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Experimental study of polystyrene packaging compression resistance

E. Kibirkštis*, A. Lebedys, A. Dabkevičius***, V. Maik******

**Kaunas University of Technology, Studentų 56-350, 51424 Kaunas, Lithuania, E-mail: edmundas.kibirkstis@ktu.lt*
***Kaunas University of Technology, Karaliaus Mindaugo pr. 21, 44295 Kaunas, Lithuania, E-mail: alis.lebedys@ktu.lt*
****Kaunas University of Technology, Studentų 56-302, 51424 Kaunas, Lithuania, E-mail: arturas.dabkevicius@ktu.lt*
*****Ukrainian Academy of Printing, Podgolosko st. 19, 79020 Lvov, Ukraine, E-mail: maik@polygraf.lviv.ua*

1. Introduction

At present, a lot of products all over the world are packed in flexible and rigid plastic packaging, since it can well protect the product against environmental impact and is relatively light, durable and cheap [1].

The expansion trends of the packaging application depend on the processes of its production, exploitation and recycling. Two main present-day requirements could be mentioned as decisive in affecting the development of the packaging: preservation of the product quality and the reduction of packaging waste as an environmental pollutant. In terms of their construction, the design of plastic packages meant for liquid and paste-type products of different consistencies may be different even when packing the same type of production; however, there exist certain major, globally accepted solution groups. The most popular plastic packages are truncated-cone-shape containers, tapered downwards, often thermally sealed with laminated multilayered foil lids or pressed plastic closures, etc. Recently, the application of plastics in packaging has been successfully competing with the industry of traditional packaging materials (paper, cardboard, glass and metal). Huge amounts of plastics as relatively cheap and easily recyclable material are used in packaging. For example, since the year 2002 the flow of plastic package waste in Lithuania has increased by 3.000 tons (from 25.000 tons in 2002 to 28.000 tons in 2006) [2].

It is very important to use plastics economically, therefore, when designing new plastic packages, it is essential to reduce production waste, and at the same time, when minimizing the mass of the packages, not to lose their rigidity and resistance. It should be admitted that the world practice has not got a sufficiently developed calculation and design methodology for this type of packaging. Thus, Western experience is the most often relied upon when producing packages. Lithuanian producers have internal enterprise standards [3] which refer to Lithuanian standards [4] and hygienic norms [5]. The production of polystyrene packaging in Ukraine follows the technical norm [6].

One of the most important mechanical characteristics of packaging is its resistance to vertical compression load. This load increases significantly when the packed goods are loaded on pallets which, in their turn, are stacked one upon another. In such cases the greatest loads are affecting the packages at the bottom and the forces are directed vertically downwards. The packed product can sometimes overtaken part of the loads and thus diminish the damage danger; however, this is not characteristic of the packages under discussion as they are usually filled up to the top (lid).

The data obtained when testing plastic containers subjected to static forces are important in developing the packaging more suitable for industry and usage in accordance with environmental EU requirements which define that further development of packaging is related to the manufacture of durable packages, minimizing the amount of packaging materials [7, 8]. One of the main requirements for minimizing the amount of packaging materials in Directive 94/62/EB is formulated as follows: “Packaging shall be so manufactured that the packaging volume and weight be limited to the minimum adequate amount to maintain the necessary level of safety, hygiene and acceptance for the packed product and for the consumer”.

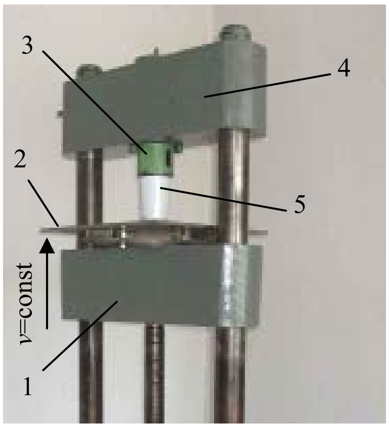
For studying mechanical characteristics, different compression and tension tests with various materials (polymers among them) and products (packages included) are performed. Compression resistance of polymer films as a printing material as well as of their seams is analyzed in paper [9]. Polystyrene tension tests have been performed by Adhikari, Huy, Henning, Michler and Knoll and published in [10]. In the paper by Berthoud, G’Sell’ and Hiver [11] polystyrene (PS) samples in compression and pressure tests are compared with polymetylcrylate (PMMA) samples. Rodriguez in his paper [12] presents calculation methodology for the deformation of a sideways compressed polystyrene container by using the finite element method. Barrier properties of polystyrene are also studied extensively: water diffusion through a polystyrene membrane was described by Brandao, Meireles, de Assuncao and Filho [13]. Bureau and Gendron presents the results of shock load tests on polystyrene packaging in [14]. The latter tests were based on standard test methods ASTM C165 and D3763. Results of testing cardboard packaging for resistance to vertical compression load are studied in [15].

The analysis of the available research publications leads to a conclusion that the resistance of polystyrene packaging to compression has not been studied sufficiently.

The aim of the present paper is to define the most popular types of truncated-cone-shape containers, tapered downwards, produced in Lithuania and Ukraine, and to carry out tests on their compression resistance under vertical loads.

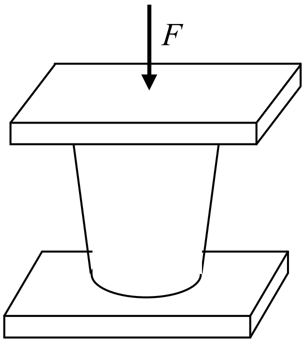
2. Testing procedures

A compression stand (Fig. 1 a) was used for testing, and special computer equipment was used for processing the measuring results and visualizing the data (Fig. 1, b).



a

b



c

Fig. 1 Compression test system for plastic containers: a) container compression stand: *1* – moving base, *2* – bottom slab, *3* – upper fixed support, *4* – fixed base, *5* – package under compression; b) signals processing and measuring module: *6* – tensometer amplifier TS-3, *7* – oscilloscope Pico Scope 3424, *8* – portable computer with special oscilloscope software; c) scheme of package compression under vertical axial load *F*

The experimental study was carried out by using different size samples (plastic containers) made from polystyrene (PS), whose exterior view is presented in Table 1. The selection of the samples was determined by the fact that this type of packaging is widely used both in Lithuanian and Ukrainian food industry. When analyzing the geometric variety of the package exterior shape, eight characteristic types of containers were distinguished. They differed in the configuration of the top and bottom parts (see Table 1). The load and deformation dependence curves were obtained by performing empty polystyrene container tests under vertical load.

During the testing, the packaging under investigation were placed on the bottom slab 2 which is the component of compression load measuring unit (Fig. 1, a). The bottom plane of base element *3* is parallel to the bottom base slab *2*. This slab is connected to the tensoresistor measuring unit. During package testing, the electric signal received from the sensors was amplified by amplifier TS-3 (position *6*, Fig. 1). The received analogous signal was transmitted to oscilloscope Pico Scope 3424 (position *7*, Fig. 1), where it was converted into a digital and transmitted to the personal computer (position *8*, Fig. 1). The dependence of compression force and package deformation was displayed on its monitor. For processing the testing data and visualizing the obtained dependencies, a PC with oscilloscope software Pico Log for Windows Release 5.14.6 was used. During the test, the bottom stand slab with the package under test moves vertically upwards at the regular speed of v=3.5x10^{-4} m/s, when the upper package part touches the fixed upper base element, the process of package compression starts. The personal computer receives the concrete test data, expressing the dependence of the electric signal from the load measuring unit upon the time, which is transferred into the dependence of compression force upon package deformation in vertical direction.

The tests were carried out at the temperature 20±2° C and air humidity 65± 2%.

3. Analysis of the obtained testing data

Figs. 2-8 and Table 1 present the findings of compression resistance tests of all the main types of packaging samples produced in Lithuania and Ukraine. Table 2 gives the general view of the containers before and after compression.

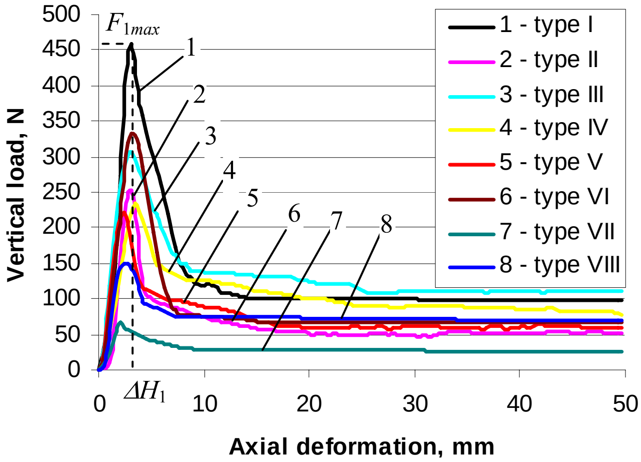
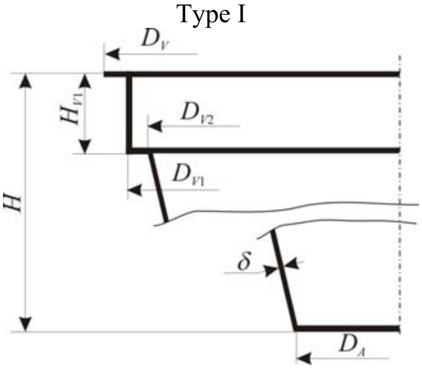
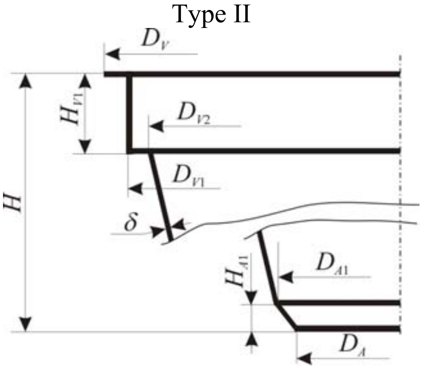
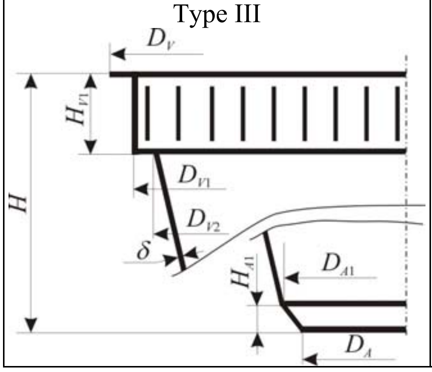


Fig. 2 Compression resistance of empty polystyrene containers (package types: Type I (7000/L), Type II (4241), Type III (4235), Type IV (7001/L), Type V (5725/L), Type VI (7060/L), Type VII (5721/L) and Type VIII (5713/L)): F_{1max}– maximum compression load of the first package, ΔH_1 – deformation of the package in mm, under maximum compression load

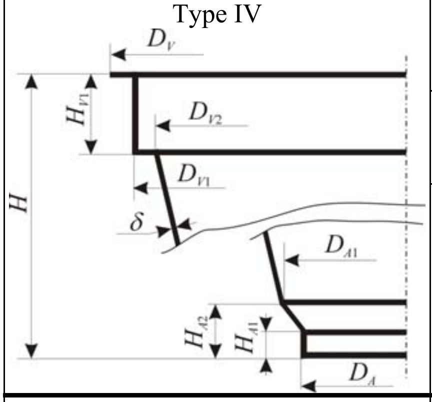
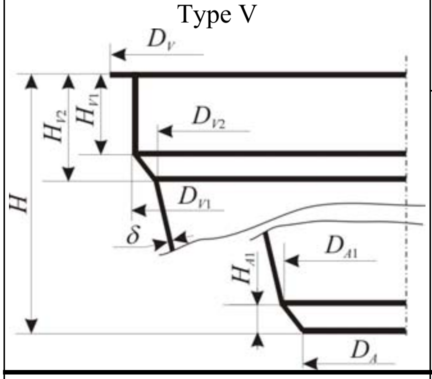
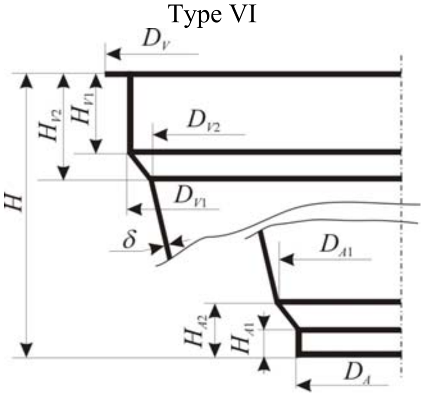
Fig. 2 shows graphic dependencies of container loads and deformations when they were compressed under vertical load (compression velocity v=3.5×10^{-4} m/s) and deformed in the axial direction ΔH=50 mm.

Table 1
Geometric parameters of tested packaging and maximum values of vertical compression and deformation under maximum loads

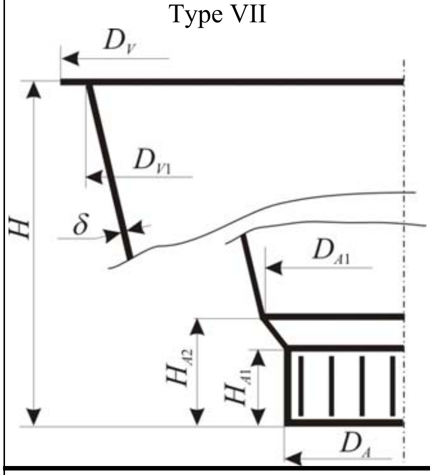
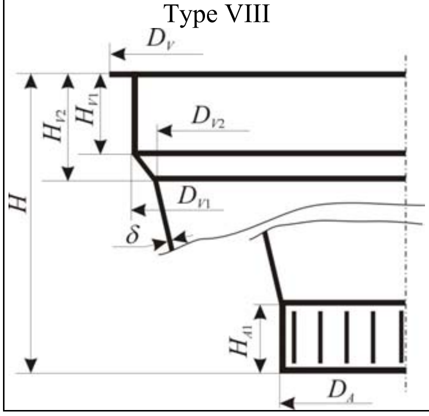
Geometry of the top and bottom parts of the package	Package code	Characteristic geometric parameters of the package, mm	Wall thickness, mm	Package volume, ml	Maximum compres-sion load F_{imax}, N	Deformation under maximum compression load, ΔH_i, mm
Type I 	4402	D_V=75; D_{V1}=68; D_{V2}=64; D_A=57; H=52; H_{V1}=7	0.19	125	119.80	3.5
	4403	D_V=75; D_{V1}=68; D_{V2}=63; D_A=53; H=89; H_{V1}=10	0.19	200	76.22	3.5
	5000/L	D_V=75; D_{V1}=67; D_{V2}=63; D_A=54; H=97; H_{V1}=13	0.2	200	139.7	2.45
	6006/L	D_V=95; D_{V1}=90; D_{V2}=84; D_A=75; H=57; H_{V1}=9	0.21	200	134.62	2.45
	7002/L	D_V=95; D_{V1}=90; D_{V2}=84; D_A=73; H=104; H_{V1}=13	0.25	450	320.04	2.8
	5612/L	D_V=75; D_{V1}=68; D_{V2}=64; D_A=57; H=50; H_{V1}=8	0.34	100	322.58	2.45
	5717/L	D_V=75; D_{V1}=67; D_{V2}=63; D_A=54; H=70; H_{V1}=10	0.33	150	447.04	2.45
	7000/L	D_V=95; D_{V1}=90; D_{V2}=84; D_A=67; H=90; H_{V1}=12	0.34	350	459.74	3.15
	7067/L	D_V=95; D_{V1}=90; D_{V2}=84; D_A=80; H=43; H_{V1}=13	0.34	150	416.56	2.8
	7068/L	D_V=95; D_{V1}=89; D_{V2}=84; D_A=78; H=63; H_{V1}=13	0.29	250	391.16	2.8
	7069/L	D_V=95; D_{V1}=90; D_{V2}=84; D_A=79; H=53; H_{V1}=13	0.33	200	365.76	3.15
Type II 	4226	D_V=95; D_{V1}=90; D_{V2}=85; D_A=75; D_{A1}=81; H=59; H_{V1}=10; H_{A1}=12	0.31	250	144.88	2.45
	4241	D_V=95; D_{V1}=84; D_{V2}=80; D_A=61; D_{A1}=70; H=102; H_{V1}=10; H_{A1}=14	0.23	400	253.48	3.15
	4250	D_V=95; D_{V1}=90; D_{V2}=84; D_A=65; D_{A1}=71; H=120; H_{V1}=13; H_{A1}=12	0.23	500	330.67	3.5
	7075/L	D_V=95; D_{V1}=88; D_{V2}=85; D_A=63; D_{A1}=72; H=91; H_{V1}=9; H_{A1}=14	0.34	360	454.64	2.1
Type III 	4235	D_V=95; D_{V1}=88; D_{V2}=80; D_A=56; D_{A1}=73; H=83; H_{V1}=24; H_{A1}=16	0.31	350	306.32	3.15

Note: containers made in Lithuania are marked with index „L“. Containers without an index are made in Ukraine.

Continuation of Table 1

Geometry of the top and bottom parts of the package	Package code	Characteristic geometric parameters of the package, mm	Wall thickness, mm	Package volume, ml	Maximum compression load F_{imax}, N	Deformation under maximum compression load, ΔH_i, mm
Type IV 	4401	$D_V=75$; $D_{V1}=69$; $D_{V2}=64$; $D_A=46$; $D_{A1}=52$; $H=94$; $H_{V1}=9$; $H_{A1}=5$; $H_{A2}=9$	0.21	200	73.78	2.8
	7001/L	$D_V=95$; $D_{V1}=89$; $D_{V2}=83$; $D_A=67$; $D_{A1}=73$; $H=120$; $H_{V1}=13$; $H_{A1}=4$; $H_{A2}=17$	0.23	500	233.68	3.5
	7072/L	$D_V=95$; $D_{V1}=88$; $D_{V2}=83$; $D_A=64$; $D_{A1}=72$; $H=91$; $H_{V1}=9$; $H_{A1}=8$; $H_{A2}=12$	0.23	350	259.08	2.8
Type V 	4220	$D_V=95$; $D_{V1}=86$; $D_{V2}=74$; $D_A=61$; $D_{A1}=67$; $H=57$; $H_{V1}=10$; $H_{V2}=20$; $H_{A1}=10$	0.24	200	188.23	3.5
	5725/L	$D_V=75$; $D_{V1}=70$; $D_{V2}=61$; $D_A=52$; $D_{A1}=57$; $H=76$; $H_{V1}=7$; $H_{V2}=11$; $H_{A1}=10$	0.33	150	220.98	2.45
Type VI 	4225	$D_V=95$; $D_{V1}=85$; $D_{V2}=75$; $D_A=50$; $D_{A1}=64$; $H=67$; $H_{V1}=10$; $H_{V2}=16$; $H_{A1}=6$; $H_{A2}=11$	0.24	250	166.79	2.8
	4236	$D_V=95$; $D_{V1}=87$; $D_{V2}=74$; $D_A=57$; $D_{A1}=62$; $H=112$; $H_{V1}=10$; $H_{V2}=20$; $H_{A1}=4$; $H_{A2}=12$	0.23	360	294.39	2.8
	4404	$D_V=75$; $D_{V1}=68$; $D_{V2}=58$; $D_A=43$; $D_{A1}=47$; $H=78$; $H_{V1}=6$; $H_{V2}=20$; $H_{A1}=6$; $H_{A2}=9$	0.29	170	179.95	2.45
	5716/L	$D_V=75$; $D_{V1}=70$; $D_{V2}=60$; $D_A=46$; $D_{A1}=51$; $H=72$; $H_{V1}=7$; $H_{V2}=14$; $H_{A1}=14$; $H_{A2}=14$	0.18	125	111.76	1.4
	7060/L	$D_V=95$; $D_{V1}=89$; $D_{V2}=76$; $D_A=60$; $D_{A1}=65$; $H=50$; $H_{V1}=5$; $H_{V2}=10$; $H_{A1}=6$; $H_{A2}=8$	0.33	130	332.74	3.15
	7062/L	$D_V=95$; $D_{V1}=88$; $D_{V2}=78$; $D_A=58$; $D_{A1}=65$; $H=75$; $H_{V1}=6$; $H_{V2}=11$; $H_{A1}=10$; $H_{A2}=14$	0.28	250	213.36	2.45

Continuation Table 1

<table>
<tr><th>Geometry of the top and bottom parts of the package</th><th>Package code</th><th>Characteristic geometric parameters of the package, mm</th><th>Wall thickness, mm</th><th>Package volume, ml</th><th>Maximum compression load F_{imax}, N</th><th>Deformation under maximum compression load, ΔH_i, mm</th></tr>
<tr><td rowspan="2">Type VII

</td><td>5721/L</td><td>D_V=75; D_{V1}=69; D_A=48; D_{A1}=54; H=98; H_{A1}=17; H_{A2}=20</td><td>0.2</td><td>200</td><td>66.04</td><td>2.1</td></tr>
<tr><td>7004/L</td><td>D_V=95; D_{V1}=89; D_A=67; D_{A1}=77; H=117; H_{A1}=17; H_{A2}=23</td><td>0.33</td><td>500</td><td>233.68</td><td>3.15</td></tr>
<tr><td>Type VIII

</td><td>5713/L</td><td>D_V=75; D_{V1}=70; D_{V2}=62; D_A=45; H=80; H_{V1}=9; H_{V2}=14; H_{A1}=10</td><td>0.31</td><td>130</td><td>149.86</td><td>2.45</td></tr>
</table>

Tests with the rest of the packaging were carried out deforming the containers by 25 mm, since during the initial deformation stage the critical deformations occur, which means that under working conditions the packaging filled with grainy or liquid products is already not suitable for usage.

When analyzing the dependences (Figs. 2-8) obtained during the tests, it can be noted that at the initial compression stage the resistance of all the containers to vertical load is the largest, and the obtained deformation-compression load dependence can be considered as close to linear. When maximum load is reached (e.g., in Fig. 2, curve *1* would reach it when F_{1max}=459.74 N, deformation ΔH_1 at 3.5 mm), the packaging resistance to compression starts falling rapidly. Such fall of the container's resistance is typical for all the tested packaging. It can be stated that at this initial stage of packaging resistance decrease the deformation-load dependence is close to linear in certain cases (see Fig. 2, curves *1*, *2* and *3*; Fig. 3, curves *1* and *2*; Fig. 4. curves *1* and *3*; Fig. 5, curves *1*, *3* and *5*; Fig. 6, curves *1* and *2*; Fig. 7, curves *1* and *2*; Fig. 8, curve *1*). However, there are some cases when the above mentioned dependence at this compression stage cannot be considered linear (see Fig. 2, curve *7*; Fig. 3, curves *3* and *5*; Fig. 4, curve *4*; Fig. 5, curves *2* and *4*; Fig. 8, curves *2* and *3*, etc.). In further deformation stages, it is not possible to express the clear and regular deformation-load dependence: in some cases, compression resistance clearly decreases with increasing deformation, while in other cases the changing increase-decrease tendencies are observed (e.g., Fig. 2, curves *1* and *8*). However, this last stage of container deformation is not important for further study since, judging by the test findings, during usage some of the tested containers can be deformed up to approximately 3 mm, later the container walls get irreversible plastic deformations and they are no longer suitable for usage. During the testing other regularities were also observed. For example, under the load when the container's resistance to deformation is the highest (e.g., F_{1max}=459.74 N, see Fig. 2, curve *1*), its walls start deforming, bending in different directions, in some places cracks or folds appear, and so on. These maximum values of loads and deformations that cause cracks in the walls of containers during the compression process are presented in Table 1.

Table 2

Types of packages (samples) and their external view before and after compression

Package type	Package code	Container before compression	Container after compression	Package code	Container before compression	Container after compression
Type I	4403			7000/L		
Type II	4226			4250		
Type IV	4401			7072/L		

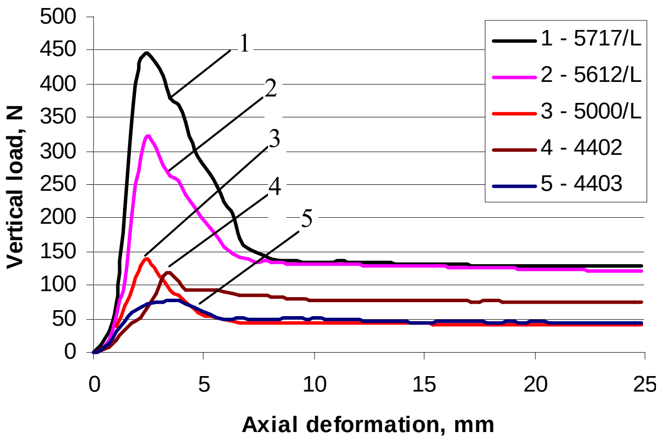


Fig. 3 Deformation resistance of empty Type I polystyrene containers with top diameter D_V=75 mm

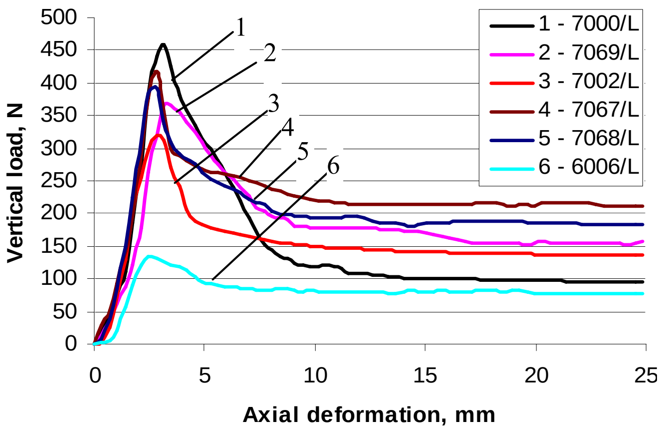


Fig. 4 Deformation resistance of empty Type I polystyrene containers with top diameter D_V=95 mm

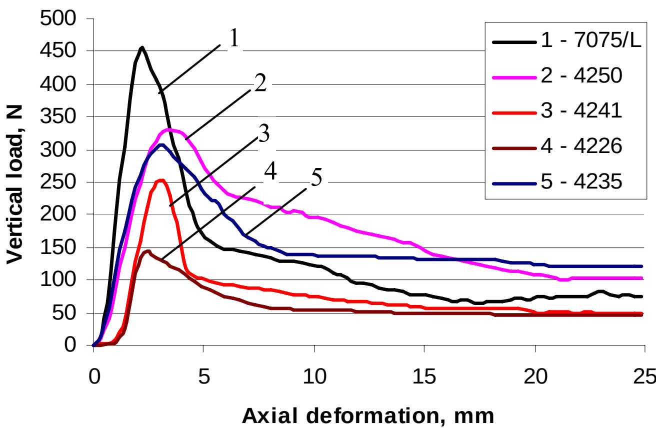


Fig. 5 Deformation resistance of empty Type II and III polystyrene containers

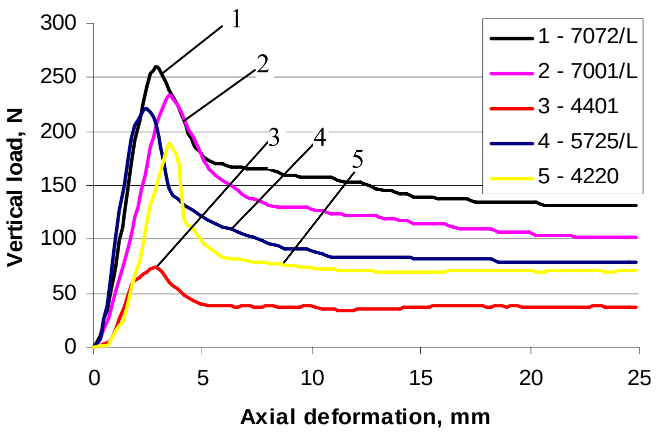


Fig. 6 Deformation resistance of empty Type IV and V polystyrene containers

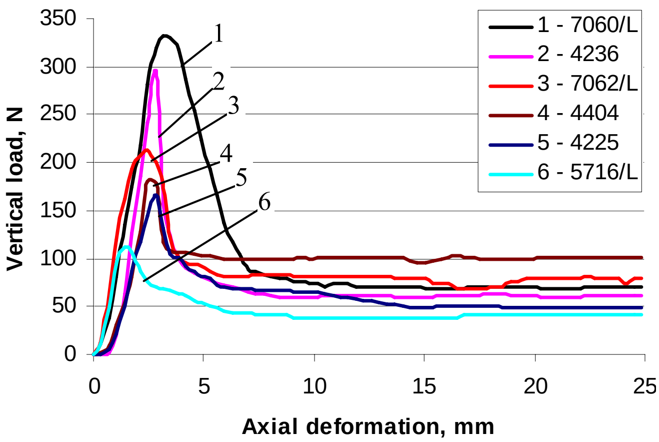


Fig. 7 Deformation resistance of empty Type VI polystyrene containers

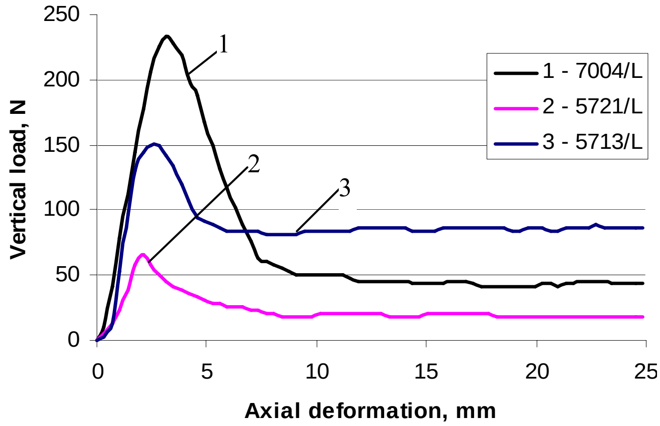


Fig. 8 Deformation resistance of empty Type VII and VIII polystyrene containers

The general view of the packaging before and after the compression tests is presented in Table 2. We may conclude that according to the external view of the compressed containers it is not possible to clearly define which type of the package it belongs to, since the external view of all the deformed packages is similar.

When comparing the polystyrene packaging made in Lithuania and Ukraine in terms of dependences of compression resistance upon deformation, no significant differences have been noticed.

For more precise analysis of package resistance to vertical compression load it would be reasonable to introduce nondimensional values, relating geometric parameters (wall thickness, container‘s cone angle), vertical load value, characteristics of the polystyrene which the container is made of, and kinematic and dynamic parameters of the load.

At this work stage we did not aim to investigate the effect of the container‘s geometric shape, including the top and bottom configuration, upon the package resistance to compression. Evaluation of this effect is important both theoretically and practically, and it will be performed in the future study in this area.

The analysis of the obtained study results have led to the following conclusions.

4. Conclusions

1. Classification of a wide range of polystyrene containers for product packaging has been accomplished and eight most popular geometric types of truncated cone shape polystyrene containers (packages), tapered downwards, produced in Lithuania and Ukraine have been distinguished.

2. Maximum values of package resistance to vertical compression loads and the values of package deformations in their vertical axis direction have been determined.

3. The changes of deformation-compression load dependences for all the types of packaging under the study were similar. At the initial sample compression stage, certain zones can be distinguished where the deformation-compression load dependence is close to linear.

4. No essential differences have been found compression resistance of the packaging produced in Lithuania and Ukraine.

5. The obtained testing results can be applied in designing packages, since the data, depending on the estimated package compression loads, allow us to make reasonable solutions how to minimize its mass while preserving the desired level of the package function.

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E. Kibirkštis, A. Lebedys, A. Dabkevičius, V. Maik

EKSPERIMENTINIAI IŠ POLISTIRENO PAGAMINTŲ PAKUOČIŲ ATSPARUMO GNIUŽDYMUI TYRIMAI

R e z i u m ė

Pateikti eksperimentiniai plastikinių pakuočių, pagamintų iš polistireno (PS) ir skirtų biriems bei įvairios konsistencijos skystiems maisto produktams pakuoti, tyrimai. Pakuočių bandiniai buvo pagaminti Lietuvoje ir Ukrainoje. Analizuojant pakuočių išorinės formos geometrinę įvairovę, buvo išskirti aštuoni būdingi indelių tipai, besiskiriantys viršutinių ir apatinių dalių konfigūracija. Atlikti šių pakuočių atsparumo gniuždymui jų vertikalios ašies atžvilgiu tyrimai. Sudarytos gniuždymo apkrovų ir pakuočių deformacijų grafinės priklausomybės, nustatytos maksimalios gniuždymo apkrovų reikšmės. Nustatytos tirtų pakuočių gniuždymo apkrovų ir jas atitinkančių deformacijų priklausomybių zonos, kuriose galima skirti artimą tiesiniam ir netiesinį parametrų kitimo pobūdį.

E. Kibirkštis, A. Lebedys, A. Dabkevičius, V. Maik

EXPERIMENTAL STUDY OF POLYSTERENE PACKAGING COMPRESSION RESISTANCE

S u m m a r y

Experimental study of plastic packages made of polystyrene (PS), used for packing grainy and liquid products of different consistency, is presented. The packaging samples were produced in Lithuania and Ukraine. When analyzing the external shape variety, eight popular container types were distinguished, differing in their top and bottom part configuration. The study of packaging resistance to compression along its vertical axis has been performed. Graphic dependences of compression loads and deformations of the packages have been obtained and the maximum values of compression loads have been determined. Certain zones of the tested package compression and corresponding deformation dependences have been defined in which the parameter change close to linear can be observed.

Э. Кибиркштис, А. Лебедис, А. Дабкявичюс, В. Майк

ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ УПАКОВОК ИЗ ПОЛИСТИРОЛА НА СОПРОТИВЛЕНИЕ СЖАТИЮ

Р е з ю м е

Представлены экспериментальные исследования упаковок из полистирола (PS), предназначенных для размещения сыпучих и разной консистенции жидких пищевых продуктов. Образцы упаковок изготовлены в Литве и Украине. При анализе геометрических разновидностей внешних форм упаковок было выделено восемь характерных типов стаканчиков, различающихся конфигурацией верхних и нижних частей. Произведены исследования прочности этих типов упаковок при их сжатии в направлении вертикальной оси. Получены зависимости нагрузок и деформаций упаковок, которые представлены в виде графиков, найдены максимальные величины нагрузок при сжатии. Установлены зоны зависимостей нагрузок при сжатии и им соответствующих деформаций упаковок, в которых можно выделить близкий к линейному или нелинейный характер изменения параметров.

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