Using Degradable Foam Cushioning in a Product – Packaging System

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Abstract Our daily life is pervaded with the plastic materials. Although these devices, materials and foams provide numerous benefits, they also cause a significant environmental waste problem. From this aspect if we investigate the field of packaging, the result will be very complex and disillusionizing. Very huge amount of the plastics used by the packaging industry whose counteraction is the main task of the different type of engineers.

In first part of this paper, I investigate those parameters, which increased the demand of packaging materials and which are the most important parameters which can affect the product – packaging system and which are the basic defence solutions against these effects.

In the main part, I investigate the possible ways which can help us to solve the continuously changing environmental requirements. In this process, the Environmental Degradable Plastic (EDP) foams can be a possible solutions, but not enough is known about the biodegradation process of synthetic plastic and plastic based foams.

These information are essential to develop and re-think the process of systematic approached product - packaging design methods. This paper describe the complexity of this development, which would be a possible right way to use environmental plastics and keep the products in safe.

Keywords: cushion, EDP, packaging development

1. Introduction

In a logistic system when we have to design a “suitable” product - packaging system, we always meet a many-degree-of-freedom system where we have to solve or expose many questions and problems both in economic and engineering aspects. In this paper I investigate the field of cushioning, and which problems and questions are in this field. Closing the paper I try to explain those ways or methods which we have to use during a product – packaging development if we would like to pass the more and more strictly environmental requirements, for example the degradability of packaging materials.

2. Nowadays' changes in the packaging

Nowadays, if we try to analyze a products Life – Cycle (for example an electronic product), the most of the papers in this field investigate only the products LC. Those professionals, who are work in, developing or researching in the packaging know that the packaging system of a product, hide very wide range of potentials which are be able to minimize and decrease the packaging waste which mostly arises from the manufacturing and logistics processes.

Arguments which increase the packaging material demand [1]:

- Demographic and life-style changes (ageing population, increased demands on health and hygiene, convenience required, - Packaging in harmony with product and brand image , individualism, etc)
- Technological changes (electronic and home shopping)
- Supply chain management changes (IT as a supplement to packaging communication, virtual corporations, etc)
- Manufacturing changes (concentration on core business and out-sourcing, part-manufacturing, etc.)
- Problems with package design methods (counting only the "household" stresses, empirically development, "over-packing", etc.)
- Environmental issues (pass the more and more strictly 5R requirements)

As we re-think the above mentioned facts, we are able to recognise that these were the modifier elements which converted the packaging's classic 3P function to 5R. To pass more and more from the 5R (Reduce, Reuse, Recycle, Buy Recycled, Rot (Compost)) requirements, we have to re-think one of the most huge packaging waste indicator, the nowadays applied cushioning systems.

3. The appearance and the importance of the most common dynamic mechanical stresses

The packaging system is mostly set-up based on four components:

Product (with its critical elements) → consumer packaging → collector package → transportation packaging (with the fixing system).

The package-product system has to withstand the rigors of the distribution environment. The hazards of distribution are many and varied. In the most cases is usually difficult or impossible to predict what a product-package system is going to encounter.

During distribution there is a need to be concerned dynamic forces encountered due to [2]:

- dropping, throwing and other abuses caused by the manual loading, unloading and handling of packages,

- the stresses applied by mechanical handling equipment,
- vehicle impacts,
- vehicle vibrations.

The previous four conditions result in impact and vibration to the product - package system. As a consequence of that from the viewpoint of package cushioning design the two significant factors are shock and vibration.

Goods are protected from shock and vibration by isolation. Isolation is generally attained by placing resilient means -cushioning materials- in the package system. In concept, the package cushioning is designed to protect the packaged item of known strength from the known shock and vibration in the given environment.

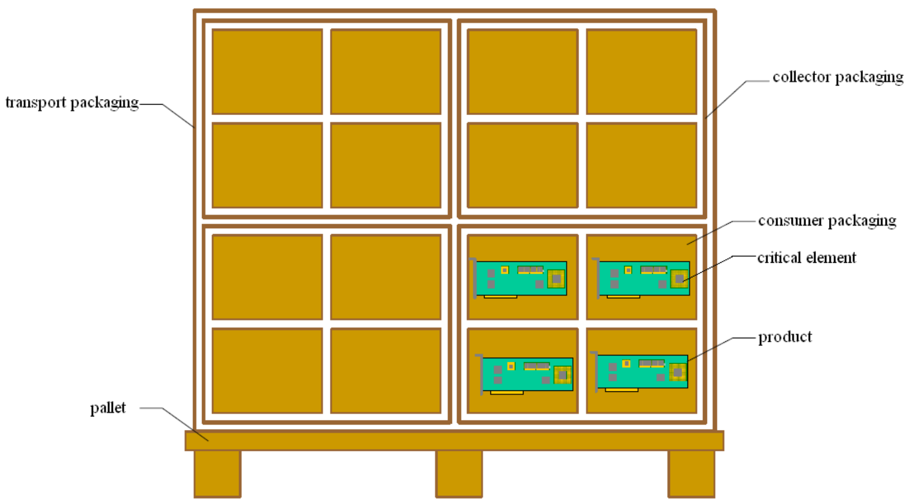

Figure 1. Product-packaging system (source: own drawing)

3.1. Shock and vibration isolation theory

- The mechanical shock

A mechanical shock occurs, when an object's position, velocity or acceleration suddenly changes. A shock may be characterized by a rapid increase of acceleration (x) followed by a rapid decrease over a very short time (t).

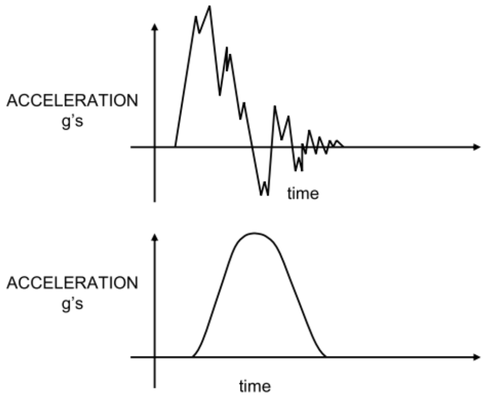

Figure 2. Representation of Mechanical Shock (source: own drawing)

Practically there are two kind of basic sources of the shock stresses.

The vertical impacts are from the falling off of the packaged products, but this is the same stress if a hoisting engine put down the load, very rude. The source of the horizontal impacts from the braking, acceleration of a vehicle, etc.

The package damage (and of course the product damage too) is related to three factors involved in mechanical shock:

– Peak Acceleration,
– Duration,
– Velocity Change.

The velocity change is numerically equal to the area beneath the shock pulse. So knowing any two of the factors allows to estimate the third [2].

– The vibration stress

The vibration forces issuing from the road bumpiness, the unbalanced and moving weights on the vehicles, the spring system of the transport devices, the characteristic of the keeping on the vehicle on the road and of course its mixture. The elements of the a theoretical system is shown on Fig. 3.

The vibration sensitivity of a product is characterized by input frequencies of the environment, which can cause resonance at the product, at the critical element of the product. To identify the vibration frequency there is need to know

– the natural frequency of the product,
– and typical forcing frequencies of distribution.

The natural frequencies of products are determined using vibration test with sinusoidal motion [3].

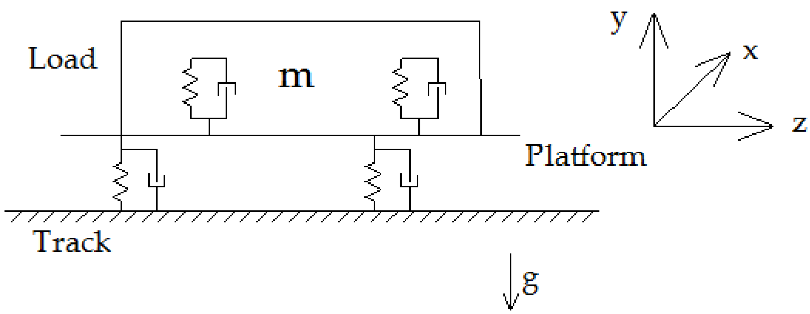

Figure 3. Track –vehicle – load system model (source: own drawing)

Table 1. The forcing frequencies of distribution vibration

Type of the transport	Frequency range [Hz]	Conditions
Rail	2 – 7 (Suspension) 50 – 70 (Structural)	Moving freight car
Truck	2 – 7 (Suspension) 15 – 20 (Tires) 50 – 70 (Structural)	Normal highway travel
Aircraft	2 – 10 (Propeller) 100 – 200 (Jet)	Flying aircraft
Ship	1 – 11 (On deck) 100 (Bulkheads)	Water and propeller vibration

During the development of a new product-packaging system, we have to count with the mixture of these mechanical stresses.

4. Cushions and movedampers as the potential solutions of defence

4.1. The theoretical system of cushioning and movedamping

The common method of shock isolation in packaging design is the use of cushioning materials. The cushion pads are inserted on the several sides of the packaged products. The theory of shock isolation with linear springs is valid only for a small deflection of the isolation medium. For larger deflections the stiffness of the cushioning material becomes nonlinear.

1. Viscous damping model with linear stiffness characteristic.

For this model, Suhir [4] presented the following equation for a single-degree-of-freedom (SDOF) system [8],

$$M\ddot{x} + C\dot{x} + Kx = 0 \qquad (1)$$

where *M* is the mass of the system, *C* is the damping coefficient, and *K* is the spring stiffness coefficient, which is assumed constant. Therefore, this model is only applicable to the linear system.

2. Un-damped model with nonlinear stiffness characteristic.

In order to describe the nonlinear characteristics of cushion buffer, Suhir [9] suggested another form of equation for the same vibration model:

$$\ddot{x} + Kx + \alpha x^3 = 0 \qquad (2)$$

In this model the damping is ignored. Furthermore, *K* remains a constant in *Kx*, only the parameter α is applied to reflect the nonlinear behaviour in αx^3. This approach introduces a nonlinear feature with respect to displacement, and stiffness coefficient as a constant in its linear part. It is generally insufficient to detect the dynamic behaviour quantitatively by virtue of this nonlinear model practically, because the parameter of nonlinearity α cannot be obtained directly from the nonlinear stress-strain curve of the cushion buffer.

A mathematical model of packaged product is depicted in Fig. 3., in which the buffer is idealized as a vibration system assembled with multi-unit nonlinear springs with unit stiffness coefficient k_c and damping ratio ξ. This system with multi-components provides sufficient flexibility to describe the arbitrary shapes of cushion buffer [5] [6].

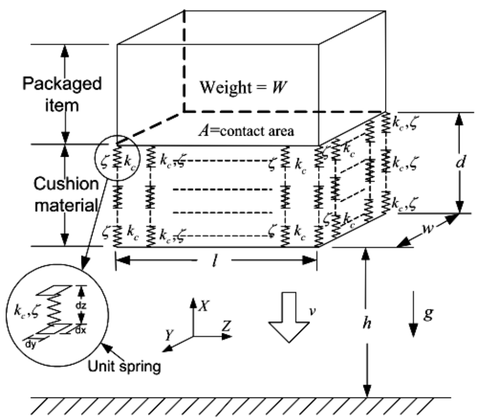

Figure 3. Mathematical model of packaged product [6]

4.2. Testing of cushioning materials and systems

Application of the shock and vibration

The behaviour of isolators is characterized by dynamic cushioning curves. A cushioning curve shows how a particular packaging material of a given thickness behaves at different impact conditions. Curves are generated by dropping a series of known weights onto a cushion sample from a specified height and measuring the amount of shock experienced by the weights as they impact the foam.

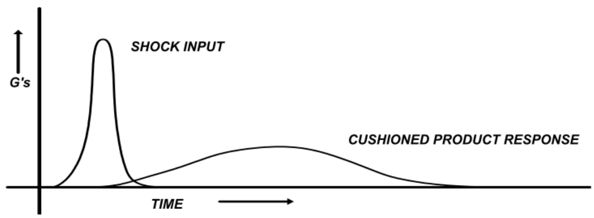

Figure 4. Idealized shock input and cushioned response (source: own drawing)

The testing represents a product dropping on a cushion from a height likely to be encountered during shipment. Practically cushioning curves are curves of maximum transmitted acceleration as a function of static stress for given thickness of material at different heights of free fall. The "static stress" is the unit loading, and is defined as a quotient of packaged weight and the area of the medium in engagement with one side of the item. Similarly height of free fallen correspondents to accepted practice specifications in discrete increments.

In package design cushioning curves are applied by selecting the figure corresponding to the actual packaging parameters. Generally the primary consideration in package cushion design is the protection against shock. But if the packaged product has a resonant frequency falling within the vibration frequency range during transportation, vibration isolation characteristics of the cushion system also have to be considered.

Successful vibration isolation of packaged systems desires significant damping of the isolator. A high damping factor of the cushioning material guaranties that the vibration amplitude doesn't become excessive in case of resonance, if the environmental conditions include vibrations of frequency equal to the natural frequency of the isolation. Degree of vibration isolation of the cushion system depends on the relation between transmissibility and the ratio of vibration frequency and the natural frequency of the cushion, which is a function of the loading stress and the thickness of the isolator. Because of many variables and unknowns transmissibility data are obtained in the praxis empirically. The natural frequency for nonlinear cushioning material can be determined by applying the stress strain relationship for isolation material.

The main property of isolation materials is their capability to absorb, store and dissipate energy. Effective cushioning recovers after impact to maintain its isolation ability for subsequent impact events. As was mentioned isolation materials have only at small deflections a linear behaviour, at large deflections they show consequently nonlinearity. In that case, equation for force – deflection under dynamic fails, that the only successful way of design is to make use from experimentally properties of the materials.

There are:

- compression versus strain characteristics (test on the Fig. 5.),
- cushioning curves (maximum acceleration versus static stress characteristics),
- creep characteristics (hysteresis loop),
- resonance behaviour, natural frequency of the isolator.

Compression strain characteristics make possible to determine the compression deflection of the cushion due to weight of the packaged product. The compression stress is calculated from the weight of the package contents and its bearing area.

Figure 5. The damping ability test on a sample, made on the TEXTENSER FY-33/3

Cushioning curves allow the determination of cushioning thickness of the given isolation material, which provides the sufficient shock absorption.

Creep characteristics give information about thickness loss of the cushion during storage. Knowledge of natural frequency makes possible to avoid "excitation" frequencies during transportation.

Furthermore recovery is an important indicator for the loading capacity of cushioning materials. If recovery is too low the permanent deflection of the isolator increases, the breaking distance of the cushion decreases, the resultant kinetic energy can no longer in the desired way absorbed.

To complete the design and development of a new cushioning form in a product packaging system, we have to know the behaviour of the exact cushion system with other parts of the packaging system, and of course with product.

In these cases, we can choose from three type of evaluation method:

- integrity testing,
- general simulation,
- focused simulation.

Focused simulation is the most powerful approach available for reshipment package performance testing. It is also the most demanding in terms of test preparation equipment and facilities. In a complete form focused simulation starts with development of detailed knowledge about means and modes of distribution:

- the transportation vehicles and their loading,
- the stacking situation,
- atmospheric profiles and extremes.

The best way to simulate those parameters, is to apply international standards (ISO, ASTM, ISTA, ec.) and their methodologies.

On the following figures (Fig. 6., 7.), results (the measured g values) of a free-fall (shock) and vibration test can be seen.

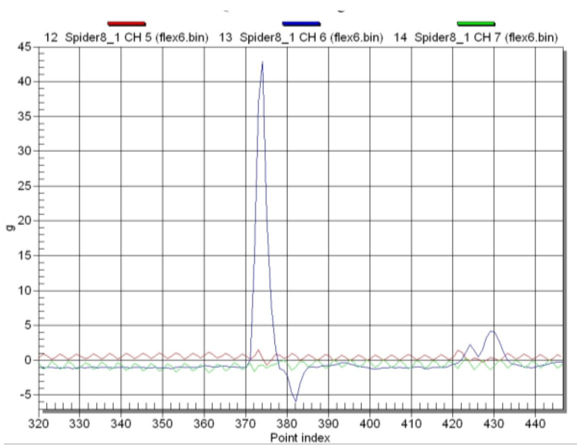

Figure 6. Answer figure of a drop test (measured on the critical element of the product)

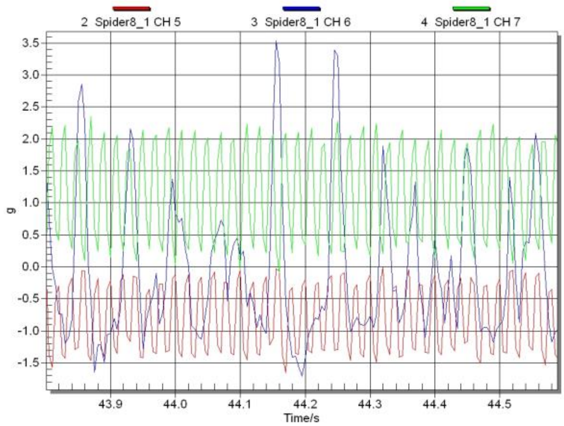

Figure 7. Answer figure of a vibration test (measured on the critical element of the product)

As I mentioned above, it can be clearly seen, that the right decision of a new constructed cushioning system, with a new characteristic material, is a very difficult and complex process[7].

4.3. Plastic foams as the most common applied product defender

Plastic foams are synthetic polymers that are used widely throughout the world for various applications. One of the main industry, which use the plastic foams in huge volume is the packaging industry. In the packaging industry, we divide the produced devices for two parts:

- Consumer plastic foam devices
- Industrial plastic foam devices

In the following, I mention and investigate only those plastic foam which are used for industrial needs.

The cushioning characteristic's of these materials are determined not only by their density (specific weight), but also by their structure [7].

EPS(PS-E) expanded polystyrene foams: PS is an elastic formed, rigid, closed cell foam. Its recovery is rather limited. The material is not hygroscopic, thus cushioning material hasn't got a tendency to absorb water vapour. PS-foams assure successful protection for package contents which are at risk of corrosion. EPS is often used in form of loose fills.

Polyurethane foams: Polyurethane foams are formed by the reaction of polyols and diisocyanates. The chemical blowing is a result of the reaction of the agents, carbon dioxide arising during the procedure produces the foam structure in the cross linked polymer. Depending upon the types of polyol there are two types of polyurethane foams polyether and polyester types. Polyurethane-ether foams are characterised by their irregular open cell structure. Polyurethane-ester foams have a regular cell structure, that can be controlled in a wide range. The two kind of materials have somewhat different static stress-strain characteristics. Polyurethanes are produced in flexible, semi-rigid and rigid forms. The shock absorbing properties of PU foams increase with foam hardness, while recovery and elasticity decline. Consequently on repeated exposure to identical stresses, this fact may cause problems with rigid grade of foam as there is a continual decline in recovery.

Special features can achieved by additives, for example flam retardancy or antistatic characteristic.

Polyethylene foams: PE foams are closed cell, non-cross-linked materials, produced by extruding polyethylene thermoplastic in conjunction with a blowing agent (carbon dioxide or hydrocarbons). PE foams have very good cushioning characteristics, with special additives father desired properties like antistatic behaviour can be assured. PE-X foams are chemically link crossed materials with a high water resistance and thermal isolation capability.

Polypropylene foams: PP foams are in the same way produced as PE foams, materials are somewhat similar in appearance, but will have different characteristics.

5. "Green" foam cushioning?

The foams provide numerous benefits but they also cause a significant environmental litter problem. Biodegradation may provide solution to the problem but nowadays the biodegradation developments work only with the consumer packaging (for example: shopping bags, foils) and not enough is known about the biodegradation process of synthetic plastic and plastic based foams.

Changes in polymer properties due to chemical, physical or biological reactions resulting in bond scissions and subsequent chemical transformations are categorized as polymer degradation [8]. Degradation reflects changes in material properties such as mechanical, optical or electrical characteristics in crazing, cracking, erosion, discoloration and phase separation.

Depending upon the nature of the causing agents, polymer degradations have been classified as:

- photo-oxidative degradation,
- thermal degradation,
- ozone-induced degradation,
- mechanochemical degradation,
- catalytic degradation
- biodegradation

In the following schematic figure, we can follow the method of a degradation process (Fig. 8.).

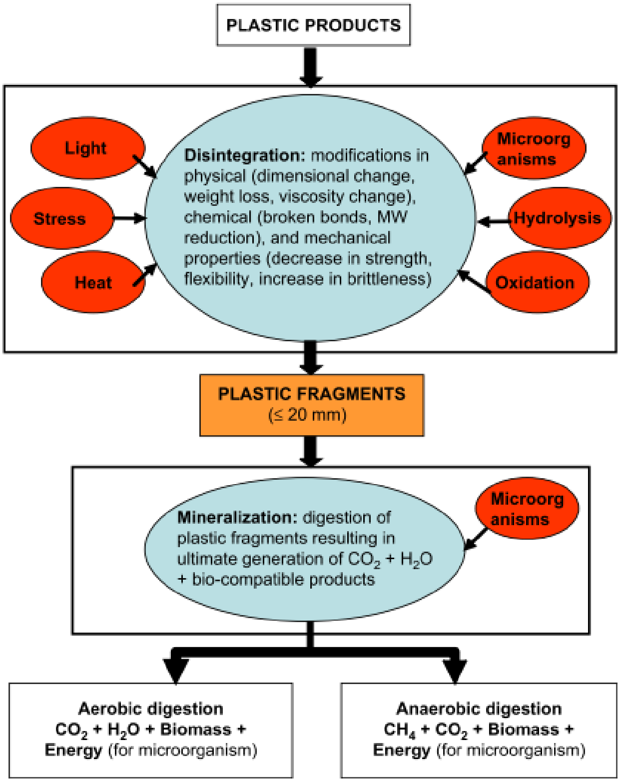

Figure 8. The schematic figure, of a degradation process (source: Krzan, 2006)

Degradation can be defined as a process which leads to a deterioration of any physical property of a polymer which used as a cushion in our product packaging system. In the practice, there are many parameters, which are also able to influence on the degradation of our cushion. These factors:

- Chemical composition
- Molecular weight
- Hydrophobic character
- Size of the molecules
- Introduction of functionality
- Additives
- Chemical bonding

- Methods of synthesis
- Effect of substituent's
- Effect of stress
- Environmental conditions

5.1. Potential serviceable environmental friendly cushions

The Environmental Degradable Plastics [9] (EDP) can be synthesized either from petrochemical or natural resources of vegetal, aquatic, and animal origins. The feedstocks are derived by three main routes: biosynthesis (e.g. fermentation by microorganisms), chemosynthesis (e.g. chemical synthesis and polymerization processes), and a direct application of natural materials with or without chemical modification (e.g. fibers or extracts). Groups of starting compounds currently utilized or being developed for the production of EDPs are shown in *Table 2*.

Table 2. List of classes of polymers used for the production of EDPs (source: Krzan et al 2006)

Biological origin	Synthetic origin
Proteins	*Aliphatic polyesters*
Albumin	Poly(glycolic acid), PGA
Casein	Poly(lactic acid), PLA
Collagen/gelatin	Poly(lactide-co-glycolide), PLAGA
Fibrinogen/fibrin	Poly(b-malic acid), PMLA
Wheat gluten,	Poly(e-caprolactone), PCL
soy protein	Poly(alkylene succinate)s
Zein	Poly(p-dixanone), PDO
Polysaccharides	*Poly(ethylene terephthalate)*
Animal	*modified copolyesters*
Heparin	Ecoflex, EastarBio,
Hyaluronic acid	Biomax
Chitin/chitosan	*Poly(vinyl alcohol)*
Vegetal	*Polyamides*
Cellulose and derivatives	Copolyamides
Lignin	Poly(ester amides)
Starch and derivatives	Poly(amino acids)
Microbial fermentation	Poly(b-hydroxy alkanoate), PHA
Dextran	Poly(b-hydroxy butyrate), PHB
Xanthan	Poly(b-hydroxy butyrate-co-valerate),
Pullulan	PHBV
Plant algae/extracts	*Pseudopoly(a-amino acids)*
Pectin	Poly
Inulin	(a-amino acid ester)
Alginate	Poly(ester-ureas)
Carrageenan	Poly(iminocarbonates)
Agar	*Polyanhydrides*
Gums	*Poly(ethyleneglycol)/poly(orthoester)s*
Xyloglucan	*Polyphsophazenes*
Levan	*Polyurethanes, PUR*
	Poly(ester urethane), AU
	Poly(ether urethane), EU
	Poly(urethane urea)s, PUU
	Polyolefins

This list is a good representation of the potential solutions, but from the many different version we have to choose only those which can be able to pass not only on the very strictly environmental regulations, they have to pass – on that level as the well known normal plastic cushions – the very high level mechanical requirements too.

5.2. What we have to know to be “green”?

As well known from many papers, if we develop a new product – packaging system, it is ineluctable to clear and define the many times mentioned logistic stresses, which includes both mechanical and environmental stresses.

If we can describe these stresses clearly, for example by a data logger, which be able to store the following parameters during the whole logistic link, we can start to choose the potential right EDP foam.

Parameters which ineluctable using any kind of movedamping system:

- Number and duration of the impacts [ms, m/s^2]
- Vibration stresses [s, m/s^2]
- Temperature and humidity inside the packaging [^oC, Rh%]
- method of manipulating and handling

Additional parameters, we have to know, if we would like to use EDP foams:

- Storage times (at raw material supplier, packaging supplier, product manufacturer, distribution center, etc.)
- Degree of sunshine or light exposure

These additional information also have to be the base data of the development because, as I described in the earlier chapter, there are many types of EDP foams which answer differently to the described stresses. Many of the biological origin EDPs don’t like the humidity. The water vapour can be able to decrease their physical characteristics, and of course it also influences the cushion characteristic. Other way, many of the synthetic origin EDPs are sensitive to the temperature and to the light exposure. These effects, if we don’t care about them can be able to start a disadvantageous process, which also can be able to modify the characteristic of the cushion.

6. Conclusions

Summarizing the paper we can clearly see that the innovation of new type movedamping system, is a very complicated task. We have to know everything about take product, about the characteristic of each cushion material (both normal and degradable), about the possible environmental and mechanical stresses, etc. This development process additionally have to be connected with the product development, which have to be done parallel with the development of packaging system.

Therefore, there is a huge potential for conducting research and large-scale biodegradation studies in this field to make valuable contribution in solving environmental and resource depletion problems of the world.

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