sensor is measuring by frequency of 2000Hz i.e. within 1s it takes 2000 measurements. The block diagram of the measurement system can be seen in appendix A.2. [20]

See table 9 for description of materials.

Table 9. Description of the materials

Material	**Length (mm)**	**Width (mm)**	**Thickness (mm)**	**Density (kg/m^3)**	**Quantity (pc)**
EPE	100	100	45	30	4
Corrugated cardboard	100	100	45	N/A	4
EPP	100	100	45	35	5
XPS (polystyrene)	90	90	50	30	5
EPS50 (Expanded polystyrene)	100	100	45	50	5
EPS120	90	90	45	120	5
Honeycomb	100	100	20	N/A	5
Granules of EPS standard	150	150	110	N/A	3 bags

Test procedure

- Measure the original thickness of the test pieces.
- Ensure the drop hammer is in safe position.
- The test pieces were placed on the anvil of the apparatus and prepared the drop hammer to impact on the test piece. Impacting of the specimen was done three times at intervals of 60s ± 15s.

After three impacts of the specimen, it was allowed for it to recover 5 min. and remeasured the thickness. Refer to ISO 4651:2000 for more detailed information. [3]

Due to it was hand dropped and graphs were going to have different curves from each other as the drop couldn't be guaranteed to always impact the material the same way (orientation wise) then the constant height was chosen.

Drop height is 250mm, corresponding to free fall impact velocity of 2.21 m/s, drop height which conditions of free fall in vacuo under standard gravitational acceleration.

The equivalent free fall velocity shall be calculated using the equation 1. [18]

$$V=\sqrt{2gn * h} \quad (1)$$

Where V is the final free fall velocity in metres per second.

g is the standard acceleration of free fall, i.e. 9,80666 m/s^2

h is the measured height, in meters, of the hammer above the test piece, referred standard was ISO 4651:2000. [3]

Packaged product impact testing was hand carried and dropped from height of 600 mm. There was carried out 14 drop tests. The drops were directed at flat surface of side 1,2, 3, 4,5,6. Also to the edge of 21, 25, 41, 51, 61. And at corners 236, 345, 346. The referred standard was ASTM D5276. [44]

Onto the box was drawn numbers from 1-6. See figure 16. Example: corner 345 = the corner where side 3, 4 and 5 meet. [1]

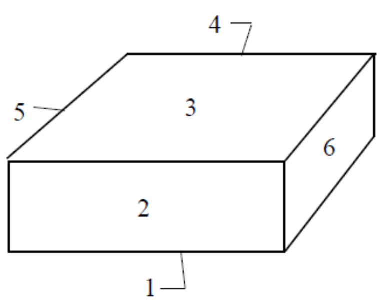


Figure 16. Impact box

Test results:

Data was expressed in the pulse shock wave which plotted to the duration of a shock in milliseconds and its magnitude in units of g (1 g = acceleration of gravity =9.8 m/s^2).

Bubble film was not tested as it was seen that it's not very reliable solution, especially those big bubble films which was tested during compression test, air tightness is rather under question and also to make sure that there is the same level of air in each bubble is another question. See figure 17 and 18.

Firstly it is material testing and then the packaged product testing results.

Figure 17. EPS Granules

Figure 18. EPS granules ready to be impacted

EPS 120 is shown in figure 19.

Figure 19. EPS120 ready to be impacted

EPS50 is shown in figure 20

Figure 20. EPS50 ready to be impacted

Linear cardboard is shown in figure 21

Figure 21. linear cardboard ready to be impacted

EPE is shown in figure 22

Figure 22. EPE ready to be impacted

Honeycomb is shown in figure 23

Figure 23. Honeycomb after the impact

EPP is shown in figure 24

Figure 24. EPP before impact force

Results:

See below figure 25 where from three impacts it is brought out the worst acceleration for each material and put into different comparison and in table 10 is their results in more details. Reminding here that for each material there was done three impacts in a row. So, the shock g gets worse with every impact.

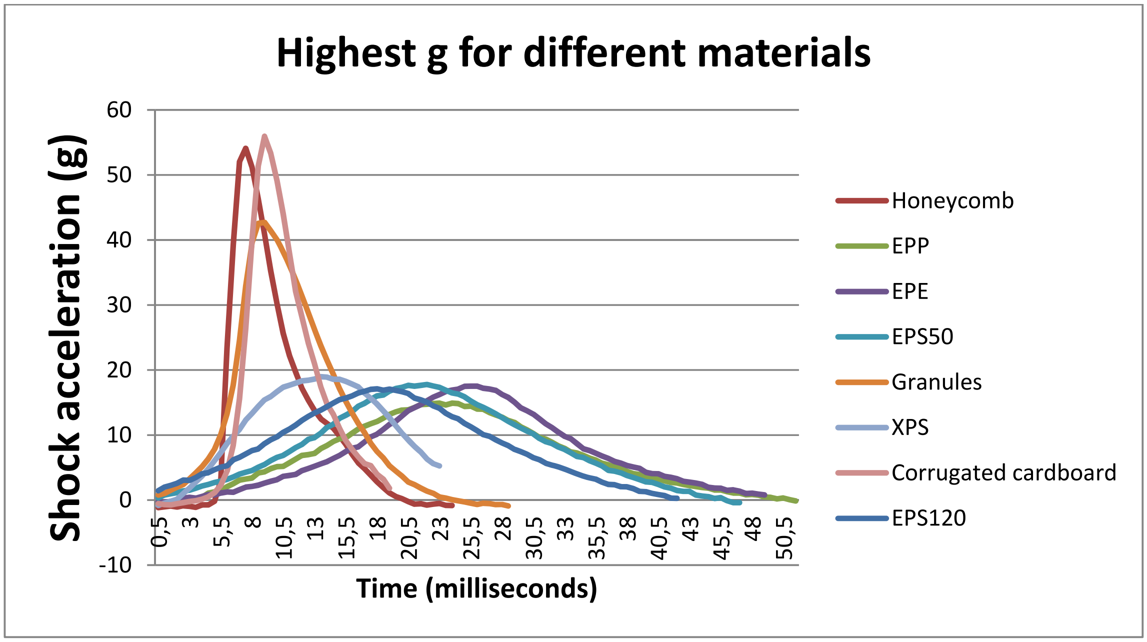


Figure 25. Highest shock for different materials

Honeycomb made the highest shock out of all tested materials, ca 55g (worst case), see figure 26, deformation 75% from original size.

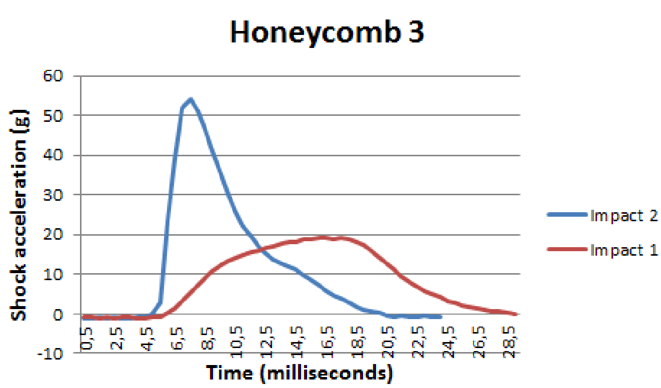


Figure 26. Honeycomb highest shock

Table 10. Materilas highest acceleration and deformation

Material	Highest acceleration g	Deformation (%)	More graphs in Appendix B
EPP	15	6	Figure B.3.to B.6.
EPS granules	42	50	Figure B.14. to B.16.
XPS	18	20	Figure B.17 to B.20.
Corrugated liner cardboard	53	30	Figure B.21. to B.23.
Honeycomb	55	75	Figure. B.1 to B.2.
EPE	18	5	Figure B.7. to B.9.
EPS50	18	7	Figure B.10. to B.13.
EPS120	17	12	Figure B.24 toB.27.

EPS granules were in the bag, made highest 42g. Ca.10 mm was the distance between anvil and hammer surface after the impact. 110 mm was the original size of the bag the granules were in. Bag busted during impact. On granule height originally was 20mm, so those in height wise position did deform 50%.

EPE shock 1 in appendix B. Figure B.7. is showing some possible error in measurement (over 30g), as its other specimens results were around 18 g.

Honeycomb is the stiffest and absorbs shock badly 55g, 75% deformed. Corrugated linear board is in second place of bad shock behavior, also 53g but 30% deformation. And third worse is EPS granules.

EPE, EPP, EPS share similar characteristics of shock absorbing and being best choice in impact wise (drops, sudden collapses against other objects etc.) to avoid product damage during transportation.

2.2 Impacts for packaged product

For impact testing for packaged product 4 pcs sensors were mounted on top of the product, the average result of g factor from those sensors were calculated and plotted to graph against time (ms). Additionally was learned from material impact testing the material testing rack has to be solid, the guidelines through which the hammer drops has to be parallel and aligned and in this case also bit oiled to decrease rubbing.

Results:

The highest g for packaged product was at side 1 resulting 26g (40ms). See figure 27 below, whole shock duration was approximately 50ms long. The lower the milliseconds on peak is considered to be more harsh compared to a high millisecond time (26g/ 40ms is much better than 26g/5ms). This shows how well the shock absorber fitments are performing.

Seems the shock wasn't entirely flat, that's why rising of the pulse is having a step. Impact at such sides like 21, 25,41,51,61 had shock impact below 2g. The shock didn't go over the permitted level of 50g (where product still operates normally and is intact). For the rest of the packed product results, see appendix C, figures C.1. to C.8.

Also as some material level impact testing graphs look the same like EPP and have the same geometry, then can say that when using those materials as fitments in packaged product should come out quite the same results, like for EPE and EPS. Meaning 25kg packed product weight impact could be similar.

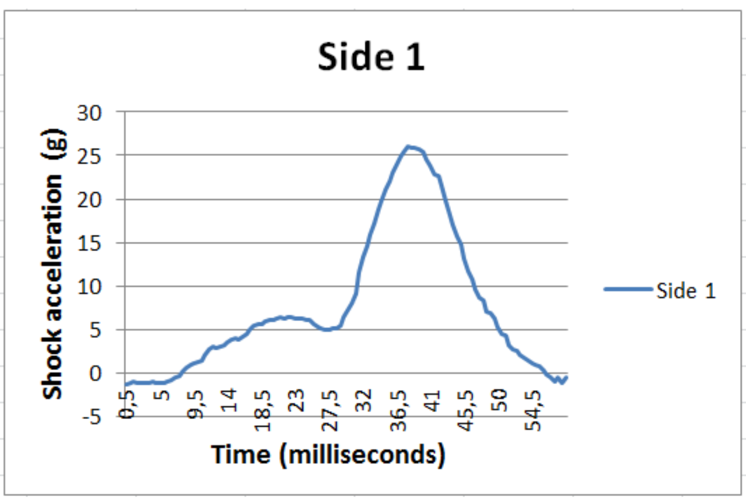


Figure 27. EPP fitment highest impact dropped at side 1

2.3 Compression test

Test equipment:

Was used Instron 5866 electro-mechanical testing system, consisting of two flat plates having dimensions larger than those of the test pieces, with spacers and clamps such that the plates are held parallel to each other and the space between the plates is adjustable to the required deflected height. Equipment was connected to PC using Instron Bluehill software. Was used 10 kN static load cell (loading capacity) as an precision force transducer. See figure 28. [25]

Figure 28. Instron load cell [25]

Description of the materials

Honeycomb, see figure 29 of two facing sheets which are bordering the middle corrugated honeycomb paperboard made of single wall structure with thickness equal to 20mm. Materials description is in table 11.

Paper honeycomb can be die cut, slit scored or cookie cut into numerous sizes and shapes to protect products "inside the box" or "outside the box". Paper honeycomb is a protective packaging alternative to wood, corrugated or EPS. [24]

Material of PE HD is the bigger bubble film, measurement of one bubble, see table 11

Expanded polyethylene foam (EPE), is a molded semi-rigid, non-cross linked and closed-cell type of polyethylene foam. [12]
Expanded Polypropylene (EPP) is also foam based of closed-cell type of polypropylene material, providing good energy absorption, impact resistance, chemical resistance etc. [11]

Table 11. of materials and sizes

Material	Length (mm)	Width (mm)	Thickness (mm)	Density (kg/m^3)	Quantity (pc)
EPE	100	100	45	30	4
EPP	100	100	45	35	5
Bubblefilm (big bubble)	130	60	45	N/A	4
Bubblefilm (small bubble)	100	100	40	N/A	3
Honeycomb	100	100	20	N/A	5

Test procedure

- Measured initial thickness in mm.
- Placed the test piece between the plates of the compression device
- Applied compression load as of flat crush.

All tests carried out on room temperature at 20º C. Refer to ISO 1856:2001. [17]

Test method:

The load and displacement (strain) graphs were plotted by a computer for all tests. The test was stopped when the graph of the test began to decrease after the maximum force.
For EPP, EPE, bubblefilm (with both big and small bubbles) was used test ending parameter compressive load 500N.
For honeycomb was used test ending time of 3 min elapsed, see the results to see maximum achieved compression load during that time.
10kN loading capacity on testing machine Instron at a speed of 1 mm/min. [25]

Test results:

Starting from honeycomb on below figure 29.

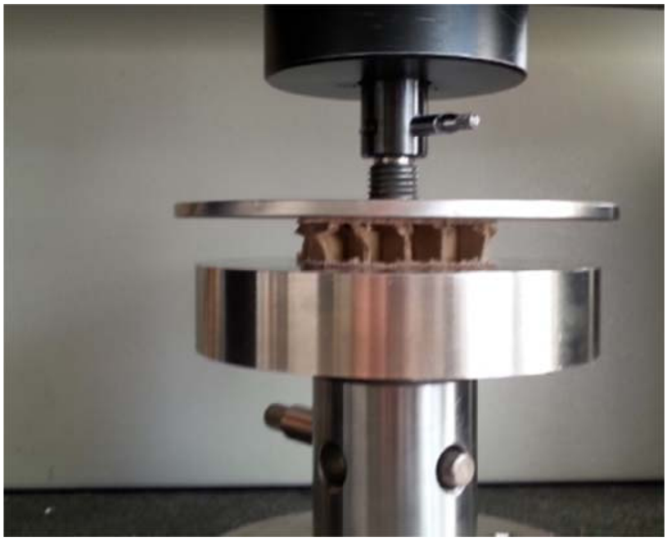


Figure 29. Honeycomb under compression

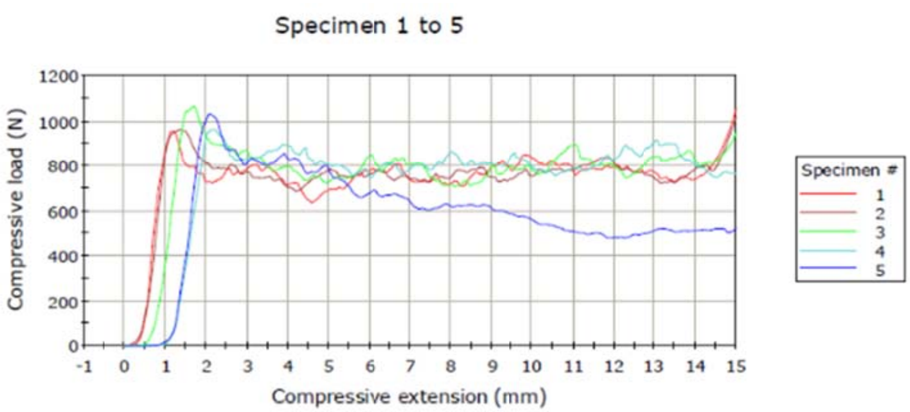
It can be seen comparison of honeycomb before and after on figure 30.

Figure 30. Honeycomb before and after compression

See figure 31 of honeycomb test result. At the beginning of raising curve has elastic deformation (behavior) and near median of ca. 1000 N it deforms.

We can see the material is more easily deformable after that point (ca. 1000N) the graph is not linear anymore, meaning the material has irreversible behavior e.g. plastic deformation, this is the region where the stress does not change with increasing strain- known as the plateau region, the material structure began to collapse at an nearly constant load. See table 10 for honeycomb elastic modulus.

Lastly in the final part is the region (starting from14 mm extension) where the stress curve again starts rapidly to rise with increasing strain, known as densification, at which point the faces of the cells were pressed against each other. [33]



	Maximum Compressive load (N)	Compressive extension at Maximum Compressive load (mm)	Compressive stress at Maximum Compressive load (MPa)	Maximum Compressive strain (mm/mm)
1	1053.21	14.99	0.42	0.75
2	1015.59	14.99	0.41	0.75
3	1062.51	1.71	0.43	0.75
4	961.56	2.20	0.38	0.75
5	1030.82	2.09	0.41	0.75

Figure 31. Honeycomb test results

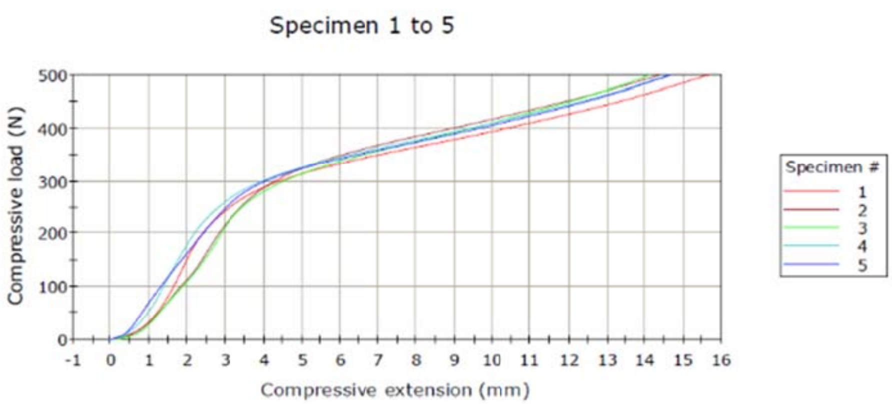
Below table 12 showing elastic modulus, showing the material resistance against deformation, the greater the number the more difficult to deform the material and vice versa. [33]

Table 12. Honeycomb elastic modulus

Modulus (Chord 0.0005 mm/mm - 0.0025 mm/mm) (MPa)	Elastic modulus
0.18	0.18
0.44	0.44
0.01	0.01
0.00	0.00
-0.01	-0.01

EPP testing in figure 32, and results in figure 33 and in table 13.

Figure 32. EPP testing



	Maximum Compressive load (N)	Compressive extension at Maximum Compressive load (mm)	Compressive stress at Maximum Compressive load (MPa)	Maximum Compressive strain (mm/mm)
1	499.63	15.63	0.20	0.52
2	499.24	14.38	0.20	0.48
3	499.49	14.11	0.20	0.47
4	499.29	14.62	0.20	0.49
5	499.50	14.66	0.20	0.49

Figure 33. EPP test result

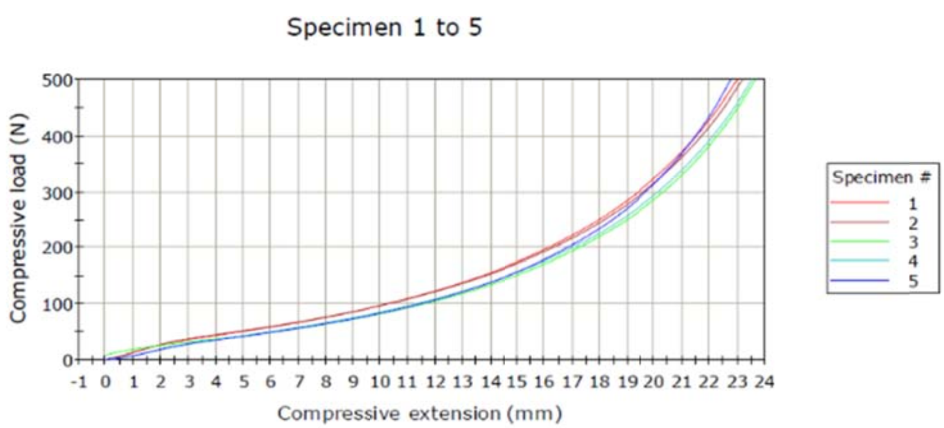
In furthermore comes the EPE result also and then is the conclusion of the curve behavior

Table 13. EPP elastic modulus

Elastic modulus
0.12
0.19
0.09
0.23
0.16

Now the EPE testing in figure 34 below and results in figure 35 and in table 14.

Figure 34. EPE testing



	Maximum Compressive load (N)	Compressive extension at Maximum Compressive load (mm)	Compressive stress at Maximum Compressive load (MPa)	Maximum Compressive strain (mm/mm)
1	499.31	22.98	0.20	0.77
2	499.28	23.17	0.20	0.77
3	498.80	23.63	0.20	0.79
4	499.21	23.52	0.20	0.78
5	498.79	22.74	0.20	0.76

Figure 35. EPE testing results

Table 14. EPE elastic modulus

Elastic modulus
0.12
0.14
0.28
0.06
0.05

As the very elastic behavior from both materials (EPP, EPE), for both the curve is nearing infinity, as for EPE, EPP the compressive strength cannot be seen in terms of where is yield point (above which plastic deformation starts), then can only compare the extension interval and see from vertical axis the corresponding force load. As the deflection of EPE is 5mm the force is 50 N whereas for EPP corresponds to ca. 350 N and one more for example from 10 mm, resulting for EPE as 100N force compared to 400N for EPP. Meaning the EPP needs more force to deflect to same level as EPE, meaning the latter is softer material. Also when doing this testing, the material needs to be even on size, any residue over the edge which touches the platens although lightly but still may alter the result, this shows the sensitivity of the apparatus.

Continuing on with the air films. Thin bubble film in the figure 36 and in figure 37 is it results

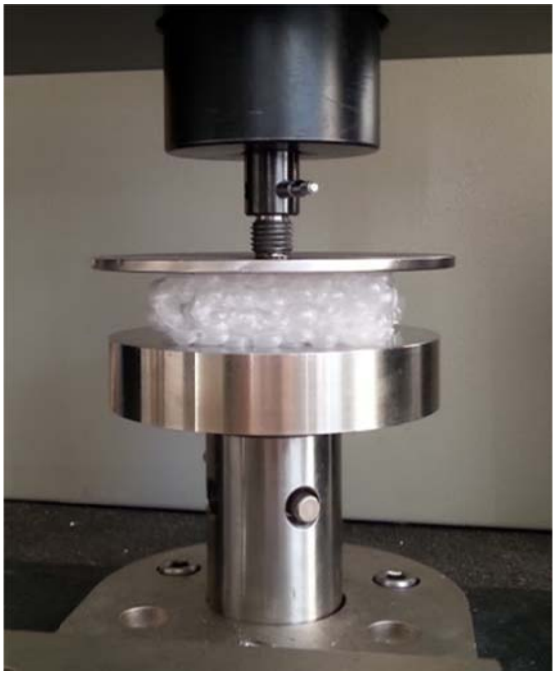
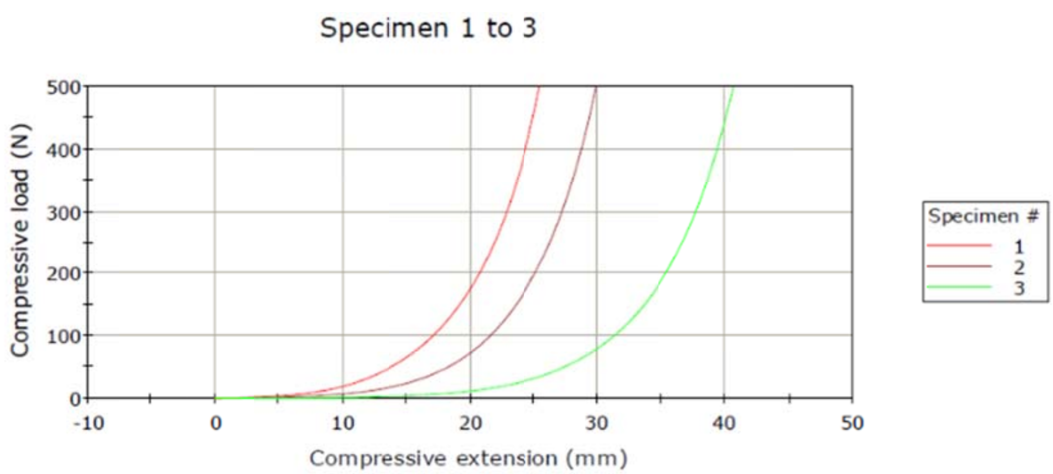


Figure 36. Thin bubblefilm testing

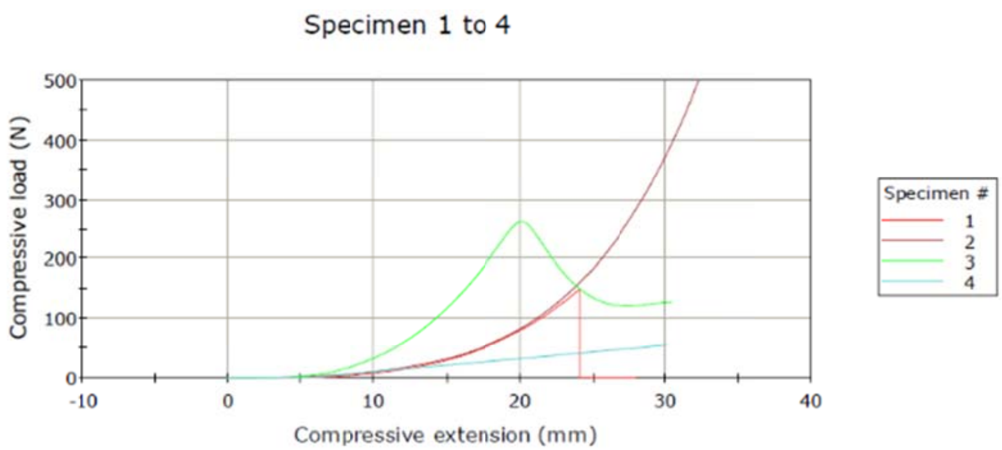


	Maximum Compressive load (N)	Compressive extension at Maximum Compressive load (mm)	Compressive stress at Maximum Compressive load (MPa)	Maximum Compressive strain (mm/mm)
1	499.15	25.43	0.20	0.64
2	498.88	29.83	0.20	0.75
3	498.86	40.59	0.20	1.01

Figure 37. Thin bubblefilm results

The bubble film with big bubble in figure 38 and results in figure 39

Figure 38. Big bubblefilm



	Maximum Compressive load (N)	Compressive extension at Maximum Compressive load (mm)	Compressive stress at Maximum Compressive load (MPa)	Maximum Compressive strain (mm/mm)
1	149.96	24.06	0.06	0.62
2	499.38	32.24	0.20	0.72
3	262.73	20.13	0.11	0.76
4	56.52	30.06	0.02	0.75

Figure 39. Big bubble film results

Concluding from both (thin bubble and bigger one) that it's quite unreliable and to makes sure there is the same air level in bubble compared to each other and in the bigger bubble the air tightness is questionable. Additionally about big bubble specimen the first specimen burst and the rest just deflated under compression.

Results:

From the rest the best material with the smallest deformation EPE, by having biggest elastic modulus 0.77 on average. On comparison EPE, EPP vs honeycomb at the same load of 500N had only deformed ca. 2mm whereas the EPP, EPE had already 15 and 20mm respectively, so at least in static stacking the honeycomb has an advantage.

3. FINDING ALTERNATIVES

The finding of packaging alternatives was done through brainstorming between project members, in total of 22 ideas sketches were generated as a possible new design, based on that the designs were put into evaluation matrix, then was listed different materials for the chosen design with criteria's and based on that they were evaluated. Of course it all depends on exact design around the product which company development have to consider before making final conclusion, but material solution can still be proposed.

As can be seen during new solution (new shape to be) selection, some general idea of material was already included. See figure 40, made by another project member, one piece to each side of the product, density 325 kg/m^3, 680g of one piece.

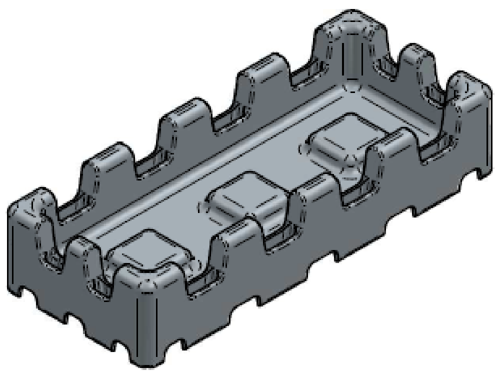


Figure 40. Design of the alternative solution. [47]

Testing of the materials helped for evaluating the alternatives, as some materials are not quite suitable like bubble solutions, honeycomb, liner cardboard, and the evaluation is mostly it's based on subjective evaluation. See table 15 for evaluation matrix.

The criteria's for green were

Effectiveness - delivering the functional requirements, is it reliable that it will support the product. Design should try to avoid using many different types of materials.

Efficiency – material usage, energy and water throughout its life cycle, is it reasonable usage of material. Replacing heavy materials with lighter ones.

Recyclable/Cyclicality - Use of renewable materials, like wooden particles, paper mold. Bio plastic.

Safety - for people and the natural environmental, is it compostable, biodegradable.

And additionally to it the criteria's for the price:

Additional tools (complicity to manufacture) - need of new machines or tools to produce, how complex tools it could need, like 3D machine.

Properties -does the material suit for this solution, for example too rigid material will not absorb shock well. For example big bubble material has air tightness issue.

Weight - material density and material usage, using as little material as possible. Over packing for example with extra or higher density foams, will not solve product damage issue.

Assembling - Difficult to assemble into the box, also like too many objects to put into

The color gradient is changing according to number put in each cell between 1-5. For example red means it's bad for this criteria and the other end of the gradient is green, which means it's very good for the criteria in question. For all related criteria's description also see chapter 1.7.

Table 15. Design evaluation matrix

		GREEN					PRICE					
	Percentage	40%	20%	15%	25%	100%	30%	15%	30%	25%	100%	
Version	Material\properties	Effectiv	Efficien	Cyclical	Safety	Total	Additio	Weight	Asseml	Proper	Total	All tota
Soft pillows in corner	Foam, small particles, wooden	3,5	3	3	4	13,5	4	3,5	4	3,5	15	28,5
Extruded Clamp	(Bio)plastic, paper board	3	3,5	3	4	13,5	2,5	2,5	3	3	11	24,5
Eco pulp	Pulp, recycled paper	3,5	3,5	4,5	4,5	16	4,5	4	4,5	4	17	33
Loose foam particles	Foam	2	2,5	3	3,5	11	3,5	3	4	2,5	13	24
Bubble film	Biodegradable film	2,5	3,5	3,5	4,5	14	3	3	4,5	2	12,5	26,5
Loose thick paper	Paper	2	3,5	3,5	4	13	4	2	4	2,5	12,5	25,5
Tension springs	Plastics, rubber	1,5	2,5	2,5	3	9,5	2,5	2,5	3,5	2	10,5	20
Fiber mesh	Plastics, natural fiber	3,5	2,5	3	3,5	12,5	3	3,5	3,5	3	13	25,5
Inflatable balloons	Rubber, plastic film	3	2	2	2,5	9,5	3,5	3,5	4	3	14	23,5
Brush like fibers	Bio plastics	1,5	3	3	3	10,5	3	3	3	2	11	21,5
Standard foam plates	Foam	4	3	3,5	3,5	14	3,5	3,5	3,5	3,5	14	28
Air tubes	Rubber, plastic film	1,5	2,5	3	3,5	10,5	3	3,5	4	3	13,5	24
Small foam layer+imp reaction mat.	Foam capsules	3	2	2	3	10	2,5	2,5	4	4	13	23
Thick cardboard honeycomb	Card board	2	3	3,5	4	12,5	4,5	3,5	4	2,5	14,5	27
Magnetic leviation	Permanent magnets	2	3,5	3	3	11,5	1,5	2	2,5	3	9	20,5
Poroloon, contact	PUR	3	3	3	3	12	4	3	4	4	15	27
Pressure Balls	Tennis ball, foam ball	2	3,5	3,5	3	12	4	3	4	2,5	13,5	25,5
Foam sticks	Foam	2,5	3,5	3,5	3	12,5	4	3	3	2,5	12,5	25
4 products packages	Cardboard and foam	3,5	3,5	3	3,5	13,5	3,5	2,5	4	3	13	26,5
Minimize the material usage and cover with bubble film	Foam or other material	4	4	3,5	3,5	15	4	4	4	4,5	16,5	31,5
Foam fitments top and bottom	Foam	4,5	4	3,5	3,5	15,5	4,5	5	4,5	4,5	18,5	34

In table 16 is the best design material evaluation matrix. Of course the concrete material choice depends of the design and has to be evaluated from development side by the company.

Table 16. Material evaluation matrix

	GREEN					
	30%	**10%**	**7,5%**	**12,5%**	**60%**	**40%**
Material	**Effectiveness**	**Efficiency**	**Cyclicality**	**Safety**	**Total**	**Price**
Eco pulp (Egg box), fiber moulded pulp	4	3,5	4,5	5	17	5
EPP	4	4	4,5	3,5	16	3
EPE	3	2	4	4	13	4
PUR	1	2	4	4	11	2
Corrugated Card board (liner cardboard)	1	5	4	5	15	4
Honeycomb	3	4	5	5	17	4
PET	1	1	4	3	9	5
PCL	3	5	4	5	17	1
PLA	4	4	5	5	18	2

Results of it is below in table 17.

Table 17. Results of material evaluation

	30%	**10%**	**7,5%**	**12,5%**	**60%**	**40%**	
Material	**Effectiveness**	**Efficiency**	**Cyclicality**	**Safety**	**Total**	**Price**	
Eco pulp (Egg box), fiber moulded pulp	1,2	0,35	0,3375	0,625	2,51	2,00	**4,51**
EPP	1,2	0,4	0,3375	0,4375	2,38	1,20	**3,58**
EPE	0,9	0,2	0,3	0,5	1,90	1,60	**3,50**
PUR	0,3	0,2	0,3	0,5	1,30	0,80	**2,10**
Corrugated Card board (liner cardboard)	0,3	0,5	0,3	0,625	1,73	1,60	**3,33**
Honeycomb	0,9	0,4	0,375	0,625	2,30	1,60	**3,90**
PET	0,3	0,1	0,3	0,375	1,08	2,00	**3,08**
PCL	0,9	0,5	0,3	0,625	2,33	0,40	**2,73**
PLA	1,2	0,4	0,375	0,625	2,60	0,80	**3,40**

As can be seen the molded pulp has got the highest score and should be concentrated as alternative solution.

Little description of molded pulp:

Typically it's made out of recyclable papers or other natural plant fibers (which are essentially cellulose), they are recyclable along with other waste paper, are biodegradable, and compostable where needed facilities are available. [50]

The fiber choice is important, as the properties of fiber used will greatly influence the characteristics o the final product. Identical packaging structures made of different type of fibers will result product with different performance.

Raw material with long fibers will develop greater strength; short fiber based raw fill produce mold pulp which are more rigid. [16]

The fiber and water both are recycled and can be reused in manufacturing, meaning almost zero waste. [34]

3.1 Testing of alternative

Molded pulp is much dependent on shape (geometry), thickness and specific manufacturing process (long/short fibers used etc.), uniformity of wall thickness.

Following is the tensile testing of molded pulp

Test equipment:

Epsilon technology Extensometer for strain measurement in materials testing (epsilontech.com)

Tinius olsen electromechanical tension testing machine. [49]

Description of the materials

9 pcs specimens was tested, dimension were: thickness 1,4 mm, length 100 mm, width 15 mm. Distance between clamps was 50 mm.

Test procedure

- Measured initial thickness in mm.
- Placed the test piece between the clamps, ensuring that the test area between the clamping line is not touched with bare hands.
- Ensure that the test piece is clamped in such a manner that it is parallel to the direction of application of the tensile force. Commenced the test and continued until the test piece breaks. Recorded the maximum tensile force, referred to ISO 1924-2. [39]

The rate of elongation for first 4pcs was set to 20mm/min and for 5pcs to 100mm/min. Figure 41 shows pulp mold testing.

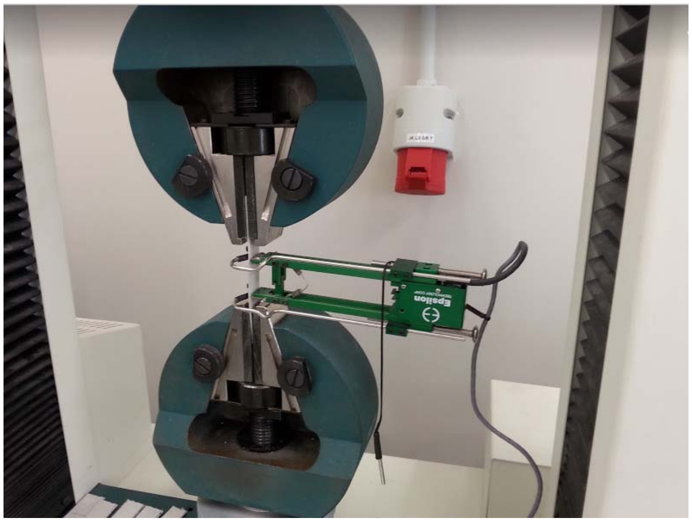


Figure 41. Tensile testing of molded pulp

Test results:

The table 18 shows results when using speed of 20mm/min

Table 18. Tensile strength at 20mm/min

Specimen	E-Mod MPa	Elongation %	Yield MPa	Tensile MPa
1	2216	1,156	10,01	10,01
2	2281	0,946	10,53	10,53
3	2203	0,536	8,05	8,05
4	1466	0,888	4,05	6,85

Elastic module mean is 2041 MPa

See appendix D, figure D.1. of figure of the 20mm/min elongation speed results graph.

In comparison the table 19 shows the specimen results at 100mm/min

Table 19. Tensile strength at 100mm/min

Specimen	E-Mod MPa	Elongation %	Yield MPa	Tensile MPa
1	2403	0,752	10,12	10,12
2	1868	0,674	7,23	7,23
3	1926	0,776	8,72	8,72
4	3029	0,658	11,90	11,90
5	2477	0,558	5,90	9,47

The average elastic modulus is 2341 MPa

See appendix D.2. of the 100mm/min elongation speed results graph.

The properties of the molded pulp in tensile strength (max stress it can bear before breaking) at speed of 20mm/min is 8,86 MPa on average and at higher speed of 100mm/min it is 9,5 MPa. Yield MPa, point where deformation is recoverable. [48]

As the force reaches the elastic limit (elastic deformation) the stress increased with strain enhanced, when the force reached the critical point, then molded pulp cracked, the stress-strain curves rapidly declined (force decreased rapidly).

Although the specimens were cut from same package the uniformity of the specimen, as in terms of wall thickness did vary from 1,35mm to 1,40mm. Also have to watch out that as thin materials as this couldn't be damaged by extensometer when attaching the extensometer to test specimen.

It's quite necessary to make additional investigation of mechanical properties when pulp mold is used in transportation and cold storage.

The pulp mold material suitability also from literature is seen to be for ≤ 5kg product weight.

Yokogawa electronic company investigated the pulp mold material by having it designed for the product and then made packed product testing and came to conclusion that they use pulp mold packaging for products weighting 5kg or less (that are manufactured at least for quantities of 300 per month and can withstand drop from 120cm, 588 m/s^2), this is because the cushion of pulp mold cannot stand a impact drop (from 1m) of the product that is heavier than 5kg of weight. [31]

But when blending some materials into molded pulp, for example possibility of polyolefin and waste paper synthesize in ration of 95% and 5% of polyolefin can very well support heavier product, even up to 30kg. [2]

Of course company needs to investigate this all from design aspect before making the final conclusion.

Also other alternatives should be investigated in the future, like there is the PLA (Polylactic acid), which is biodegradable thermoplastic, can be warped from crops such as maize. [41]

Also very interesting is the mushroom packaging, which is high performing, non-abrasive, home compostable. 72[9]

4. COST DIFFERENCE BETWEEN MATERIALS

In this chapter is considered material costs per some example of demand quantity. Then is the line capability though cycle time, followed by packaging line cost calculation per month and for one product.

Here in below figure 42 is the cost of the current packaging material, as can be seen the fitment cost is the biggest.

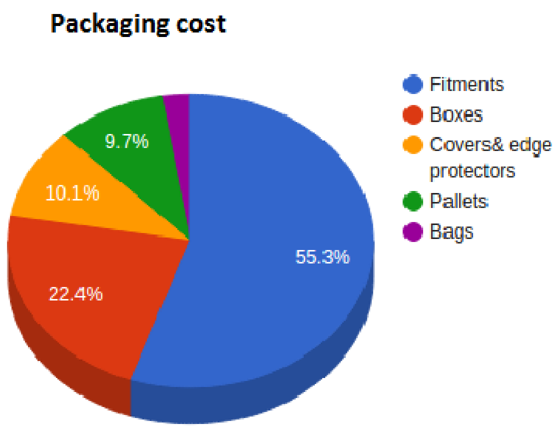


Figure 42. Packaging cost distribution

Now this same figure is taken down to materials used as fitments, as can be seen from figure 43

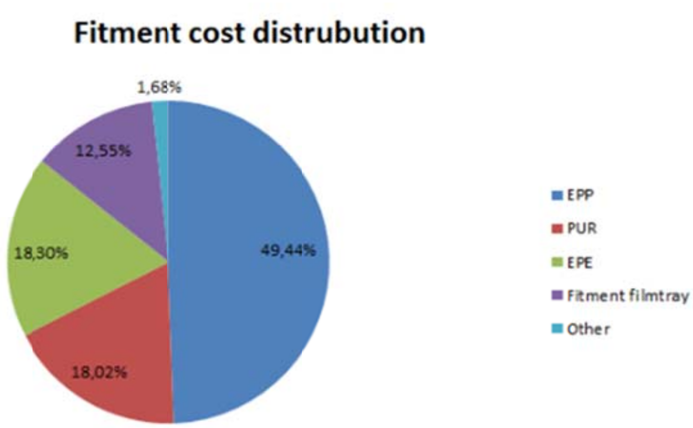


Figure 43. Fitment cost distribution

Top 2 materials which generate cost are EPE and EPP, figure illustrates both material cost from total sum of fitment cost.

Under other material is polyethylene based line paper and also corrugated fitment. For simplification later on it's compared alternative materials just to EPP and EPE.

Below it the top 4 products which generate cost, figure 44 shows taking account all packaging material for those products.

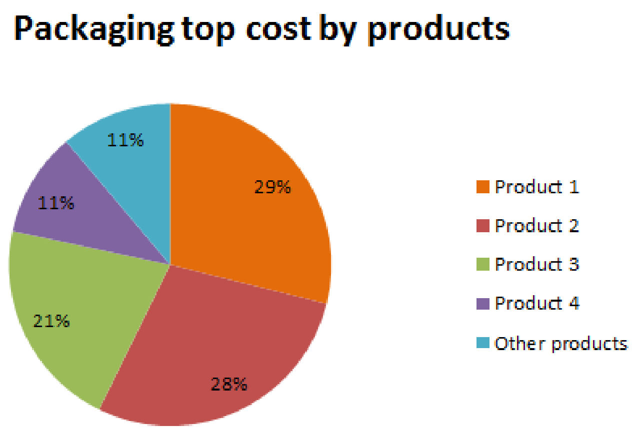


Figure 44. Packaging top cost by products

When narrowing it down to material use for top 3, EPP is for all three products. Product 1 and product 2 use the same fitment (same design). And product 3 uses another design. As the design and the mass between those products is different then the following example calculations is taken for product 1,2 to have comparison.

Here is the comparison of cost of buying the material for current vs some of the alternatives which can be used. Table 20 below shows different materials cost table.

Table 20. Material cost table which to compare against existing.

Material	**Price**
Eco pulp (e.g.used in egg package), fiber molded pulp	0,5 €/kg
EPP	12 €/kg
EPE	16 €/kg
PUR	3,5 €/kg
Corrugated Card board (liner board)	1,2 €/kg
Honeycomb	Depending of the size of the comb and plate thickness.
PET	0,7 €/kg
PCL	4,5-6 €/kg
PLA	8 €/kg

As the honeycomb need real design to say the price, then it will be coming under consideration when it happens to turn out to be chosen design.

The volume of the current fitments solution (for product 1,2) per one product is 0,0214m3, or mass of 0,750kg.

The cost of different examples of the quantity which might be needed, remarking that cost is per eur or per dollar depending on corresponding cost unit in price columnn.

Also in the same table is calculations to new design. New fitment usage is 1360g per product, one side is using 680g. Material cost in different quantity examples is in table 21.

Where the prices are taken can be seen in reference, mostly it was handled from Alibaba.com, Bioplastic.com and ocw.mit.edu. [32]

Table 21. Material cost in different quantity

		Existing solution		**New design**	
Material	Price	Price of needed qty for 1000pcs product	Price of needed qty for 10000pcs product	Price of needed qty for 1000pcs product	Price of needed qty for 10 000pcs product
Eco mold pulp (e.g.used in egg package)	0,5 €/kg	375	3750	680	6800
EPP	12 €/kg	9000	90000	16320	163200
EPE	16 €/kg	12000	120000	21760	217600
PUR	3,5 €/kg	2625	26250	4760	47600
Corrugated Card board (liner board)	1,2 €/kg	1050	10500	1632	16320
Honeycomb	Depending of the size of the comb and plate thickness				
PET	0,7 €/kg	525	5250	952	9520
PCL	4,5-6 €/kg	3750	37500	6800	68000
PLA	8 €/kg	6000	60 000	10880	108800
XPS	3,8 €/kg	2850	28500	5168	51680

5. PACKAGING PROCESS FOR CURRENT AND NEW SOLUTION

The flow of the packaging process with operation times. All times have confidential margin included.

The used content for packaging consists of following: box, tape, fitments, product labels, pallet, and top cap. Table 22 shows current solution process time.

Table 22. Current solution process

№	Task description	Figure reference
1	Bring pallet of ready products to packaging line	NA
2	Check the presence and integrity of the packaging material, also the needed accessories for it. Take the box and open it up and seal the bottom sleeves with tape, one strip lengthwise and one strip on each short side edge	Figure 84
3	Place bottom fitments: Put into the box the right side fitment and left side fitment	Figure 85-86
4	Scan the product in PC software to print out label for shipping. Put the label on the box.	NA
5	Put the product from pallet into the box	Figure 87
6	Put two fitments on top of the product	Figure 88
7	Close the box and seal it with tape, one strip lenghtwise and one strip on each short side edge. Put label on top of the box.	NA
8	Lift the box to the pallet.	NA
9	Assy lid + strapping of ready pallet	NA
10	Take ready pallet to warehouse	NA

Cycle time, the sum of all individual operation times is calculated through the following equation 2. [5]

$$T_{TK} = \sum_{i=1}^{m} Top_i \qquad (2)$$

Cycle time is summary of all operations = 240seconds. See table 24 for cycle time

Table 23. Current solution process time

Operators (qnty)	Cycle time (s)	Products packed per hour (pcs)	Products packed per month (pcs)	Allowances (s)	Real production time	Line efficiency
1	240	15	2520	20	260	92%

So, every ca 240s. there will be one product packed.

15pcs product packed in an hour

Now, for month it means, there is 168h per month, meaning 604 800 seconds. Maximum packaging capability is then ca. 2520 pcs per month.

Line efficiency = production time/real production time [30]

Actual production time involves allowances like: additional time it takes to pack, like transportation of materials, calibration etc. In this case it will be about 20 second of average on 1pc per product. This makes than 260 second of packaging on average one unit. Herewith line efficiency equals 240/260 = 92%

For packaging line cost see economy calculations in chapter 4

Below figures 45-49 illustrate to better understand some packaging operations.

Figure 45. Prepared box [4]

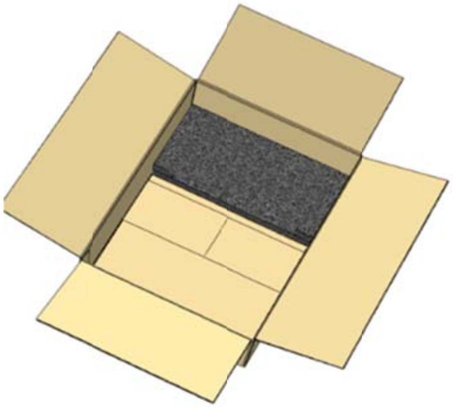


Figure 46. Fitment to the right side

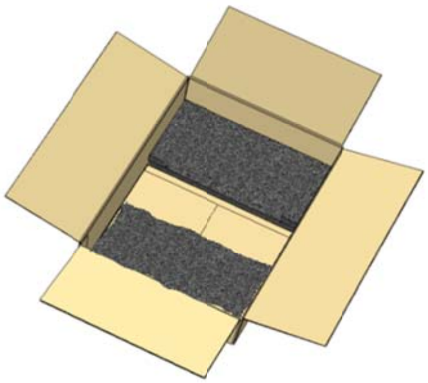


Figure 47. Fitment to left side

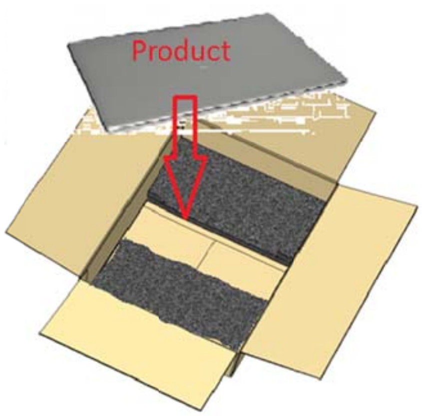


Figure 48. Product insertion

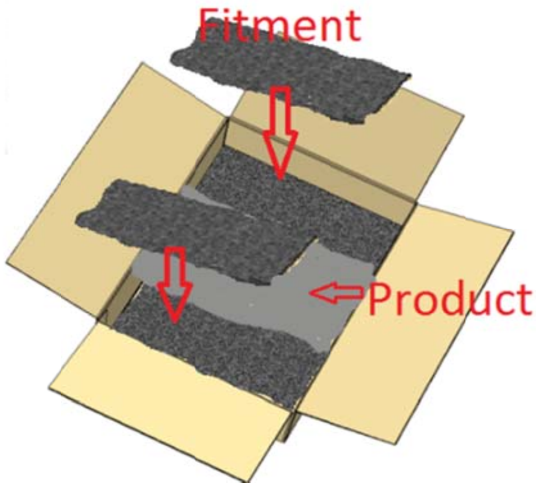


Figure 49. Top fitments

Now about the changes for operation regarding new solution, like previously brought out key steps in pictures.

Just to remind the fitment was changed, the box is the same. See figure 50-52.

Figure 50. Fitments around the product [37]

Figure 51. Cushioned product above box [37]

Figure 52. Packed product [37]

Additionally to propose of design change the proposal would be to add to the line operator 2 and then see the comparison in cycle time and economy calculations.

Below in figure 54 is the layout, it also includes the operator 2, and with red is marked the product flow

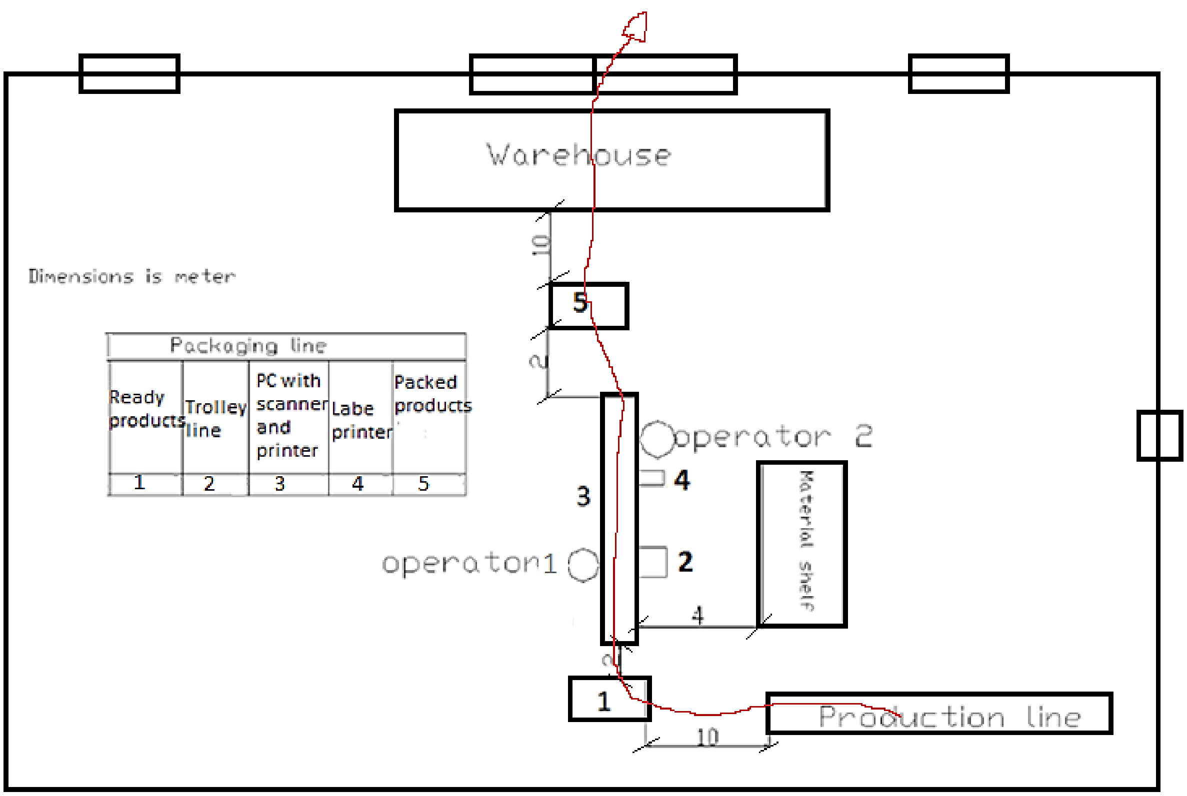


Figure 53. Process layout

The operation process of new design can be seen in table 24.

Table 24. Changed design solution process

№	Task description	Figure reference
1	Bring pallet of ready products to packaging line	NA
2	Check the presence and integrity of the packaging material, also the needed accessories for it. Take the box and open it up and seal the bottom sleeves with tape, one strip lengthwise and one strip on each short side edge	Figure 89
3	Place two fitments on each side of the product	Figure 90
4	Scan the product in PC software to print out label for shipping. Put the label on the box.	NA
5	Lift the product from pallet into the box	Figure 91
6	Close the box and seal it with tape, one strip lenghtwise and one strip on each short side edge. Put label on top of the box.	NA
7	Lift the box to the pallet.	NA
8	Assy lid + strapping of ready pallet	NA
9	Take ready pallet to warehouse	NA

Compared to existing one, one operation was removed, where two fitments were needed to put on top of the product. Table 25 and 26 show comparison between additional operator.

Table 25. Cycle time of new process using one operator

Operators (qnty)	Cycle time (s)	Products packed per hour (pcs)	Products packed per month (pcs)	Allowances (s)	Real production time	Line efficiency
1	220	16	2749	20	240	92%

Table 26. Cycle time of new process using two operators

Operators (qnty)	Cycle time (s)	Products packed per hour (pcs)	Products packed per month (pcs)	Allowances (s)	Real production time	Line efficiency
2	110	32	5498	10	130	84%

So, the sum of operation times is 220s and for two workers it is: 110s . Meaning after every 220s there is product packed and in warehouse, and with two operators it's after every 110s. Meaning compared to existing design solution it is 20s less when using one operator . And when using two operators it is 130s less (50% less time). How it affects whole packaging cost calculations can be seen on chapter: 5.1

So, taking account using two operators, its Cycle time is 110s

So, every ca 110s. there will be one product packed.

32 pcs product packed in an hour

Now, for month it means, there is 168h per month, meaning 604 800 seconds. Maximum packaging capability is then 5498 pcs per month.

So if needed on higher demand the line capability can be increased by adding one extra person.

Line efficiency = production time/real production time [30]

Actual packaging time involves allowances like: additional time it takes to pack, like transportation of materials, calibration etc. In this case it will be bit shorter about 20 seconds of average on 1pc per product, production. It can be calibration and transportation etc. This makes then 130 seconds of packaging on average one unit. Herewith line efficiency equals 110/130 = 84%

5.1 Packaging cost

Firstly about existing solution. One unit packaging time is 240 seconds. If monthly packaging is 2520 boxes. Table 27 shows cost of packaging for existing solution.

Table 27. Packaging cos for existing solution

Operators (qnty)	Cycle time	Workmanship cost (€)	Electricity+utilities (€)	Packaging material (€)	Cost per one box (€)
1	240	1260	3000	13,40	15

There are 1 worker on line. This is 168 working hours. If cost for one worker is 5 euros per hour it will make 840 euro per month. Plus we can roughly add to here another 50% of cost (social security tax, vacation pay, cost from tools/cloths etc.), summing to total ca 1260 eur/month. [29]

To keep machines running, electricity and other utilities is about 3000 euros per month

Material for one packaging set (to pack one product)

Tape for one box is 1,3m, one meter costs 0,013 euro, making per one box: 0.0170 euro. [32]

Fitment cost: 9 eur per product, see chapter 4

Product label: 0.007 eur/pc. [32]

Pallet cost: 3,5 eur. [32]

Box cost: 0.90 eur. [32]

Total: 13,40 eur

All total for 2520 boxes per month is 37 760 euro, for one box it is 15 euros on average.

For new fitment

Now the same calculation for use of new fitment

As the change proposal would be to use two operators, to see the difference in cost is in table 28 and in table 29.

Table 28. Packaging cos for new solution

Operators (qnty)	Cycle time	Workmanship cost (€)	Electricity+utilities (€)	Packaging material (€)	Cost per one box (€)
1	220	1260	3000	4,60	5

Table 29. Packaging cos for new solution

Operators (qnty)	Cycle time (s)	Workmanship cost (€)	Electricity+utilities (€)	Packaging material (€)	Cost per one box (€)
2	110	2520	3000	4,60	6,1

Then after the new design implementation and using two operators will be:

One unit packaging time is 110s. If monthly packaging is 5498 products

There are 2 worker on line. This is 336 working hours. If cost for one

worker is 5 euros per hour it will make 2520 euros per month (including previously mentioned 50% extra).

To keep machines running, electricity and other utilities is about 3000 euros per month
Material for one packaging set (to pack one product)
Tape for one box is 1,3m, one meter costs 0,013 euro, making per one box: 0.0170 euro [32]
Fitment cost 0,68€/product, see chapter 4
Product label: 0.007 eur/pc. [32]
Pallet cost: 3,5 eur. [32]
Box cost: 0.90 eur. [32]
Total: 5,1 €

All total for 5498 boxes per month is 33559 €, for one box it is 6,1 € on average.

Even when leaving out the second operator, the difference which design change makes can be seen as following: 16pcs packed in hour.

Total of 5,1*2749pcs= 14019€ and plus 1260+3000= 18279 €
All total for 2749pcs boxes per month is 18279€, for one box it is 6,6 € euros on average.

Even when having the lower line efficiency as of two operators (as 84 vs 92% with two operators) to have higher productivity (240s vs 110 s per product) the cost still pays by having 56% of lower price per unit.

6. CONCLUSION

The main objective of this research was to propose to Company the alternative packaging cushioning material which would be cheaper and if possible also to be more environment friendly as current material is plastic foam of EPP or EPE, for this it was carried out strength testing.

In compression test honeycomb had best stacking behavior of the rest, at 500N had only deformed ca. 2mm whereas the EPP, EPE had already 15 and 20mm respectively, also was found out that bubble films are unreliable as they usually deflate or burst. The compression test alone is not enough to compare, also impact testing was made- honeycomb showed stiff behavior resulting 55g acceleration (worst case), deformation for honeycomb was 75% from original size. Corrugated linerboard is in second place of 53g but 30% deformation. And third worse is EPS granules with 42g. EPE, EPP, EPS around 15g and on average 6% deformation share similar characteristics of shock absorbing and being best choice to avoid product damage during transportation. Meaning too rigid and too bubble like material is not suitable alternative.

The highest g for packaged product test of EPP (current material) was at side 1 resulting 26g (40ms). As some material level impact testing graphs look the same like EPP and have the same geometry, then can assume similar behavior for EPE and EPS. Meaning 25kg packed product weight impact could be similar.

Solution to suggest is molded pulp (essentially cellulose) compared to current material it is 60% cheaper per one unit packed from total packaging cost, it was calculated through process review and analysis for both option, whereas cycle time difference was 240 vs 220s (for new solution). Also the molded pulp is biodegradable, compostable, although was found that product weight around for 5kg product its applicable, but for weight of around 30kg its needed to blend it with other materials to make it stronger, of course Company development have to take into account the design in addition to proposed material solution to make final conclusion.

7. SUMMARY

This research study is giving idea about packaging design which aspects needs to be taken into account in material strength testing, line capability wise and packaging cost.

About material testing, firstly in general was found out that too rigid materials (such as honeycomb, liner paperboard) are having trouble meeting needs for transportation- to avoid damaged product during distribution, especially in shock wise being too stiff.

Also any bubble-like material is out of the question also, as this solution not only is prone to various spiky product edges, but as testing showed they are unreliable in terms of air, it is unevenly in each bubble, and its airtightness showed no better side, as in many cases it just deflated under pressure.

It's difficult to extrapolate the impact behavior (graph) of the foam inside the box to different packed foam material (nonlinear physics), but it's possible to assume the similar behavior based on material level testing when those particular materials are same in geometry and material level testing results were similar, which this study did and found out that EPS, EPE, EPP should have similar behavior when used as cushioning in packed box, also as the shock acceleration highest margin was 26g (40ms) for packed product using EPP (similar could be for aforementioned materials) of 25kg packed product. The lower the milliseconds on peak is considered to be harsher compared to a high millisecond time, also it didn't go over of the permitted 50g of the product functionality (fragility) level.

During the compression testing best cushioning material out of tested ones which deformation was smallest is EPE however at the 500N the honeycomb deformation was only 2mm whereas EPE had at the same loading already ca. 15mm extension. But as seen in impacts the honeycomb is too stiff and worst energy absorber, the EPS, EPE and EPP was the best choice in those comparison testing which gave rather good input to evaluation matrix to exclude some of the alternatives. It was learned that materials needs to be cut evenly for the compression, parameters of tester has to be thought out in accordance of material features, as for example the test ending criteria for honeycomb differ from standard foam.

Additionally was learned during drop testing of packed product not to drop to unwished position like impacting edge and corner simultaneously as cushioning performance might be altered by hand dropping, as the impact load might not drop every time evenly although admittedly that's what could happen in reality (not even by hand carrying).

Although more solid specialized impact drop equipment could be used, nevertheless the results were acceptable. During testing was also learned that there is no linear behavior of material thickness and g value.

Based on material testing, evaluation matrix by solution brainstorming, simulation carried out by other project member and literature it was came to conclusion that alternative design of material of molded pulp which is compostable, biodegradable is suitable replacement. Although further literature study showed that it is true for 5kg product, but adding additives, by blending it for example with polyolefin has proven to support products even of 30kg. Also was found out that molded pulp is much dependent on shape (geometry), thickness and specific manufacturing process (long/short fibers used etc.), and uniformity of wall thickness. It's quite necessary to make additional investigation of mechanical properties when pulp mold is used in transportation and cold storage.

Also study shows how much new design and changes to packaging line can really change the cost. Can see the material cost calculations, as result, the EPE is the most expensive fitment. Then it's also brought out how material cost affects the whole packaging cost per one product where in total cost was taken into account calculations from line capability (cycle times) and other cost (like workmanship, electricity etc.) and made comparison between those two. The results of packing times were 240s vs 220s (with new solution) per product, meaning 15 vs 16 pcs/h, thanks to material change to cheaper alternative the cost difference was ca 60% of cheaper packaging total cost per one packed unit, and in it the new design is 45% heavier.

So, it was indeed found out to have cheaper material and also be applicable, of course Company have to take into account the design development in addition to proposed material solution to make final conclusion.

Huge potential here for possible continuation to so called build upon those results presented in this work, to study even further those mechanical properties in various conditions, including the chemistry properties, climatic, do testing for mechanical static loading, make boxed product compression test etc. Alone from the perspective that the project continues, so can make more research based on this regarding the existing project or why not even for another project.

8. KOKKUVÕTE

Käesolev uurimistöö annab ülevaate pakendi disainimisel vajaminevatest üksikasjadest ning protsessidest nagu materjali tugevuskatsetused, pakkeliini tootlikus (ja efektivsusest) ning pakkimiskulud.

Esiteks on ülevaade materjali katsetamisest, kus leiti jäikade materjalide (nagu kärgpapi, lainepapi jms.) mittesobivuse vastamaks transpordil esitatavatele nõuetele, mille eesmärgiks on vältida toote kahjustamist. Nende materjalide miinusteks on see, et nad jäävad just löökkoormustele liiga jäigaks.

Lisaks peab välistama mull-materjalide sobilikkuse, kuna nad on altid toote teravate otste kahjustustele.Testimisel selgus ka nende ebausaldusväärsus õhupidamises. Mulliti on erinev õhutase, lisaks surve all mitmed mullid lihtsalt tühjenesid.

Sai selgeks, et on keeruline ekstrapoleerida erinevate materjalide graafilist käitumist pakendatud tootega tehtud graafikul kuju jaoks, aga kui on teada materjalide sarnane katse graafik ja kui materjalid on geomeetriliselt sarnased, on võimalik oletada nendele ka sarnast pakendatud katse testi graafikut. Seda selles uurimustöös ka tehti ning leiti nendeks materjalideks olevat EPS, EPE, EPP, lisaks saavutati EPP pakendatud toote löökkoormuse suurimaks tulemuseks 26g (40ms) (ta võib tulla selline ka eelpool mainitud materjalidele), toode kaaluga 25g, löögi suurus ei ületanud toote lubatud 50g haprusläve, mis tagab toote funktsionaalsuse. Mida väiksem on haripunktis millisekundite arvväärtus, seda raskem on materjalil löökkoormust taluda.

Survetesti ajal leiti EPE omadused olevat parimad kuna deformatsioon oli koormuse eemaldumisel väikseim. Peab tõdema, et kärgpapi survetugevusel 500N oli tema deformatsioon ainult 2mm, samal ajal oli EPE kokkusurutud juba 15mm. Samas kärgpapp osutus löökkoormuste summutamises kõige viletsamaks, EPP, EPE EPS jällegi andsid kõikide testide üldtulemustes materjalide omavahelises võrdluses parima tulemuse, andes see läbi hindamismaatriksis tulemused, mis aitasid välistada mitmed teised alternatiivid. Lisaks saavutati teadmine, et survetestil peavad materjalide katsekehad olema ühtlaselt lõigatud ning testi parameetrid peavad vastama materjali iseärasustele jms.

Pakendatud toote lööktestimisel selgus õige kukkumisasendi tähtsus. Näiteks ei langeks löökkoormus üheaegselt serva ja nurka, mille tagajärjel võib tulemus muutuda. Peab möönama, et reaalsuses võib see aset leida näiteks käest kukkumisel, siiski olid tulemused rahuldavad. Testimise käigus saadi teada, et materjali paksusel ja haprusfaktori g vahel puudub lineaarne seos.

Tuginedes materjalide katsetustele, hindamimaatriksile ja läbi eelneva ajurünnaku ning simulatsiooni, mida sooritas teine grupiliige ja kirjandusele, saadi järelduseks, et vormitud paberimass, mis on taaskäideldav ning biodegradeeruv ,on asendusmaterjalina kõlblik. Kuigi kirjanduse ülevaade tõi välja tema sobilikkuse 5kg ümber jääva toote massidele, sai uuritud ka lisaainete juurde segamise võimalust, mis tõi välja sobilikkuse isegi 30kg raskustele toodetele. Samuti selgus, et vormitud paberimass sõltub paljuski geomeetriast, paksusest, tootmisspetsiifikast (pikk/lühike kiud jms) ning ühtlasest seina paksusest. On küllaltki vajalik teha lisa uurimisi mehaaniliste omaduste kohta (transpordi käigus, külmades tingimustes).

Uurimuse põhjal selgus kui palju disain ja muudatused pakkeliinil mõjutavad hinda. Toodud on materjalide hindade võrdlusarvutused, millest selgub, et EPE on kõige kallim pehmendusmaterjal, Välja on toodud ka kuidas materjali hind summaarset pakkimiskulu mõjutab. Pakkeliini tsükliaegade erinevus tuli 240s vs 220s toote kohta, mis tähendab 15 tükki vs 16 tükki/tunnis. Materjali muutuses tuleneva odavama kulu tõttu tuli vahe ca. 60% kogu pakkekulust, kuigi uus materjali lahendus on 45% raskem.

Seega leitud lahendus on odavam ja ka rakendatav, muidugi firmal tuleb siinkohal pakutud lahendusele teostada lõplikule järelduseni viivat disaini arendust.

Töö hõlmab endas väga suurt potentsiaali jätkamiseks ning edasiarenduseks olemasolevate tulemuste põhjal. Katsetatud materjalide ning ka võimalike uute mehaanlisi omadusi saab uurida edasi mitmetes eritingimustes k.a nende keemilisi- ja klimaatilisi omadusi, viia läbi mehaanilise pinge katsetusi ja sooritada survekatseid ka pakendatud tootele.

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APPENDICES

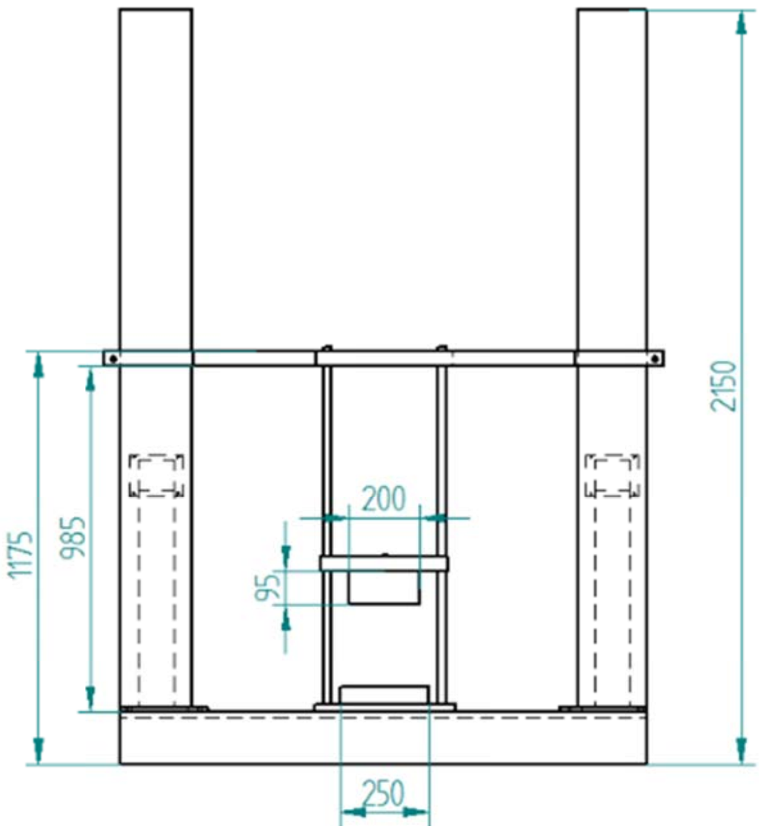

Figure A.1. Dimensions of the test rack

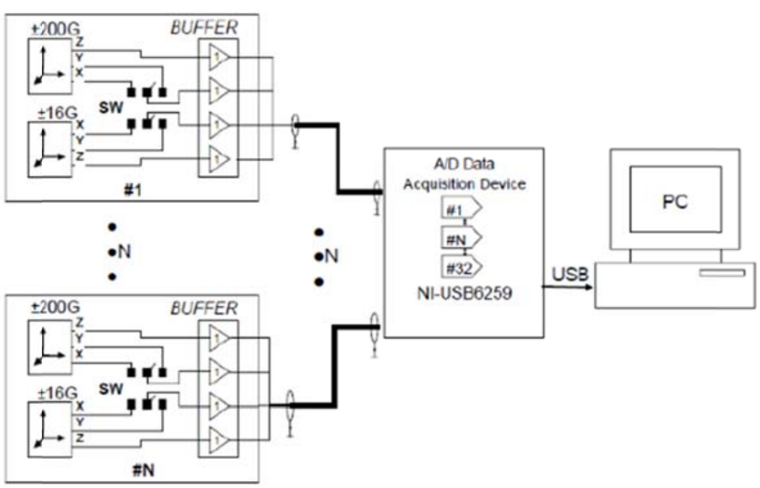

Figure A.2. Block diagram of the acceleration measurement system

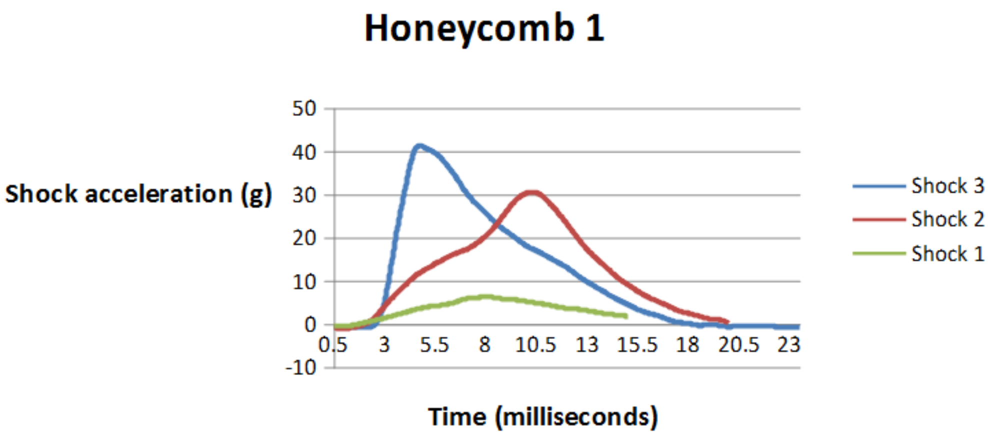

Figure B.1. Honeycomb testing result

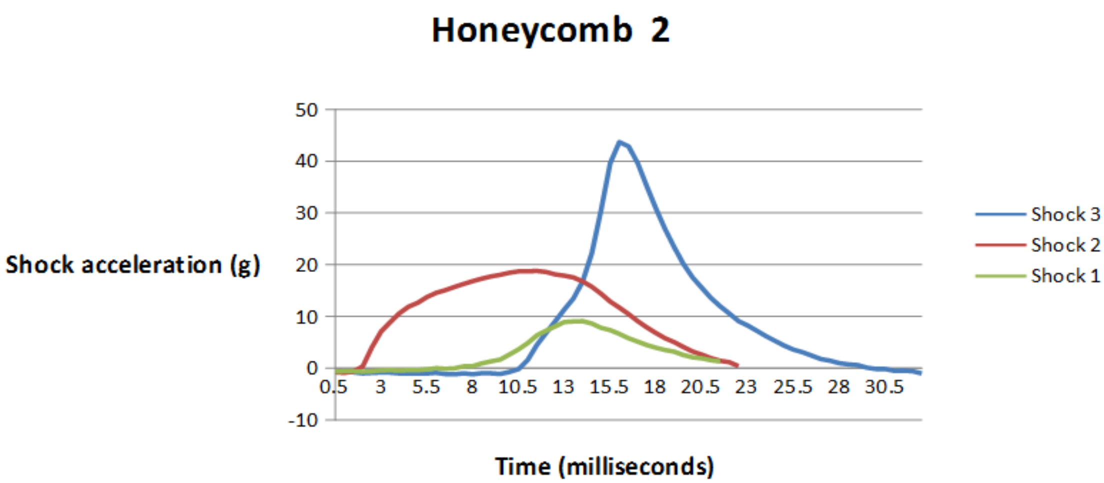

Figure B.2. Honeycomb second testing result

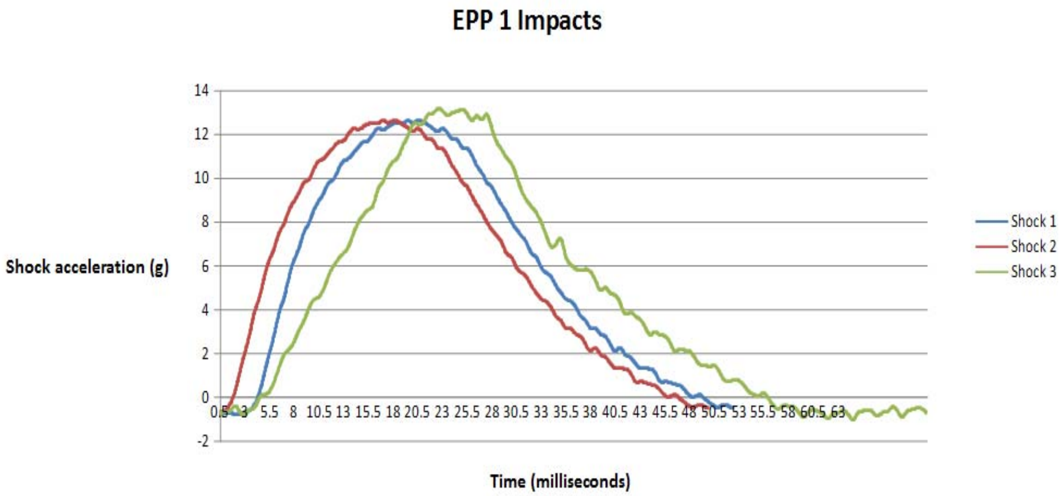

Figure B.3. EPP first result

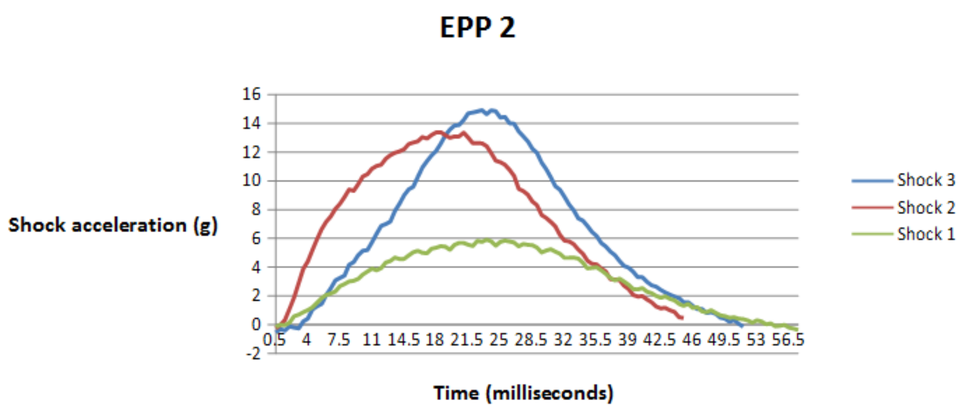

Figure B.4. EPP second result

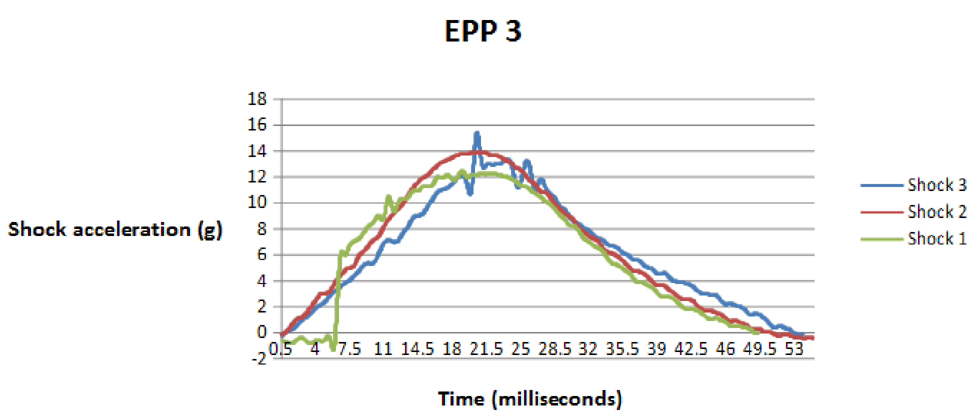

Figure B.5. EPP third result

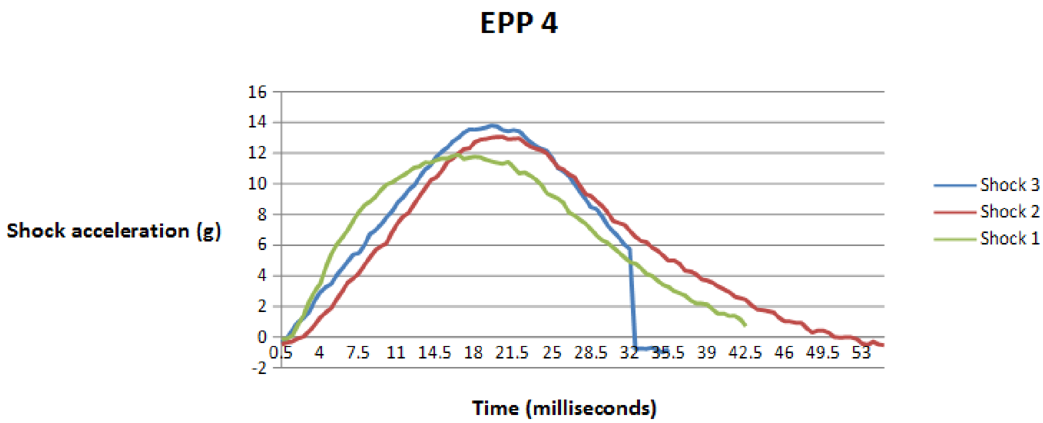

Figure B.6. EPP fourth result

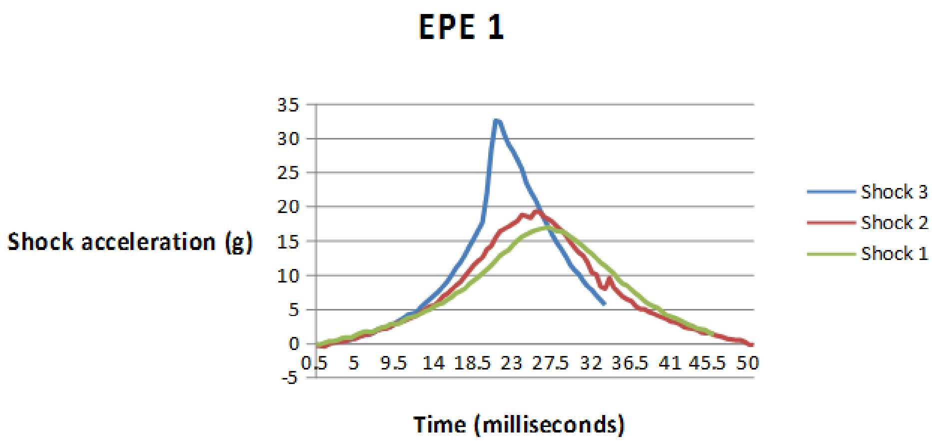

Figure B.7. EPE first result

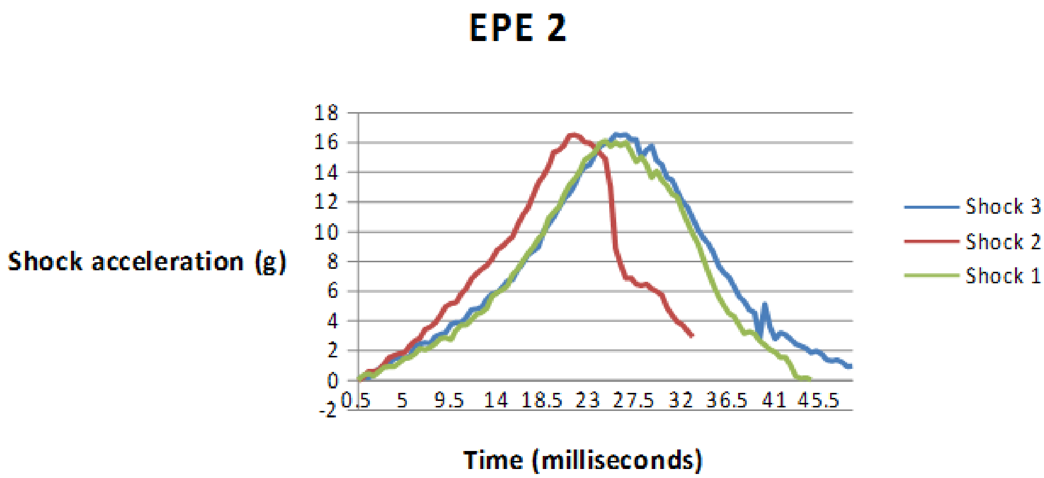

Figure B.8. EPE second result

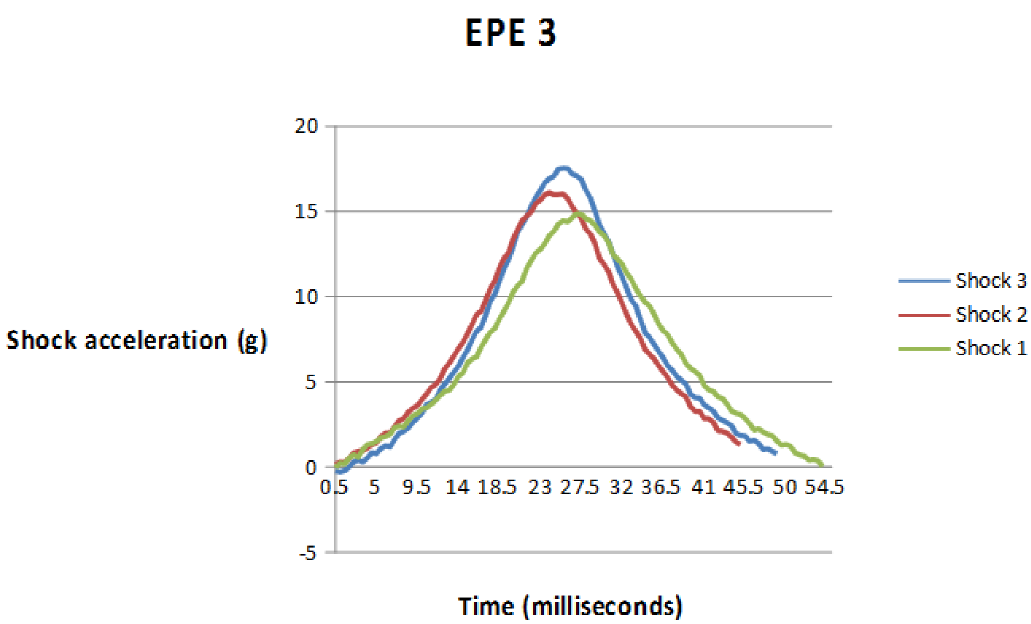

Figure B.9. EPE third result

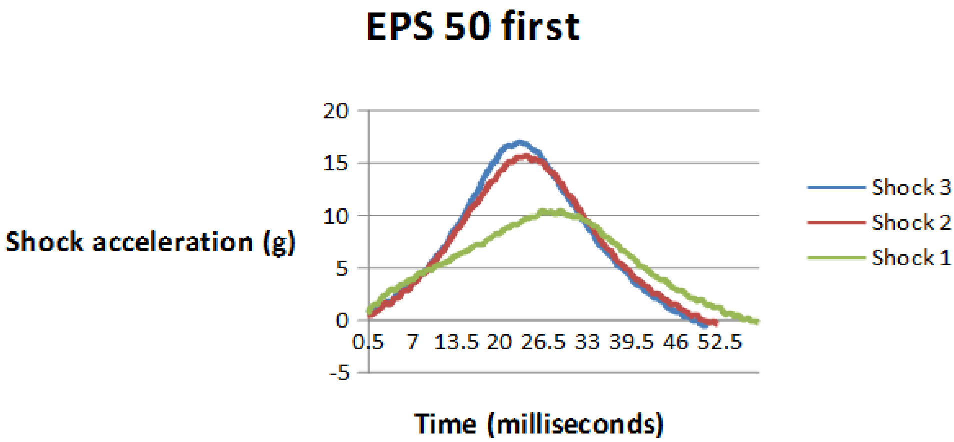

Figure B.10. EPS 50 first result

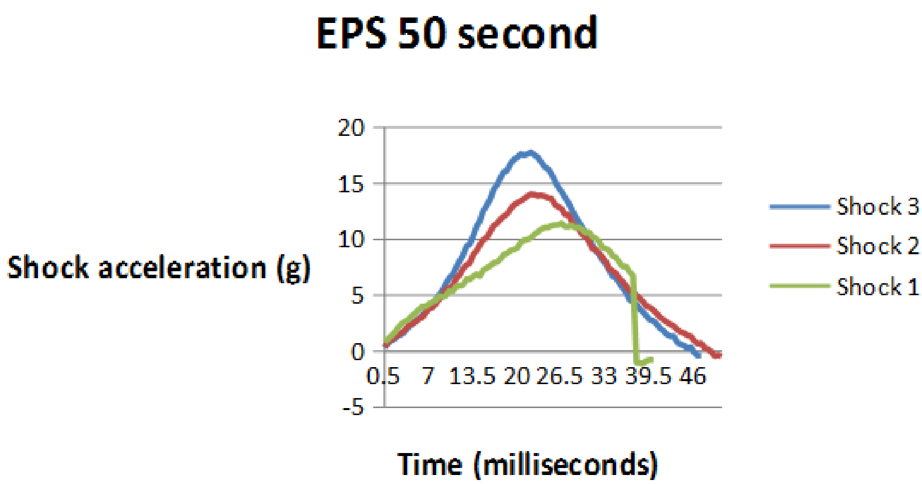

Figure B.11. EPS 50 second result

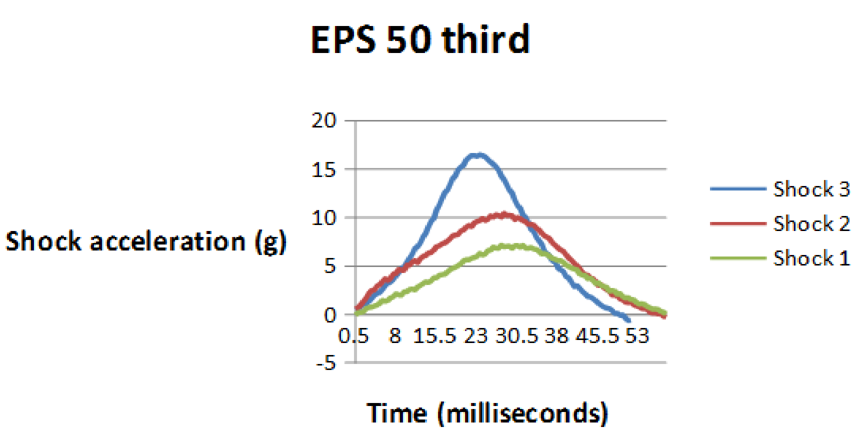

Figure B.12. EPS 50 third result

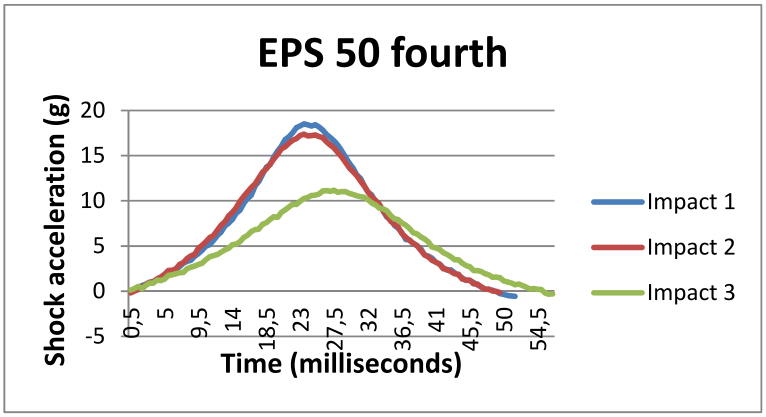

Figure B.13. EPS 50 fourth result

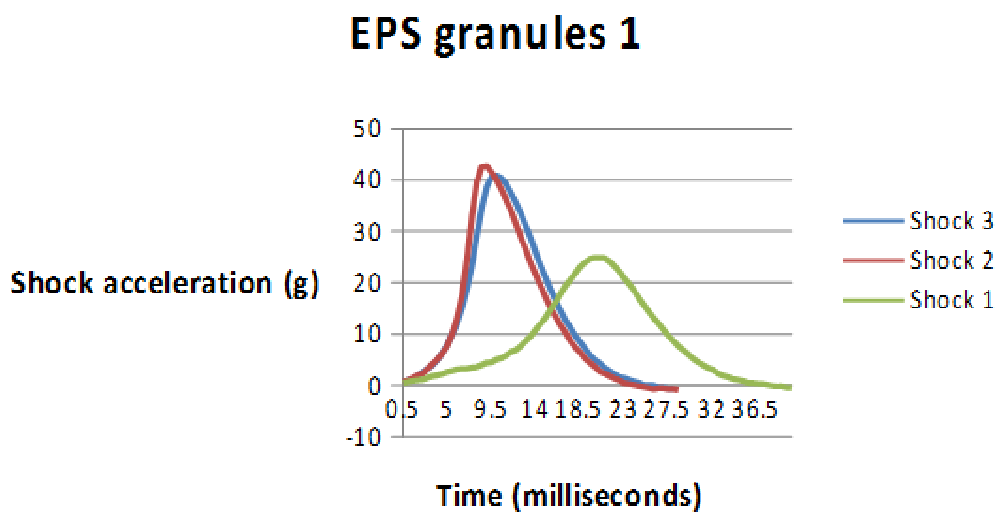

Figure B.14. EPS granules first result

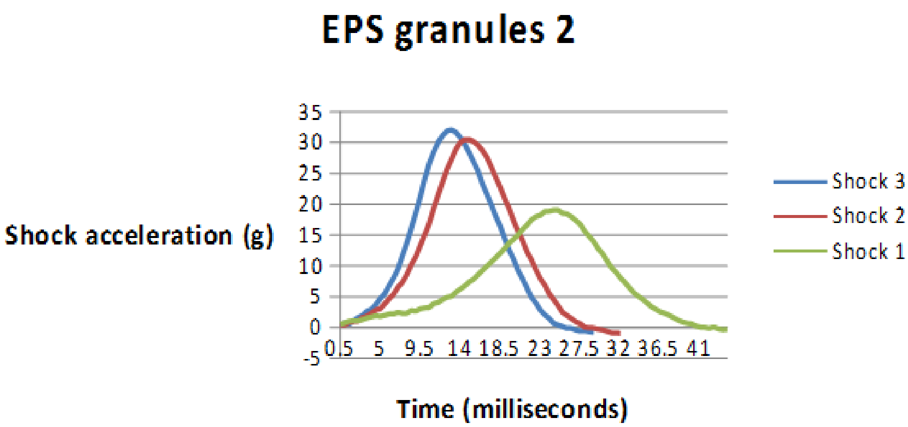

Figure B.15. EPS granules second result

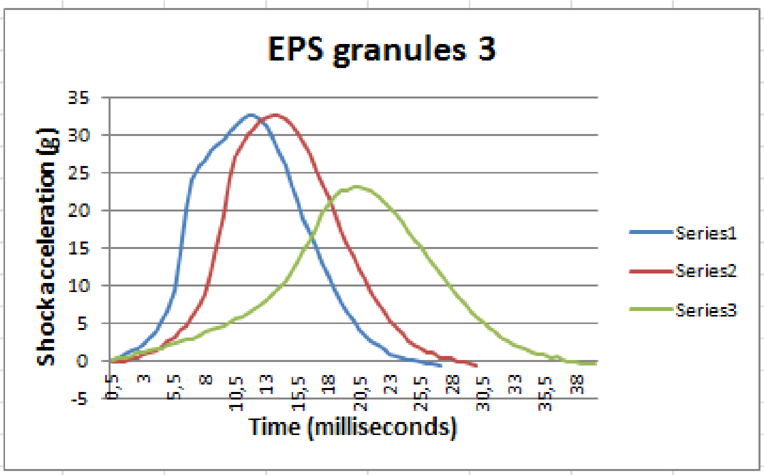

Figure B.16. EPS granules second result

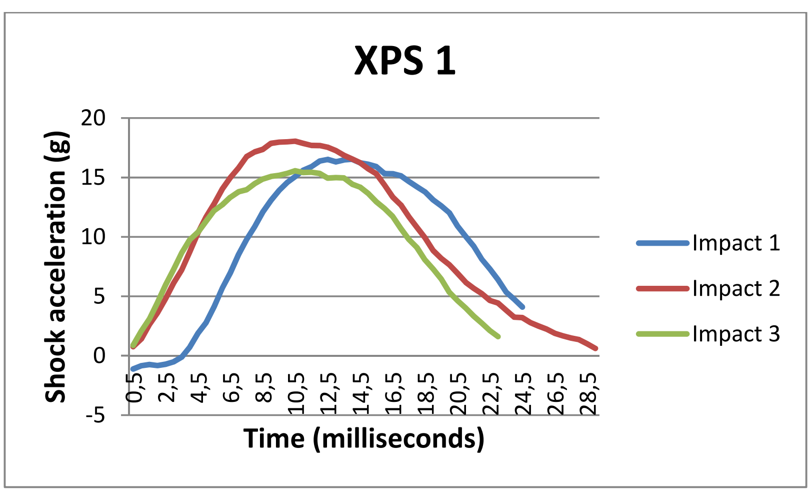

Figure B.17. XPS granules first result

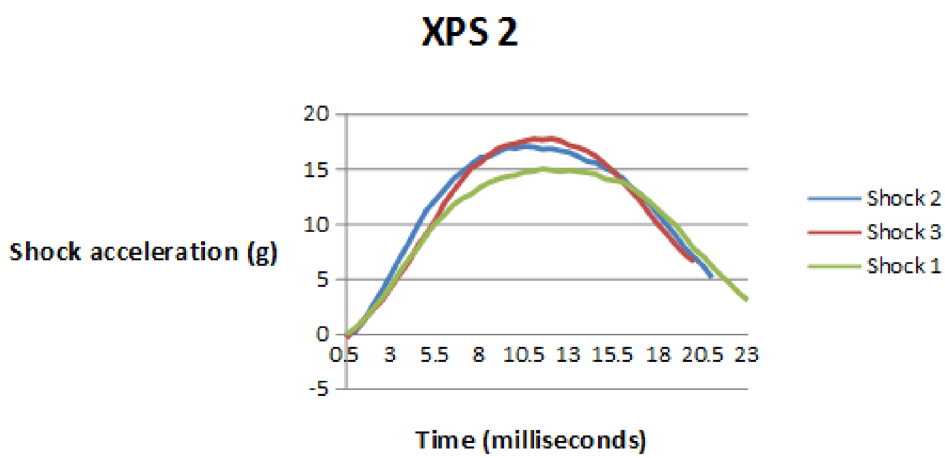

Figure B.18. XPS granules first result

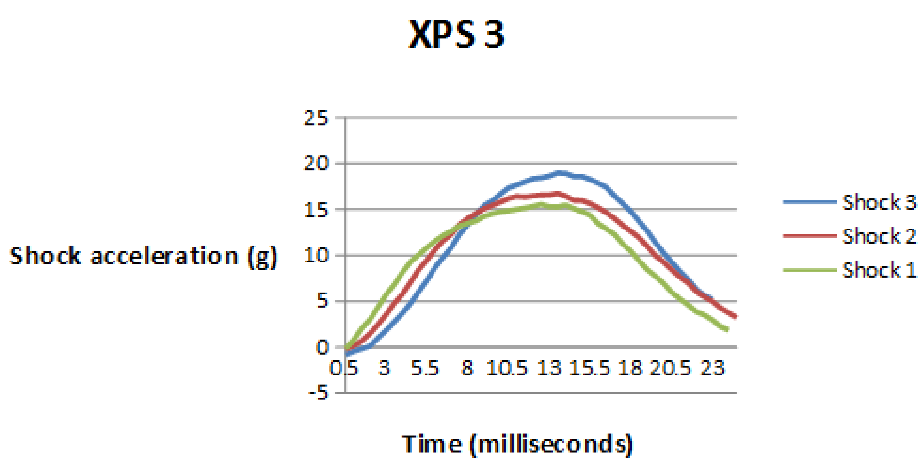

Figure B.19. XPS granules third result

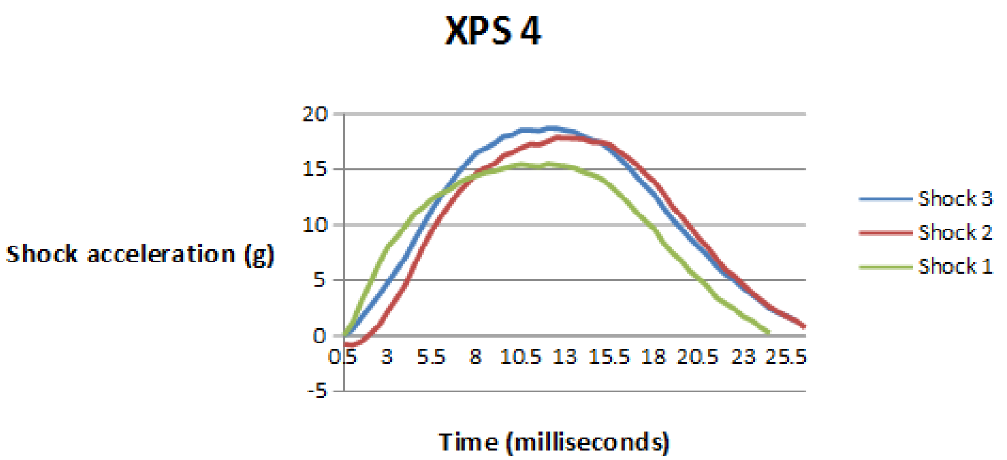

Figure B.20. XPS granules fourth result

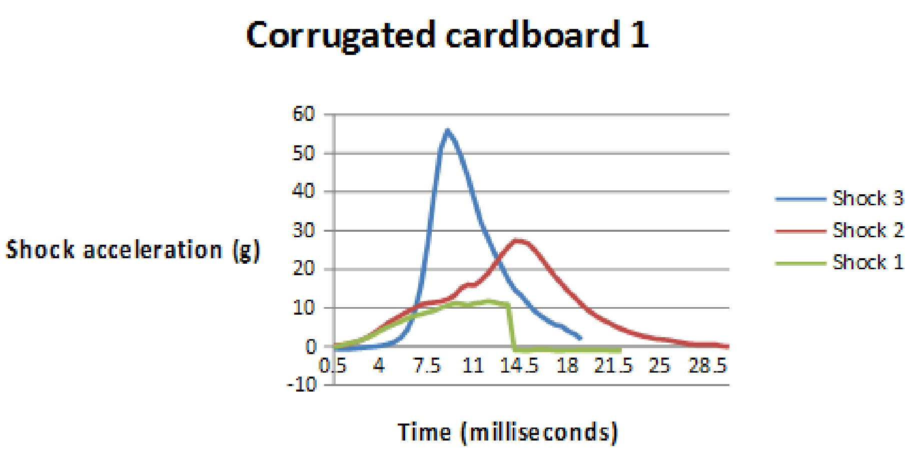

Figure B.21.Corrugated liner cardboard first result

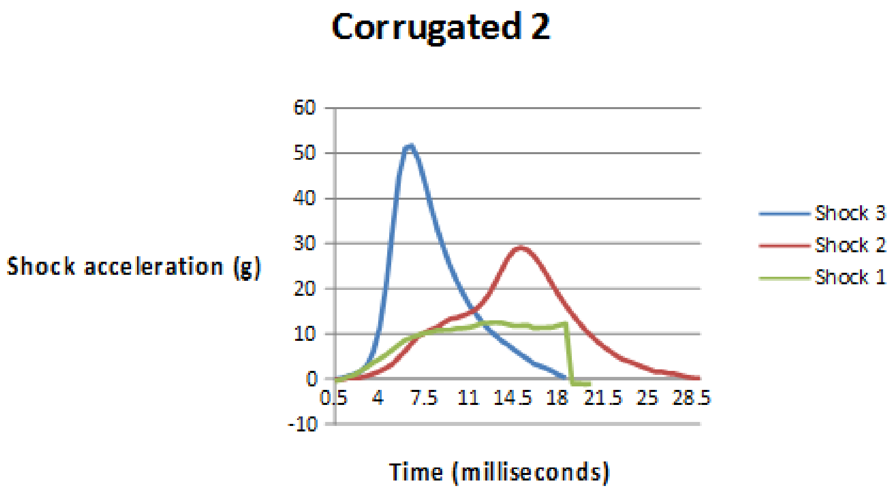

Figure B.22. Corrugated liner cardboard second result

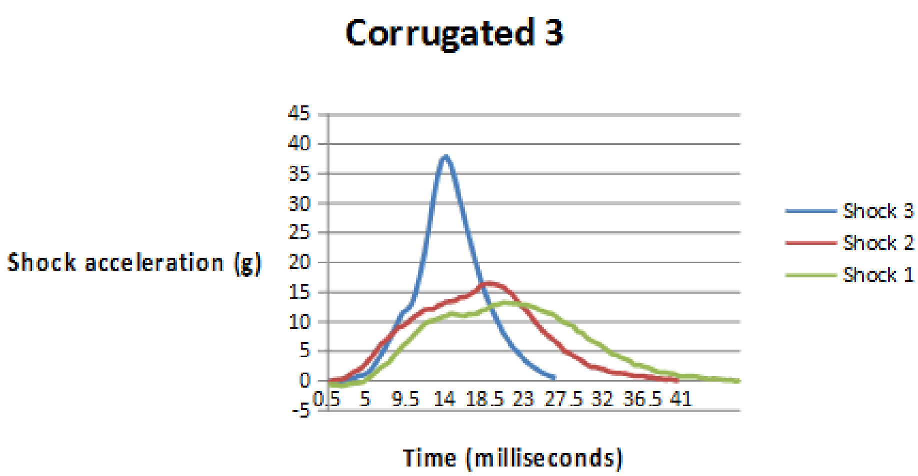

Figure B.23. Corrugated liner cardboard third result

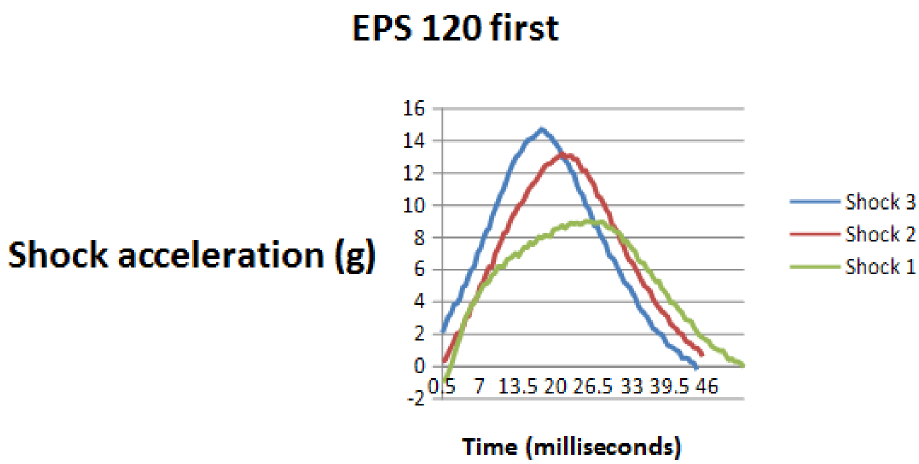

Figure B.24. EPS 120 first result

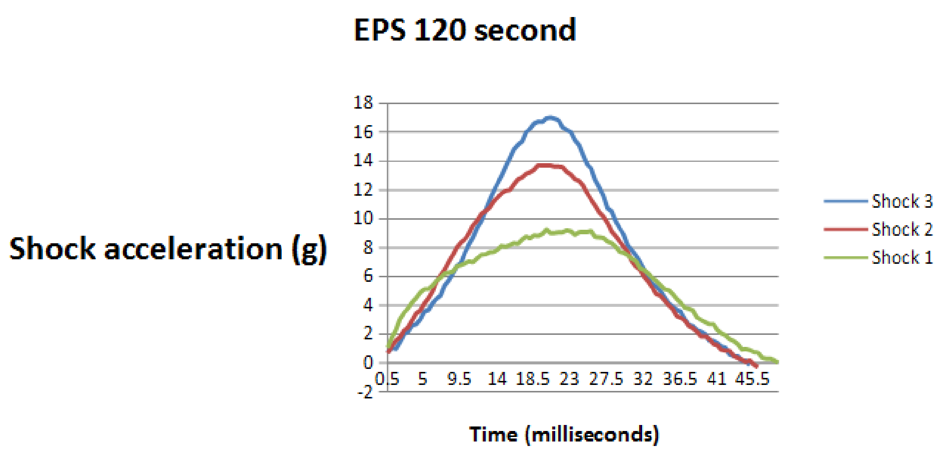

Figure B.25. EPS 120 second result

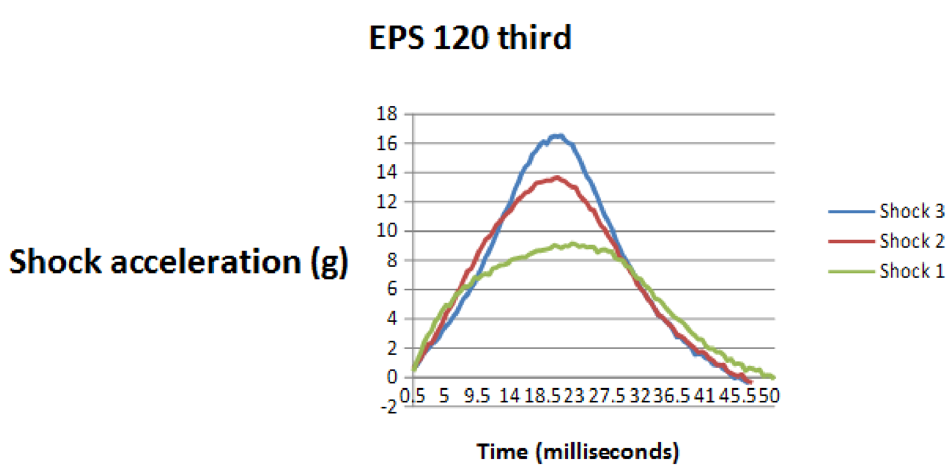

Figure B.26. EPS120 third result

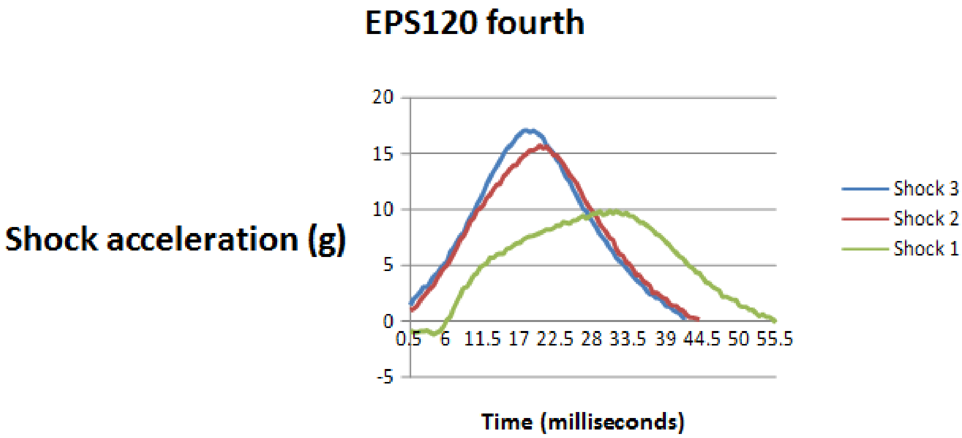

Figure B.27. EPS 120 fourth result

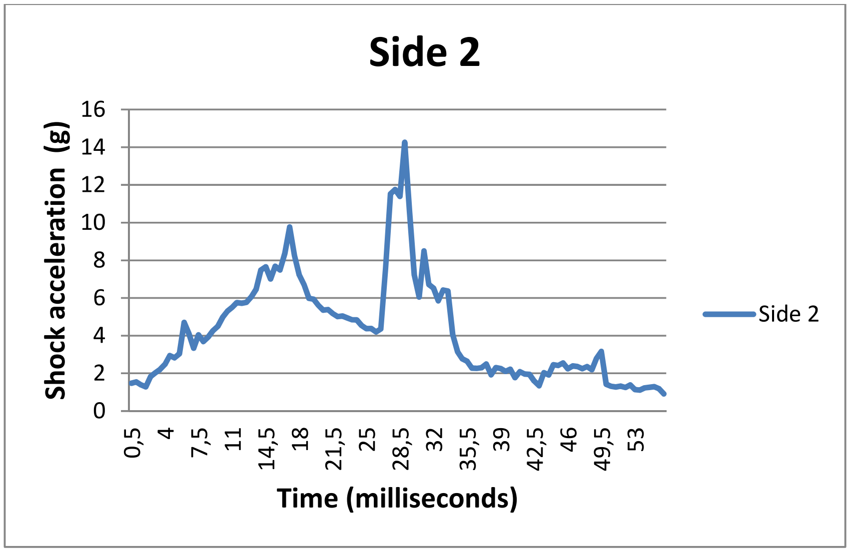

Figure C.1. Dropped at side 2

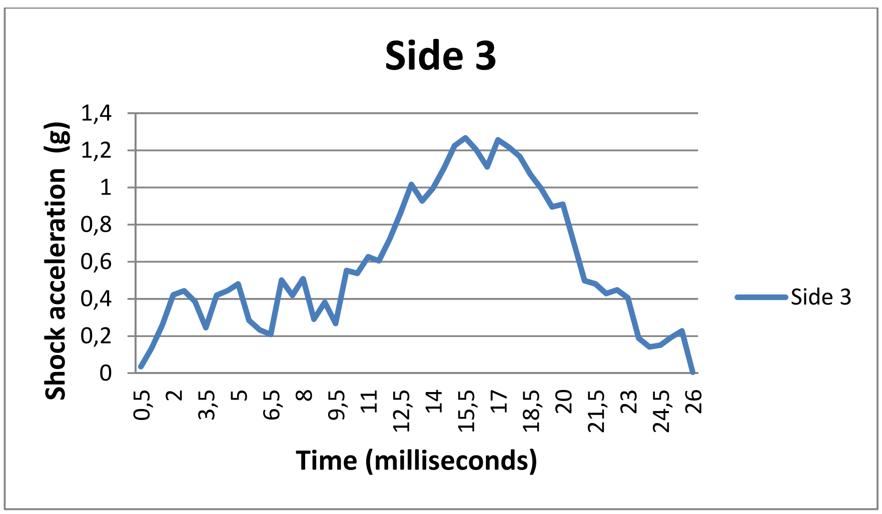

Figure C.2. Dropped at side 3

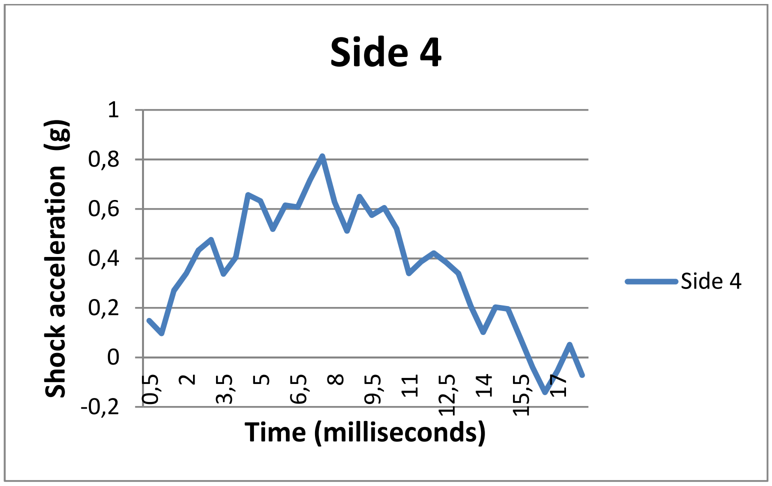

Figure C.3. Dropped at side 4

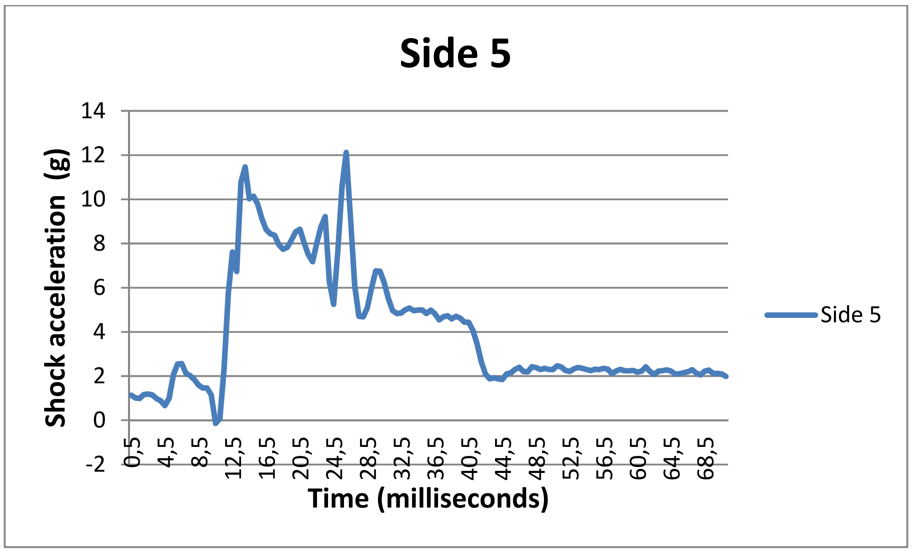

Figure C.4. Dropped at side 5

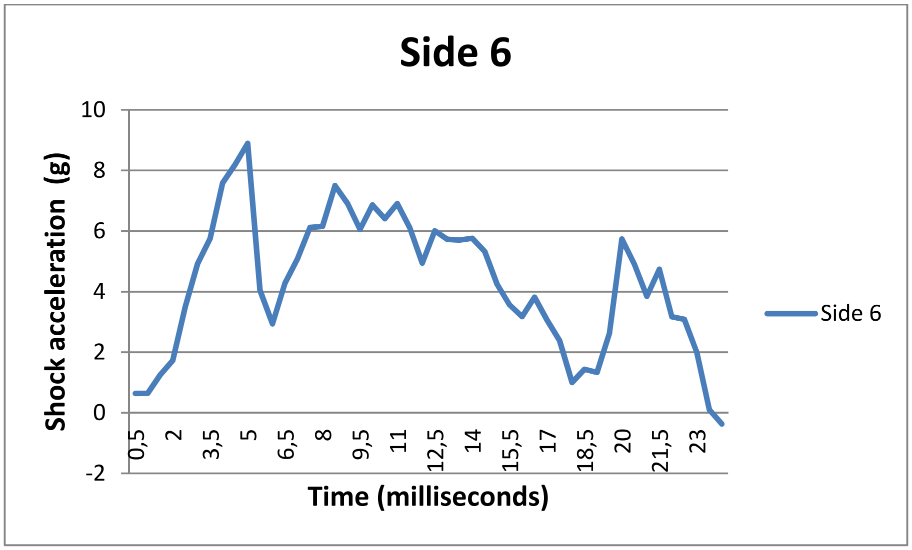

Figure C.5. Dropped at side 6

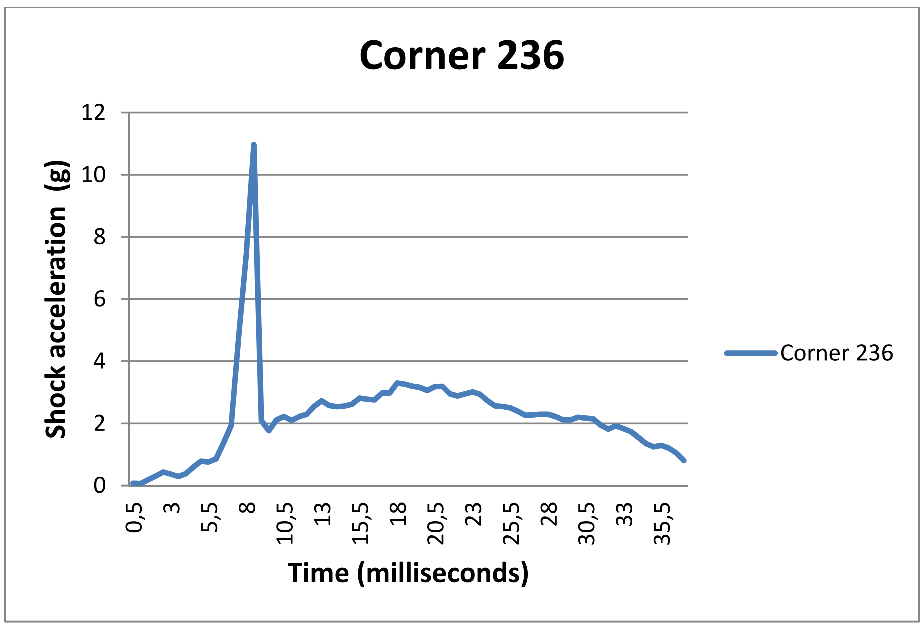

Figure C.6. Dropped at corner 236

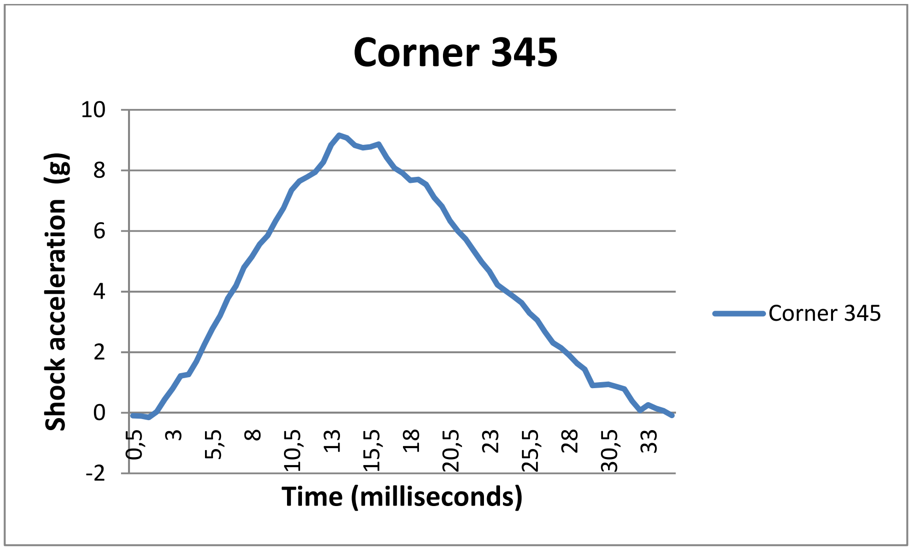

Figure C.7. Dropped at corner 345

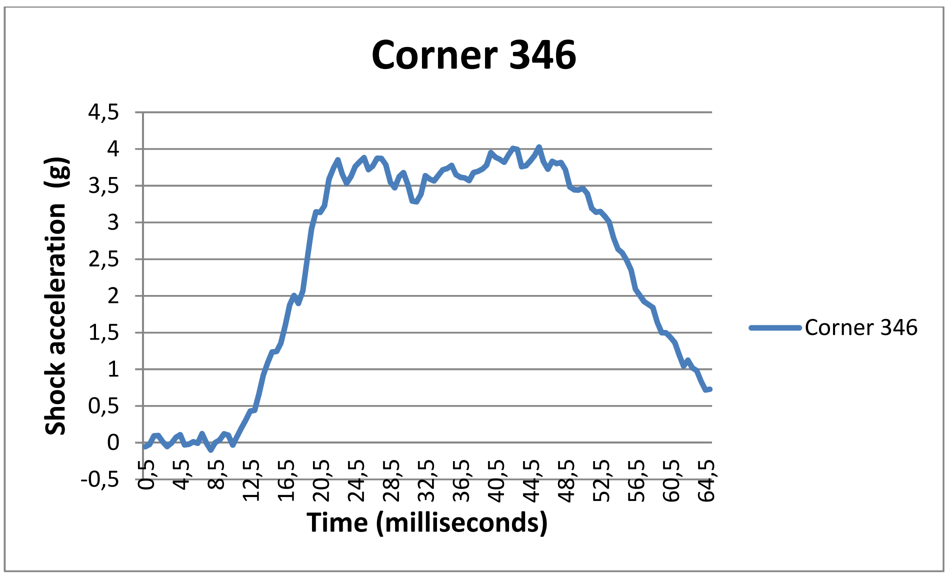

Figure C.8. Dropped at corner 346

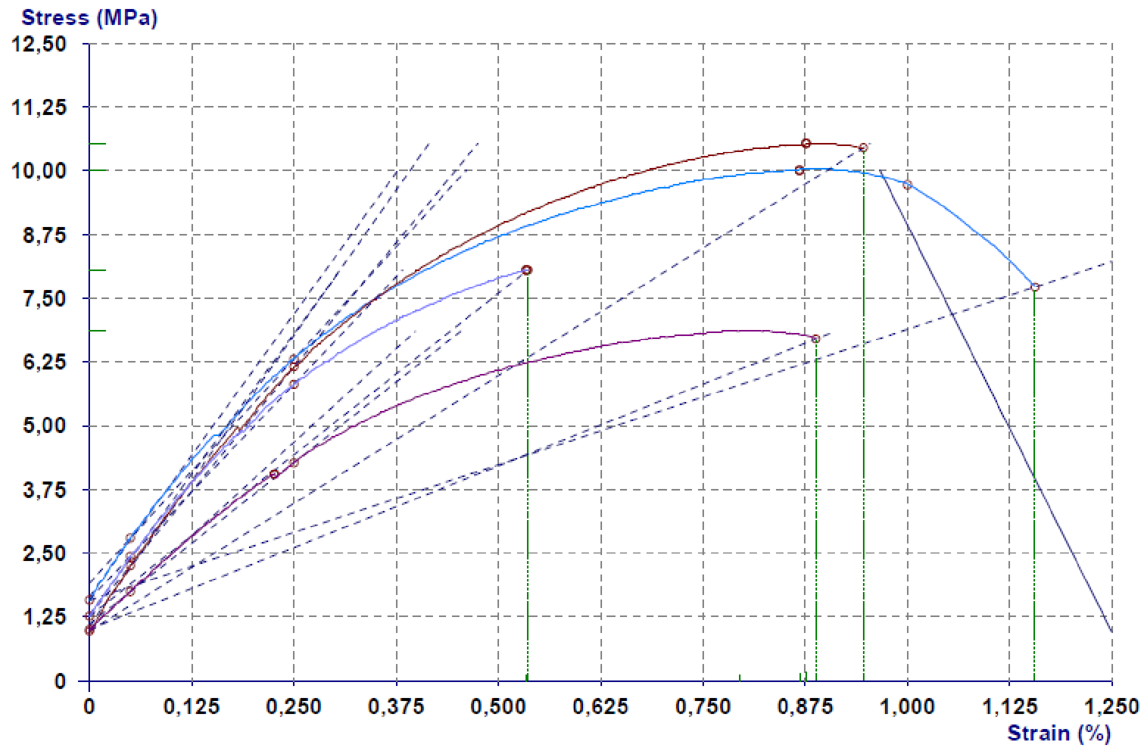

Figure D.1. Tensile strength at elongation speed of 20mm/min

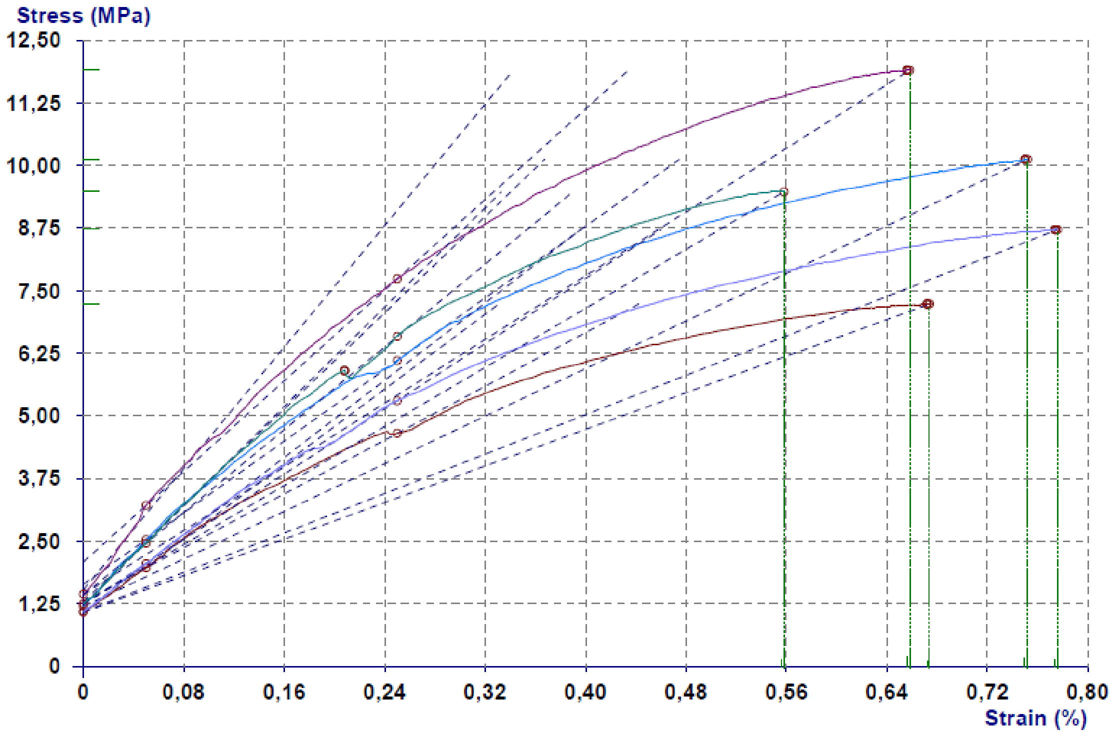

Figure D.2. Tensile testing at the elongation speed of 100mm/min