Testing the Mechanical Reliability of Plastic Bottles for Drinking Beverages

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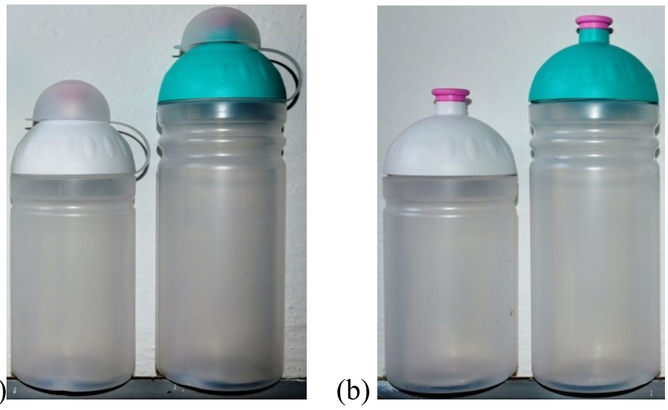
Abstract: In cooperation with industry, testing was conducted to determine the reliability (i.e. applicability in regular use by people) of "sports caps" on plastic bottles. These bottles are popular all over the world and comply with health standards. They are designed to contain various types of popular beverages. The maximum overpressures for situations of liquid leakages were measured (i.e. volumes of carbonated or uncarbonated beverages, sealing, stress analyses etc.). For the laboratory testing at the VŠB–Technical University of Ostrava, a custom-made hydraulic/pneumatic system was built, based on a PR 15 sensor with accessories (Hyrotechnik Lumburg Multisystem 5050 measurement system, Orlík 1500 W compressor, tubes, etc.). The experiments were statistically evaluated (in the form of histograms) and the sealing reliability of the bottle + "sports cap" closure system was assessed. The presented results are important for future numerical modelling, design improvements and other investigations. Stresses and their variabilities were calculated according to Laplace's theory of thin shells.

Keywords: Sealing; Reliability; Plastic Bottle Closure; Overpressures; Measurement; Hydraulic/Pneumatic System, Leakage, Stresses, Statistics, Histograms

1 Introduction

In cooperation with the VŠB–Technical University of Ostrava (Ostrava, Czech Republic), the manufacturer required an investigation of the sealing, strength and reliability of the given closure system for plastic bottles. The bottles have the popular type of closure known as a "sports cap", and they are designed for drinking still (uncarbonated) or carbonated beverages (water, Coca-Cola etc.); see Fig. 1. The bottles were produced in two versions: ones without a hygienic spout cover and the others with this cover.



(a) (b)

Fig. 1: Bottles with "sports caps" (a) without a hygienic spout cover, (b) with a hygienic spout cover.

The sealing of the bottles was tested under conditions simulating their use in ordinary conditions (i.e. with new and pre-used "sports caps"); see Fig. 2. The measurements were conducted on randomly selected bottles supplied by the manufacturer; these were numbered in ascending order. The selection was made from a set of 28 bottles. The bottles were divided into 4 types (7 × 0.75 l with hygienic spout cover, 7 × 0.75 l without hygienic spout cover, 7 × 0.5 l with hygienic spout cover and 7 × 0.5 l without hygienic spout cover); see Fig. 1.

The aim of the study was thus to test and statistically evaluate possible undesirable leakages of beverages from plastic bottles with the "sports cap"-type closure; such leaks cause dissatisfaction among the producer's customers. The results of the testing and their statistical evaluation (histograms) are original outputs and are used by the producer for ongoing research and development purposes. The study also determines the variance of stress values in the plastic bottle wall according to Laplace's theory of thin shells.

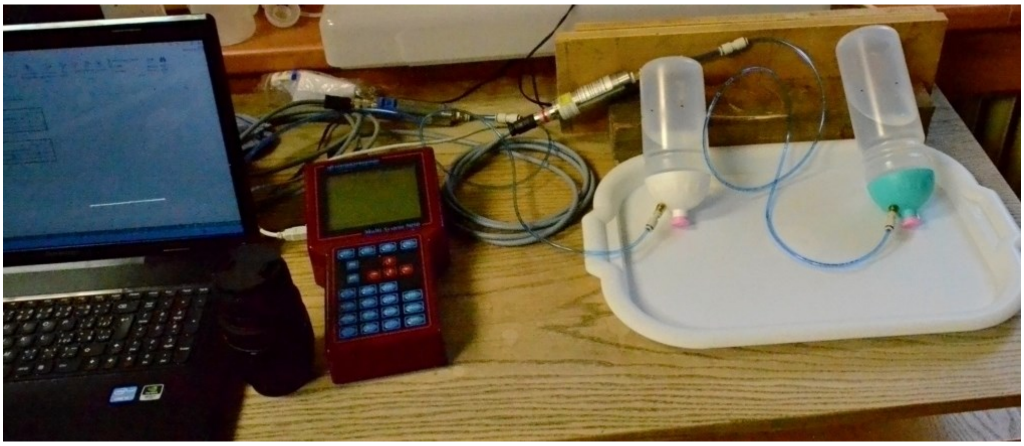


Fig. 2: Measurement equipment setup and positioning of the bottles (containing liquid).

2 Experiments

It was necessary to conduct experiments in order to meet the requirements of the producer – i.e. to verify the sealing reliability of the bottles when containing carbonated or still (uncarbonated) beverages. As a first step it was necessary to determine the overpressure in the bottle caused by the release of carbon dioxide from the beverage. An initial measurement was therefore conducted: a beverage was poured into the bottle, then the bottle was closed and shaken. After shaking, the overpressure was measured using a pressure sensor. The initial measurement showed that the overpressure inside the bottle reached approx. 1.2 bar (depending on the type of beverage and its volume inside the bottle). This was the first conclusion; it enabled us to determine the pressure interval occurring within the bottles.

It was then necessary to determine the types and methods of testing to be used. It was decided that the following tests would be conducted:

1) Identification of leakage points using pressurized air, with the bottle positioned underwater,
2) Measurement of pressure after opening the bottle closure,
3) Decrease in air pressure over a 24-hour period,
4) Determination of the extent of liquid leakage caused by released carbon dioxide.

The sealing test was conducted by a semi-destructive method as follows. A hole was drilled in the lid of the bottle, and a screw-fixture was inserted into the hole to enable the tube to be connected. First, the seal was tested underwater using pressurized air; this enables any points of air escape to be easily identified; see Fig. 2. The measurement setup is shown in Fig. 3(a). The pressure regulator was set to the required air pressure, and the bottle was pressurized underwater through the directional control valve. The design of the measurement system was based on measurements of static characteristics of pneumatic elements [1].

This test showed that in most cases leakages occurred via the bottle cap. However, in some bottles there were leakages via the screw-thread which serves to attach the cap to the bottle.

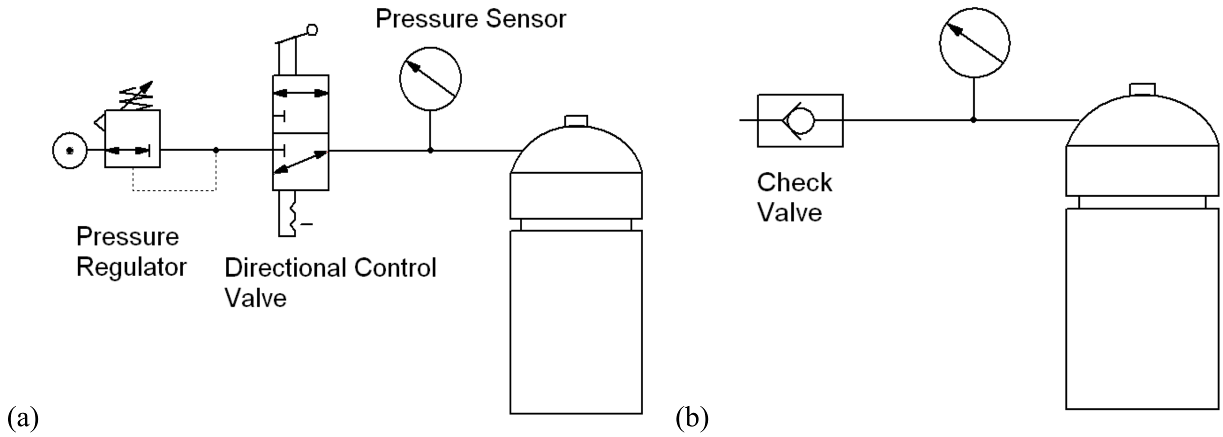


Fig. 3: (a) Setup of bottle sealing test, (b) Setup of check valve connection.

The same setup was used when determining the overpressure required to cause the spontaneous opening of the bottle cap, which was in the unlocked position. The test was conducted on both new and pre-used bottle caps. In this case, the pressure regulation valve was used to gradually increase the overpressure inside the bottle until the air pressure caused the cap to burst open (i.e. an unpleasant occurrence for the user). The overpressure at the moment of opening was determined from records taken using the Hydrotechnik M5050 measurement system. A PR 15 sensor was used, with a range of –1 to 6 bar. The mean overpressures required for spontaneous opening of an unlocked bottle cap are 1.115 bar (for a new, unused cap) and 0.889 bar (a pre-used bottle cap). The results are presented in section 3.

Measurements were also conducted to determine pressure loss from inside the bottle over a 24-hour period. In this case, the bottle was pressurized and then disconnected from the pressurized air source. In order to prevent air loss via the tube, a check valve was added to the measurement setup; see Fig. 3(b). After disconnection from the air source, measurement of the overpressure inside the bottle commenced; see Fig. 4. The results show that once the overpressure inside the bottle has decreased to approx. 0.9 bar, it ceases to decrease any further, and no further leakage occurs.

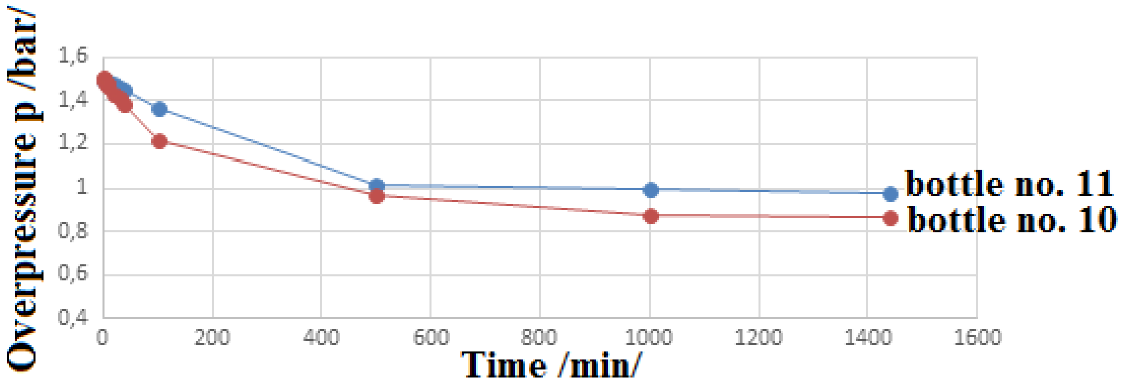


Fig 4: Graph of overpressure decrease (leakage from bottle) – results of 24-hour measurement.

The final measurement determined the quantity of liquid leaked from the bottle. A 0.75 l bottle was partially filled with 0.5 l of a selected carbonated beverage (of the Coca-Cola type). The bottle was then closed, fitted with a pressure sensor, and weighed. The same process was applied to 0.5 l bottles, into which 0.35 l of the beverage was poured. The bottles were shaken, releasing carbon dioxide. The overpressure of the gas was almost 1 bar in all cases. The bottles were then placed so that the bottle neck was positioned below the beverage surface level. In some cases, the overpressure of the released carbon dioxide caused leakage of the liquid (probability of leakage is 50%). After an hour, the bottles were re-weighed and the quantity of leaked liquid was thus determined.

All measurements were conducted at normal temperatures, i.e. 20^{o} C.

3 Results

The measurements were conducted in order to test the reliability of the bottles for normal use. The measurements determined the overpressure p in the bottle (see Fig. 5 and Tab. 1), the decrease in overpressure during the monitored period, and the quantity of liquid leaked over a certain period. The results indicate that the type of liquid inside the bottle has a major influence on leakage. There was no liquid leakage from bottles containing still (uncarbonated) water. The quantity of liquid leakage increases in bottles containing carbonated mineral water or beverages of the Coca-Cola type. Leakage of liquid from the bottles thus only occurred in cases where there was increased internal overpressure p. The largest percentage of leaks occurred via the rubber “sports cap” closure.

Liquid	Bottle no.	Bottle volume /l/	Volume of leakage /ml/	Point of leakage	Max. overpressure /bar/	Min. overpressure /bar/	Mean overpressure /bar/
Coca-Cola	12	0.75	0	-	0.803	0.787	0.782
Coca-Cola	13	0.5	8	cap	0.875	0.822	0.822
Mattoni mineral water	18	0.75	4	screw-fitting	0.935	0.897	-
Mattoni mineral water	19	0.5	0	-	0.961	0.918	-
Kofola carbonated soft drink	14	0.75	0	-	0.734	0.702	0.701
Kofola carbonated soft drink	15	0.5	2	cap	0.77	0.742	0.734
Mattoni mineral water	16	0.75	0	-	0.526	0.52	0.524
Coca-Cola	17	0.5	2	cap	1.042	1.037	1.038
Water	20	0.5	0	-			
Coca-Cola	21	0.5	0	-			
Water	22	0.75	0	-			
Coca-Cola	23	0.75	2	cap			

Tab 1: Results of measurements for bottles containing carbonated and uncarbonated beverages

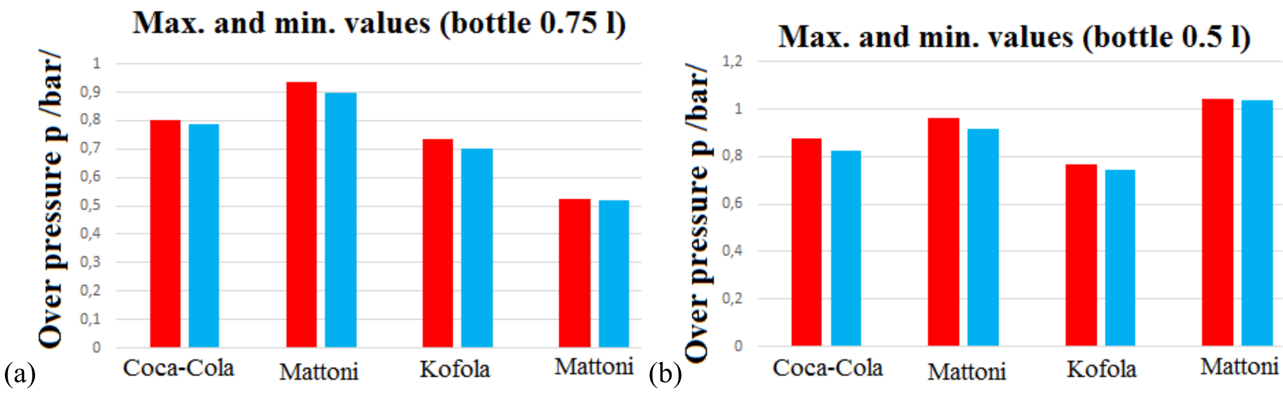


Fig 5: Plastic bottles with the “sports cap” closure (max. and min. overpressure when containing carbonated beverages).

There was a noticeable difference in the sealing reliability between new and pre-used bottles; on the pre-used bottles, the “sports cap” was manually opened and closed 500×. Leakage from these bottles occurs at much lower pressures. A completely new bottle suffers minimal (zero) liquid leakage. Another factor influencing sealing is the force and thoroughness with which the bottle cap is closed (i.e. it may not be closed properly – the influence of the human factor). Further factors include the way in which the bottle is used (opening with teeth instead of hands, dropping the bottle, etc. – these are consequences of “normal” human behaviour) and material degradation (the mechanical properties of rubber and plastics change over time). The older the bottle (i.e. the more wear it has incurred through use), the greater the probability of liquid leakage. Based on the test results, it can be stated that a bottle of this type can be safely used (i.e. with zero liquid leakage) for uncarbonated beverages (e.g. still water, fruit juice, etc.). If the bottle contains a carbonated beverage (carbonated mineral water, beverages of the Coca-Cola type, etc.), there is a 50% chance of leakage from new bottles. If the bottle is older, and its cap has incurred wear, it is no longer suitable for carbonated beverages (probability of leakage is almost 100%).

The results shown in Tab. 1 and Fig. 5 enable the determination of meridian stress σ_m and tangential stress σ_t in the bottle wall; see [3]. At a sufficient distance from the base and the cap (approx. at the mid-point of the bottle’s height), Laplace’s theory states

$$\sigma_m = \frac{pD}{4t}, \quad \sigma_t = \frac{pD}{2t}, \qquad (1)$$

where D is the mean bottle diameter and t is the thickness of the bottle wall. The stresses are given in Tab. 2 (a 0.75 l bottle) and Tab. 3 (a 0.5 l bottle).

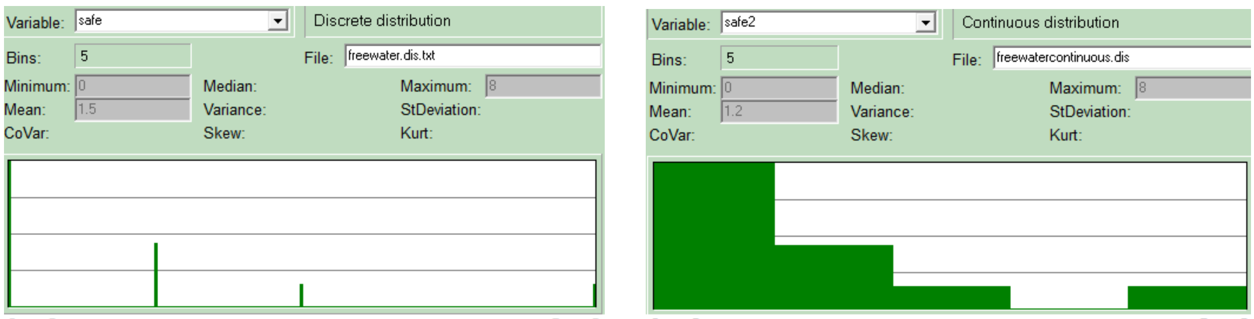
Beverage	Meridian stress σ_m /MPa/		Tangential stress σ_t /MPa/	
	MAX	MIN	MAX	MIN
Coca-Cola	2,54	2,44	5,08	4,87
Mattoni	1,99	1,91	3,99	3,81
Kofola	2,18	2,14	4,36	4,28

Tab. 2 Stress in the wall of a closed plastic bottle (0.75 l) with the "sports cap" closure.

Beverage	Meridian stress σ_m /MPa/		Tangential stress σ_t /MPa/	
	MAX	MIN	MAX	MIN
Coca-Cola	2,61	2,49	5,22	4,99
Mattoni	2,83	2,82	5,66	5,63
Kofola	2,09	2,02	4,18	4,03

Tab. 3 Stress in the wall of a closed plastic bottle (0.5 l) with the "sports cap" closure.

The results can be statistically processed e.g. via histograms, producing a suitable basis for future research and development of plastic bottle systems including the "sports cap" closure. Fig. 6 shows the histogram of the probable volume of liquid leakage (the vertical axis is frequency, the horizontal axis the leakage volume) presented discretely or continuously.



0 ml **8 ml** **0 ml** **8 ml**

(a) **Leakage of carbonated beverages** (b) **Leakage of carbonated beverages**

Fig. 6: Plastic bottle with a "sports cap" closure (statistical evaluation of the volumes of liquid leakage for carbonated beverages – (a) discrete histogram, (b) continuous histogram).

4 Conclusion

Various types of plastic bottles with "sports cap" closures are internationally popular. However, the literature still lacks even basic studies investigating these systems. For this reason, the results presented in this paper are highly original.

The results indicate that the type of liquid inside the bottle has an unexpectedly large influence on its sealing reliability. No leakage was recorded in bottles containing still (uncarbonated) water. The quantity of leakage increases if the bottles contain carbonated mineral water or beverages of the Coca-Cola type; in such cases the reliability of the closure is 50%. Leakage thus occurs in bottles with increased internal overpressure. The largest proportion of leakages occurred via the rubber seal of the bottles.

Histograms of liquid leakage or stress variability in the bottle wall are important statistical outputs which can be used in future research and development of plastic bottles for beverage consumption.

The calculated stresses and their variance (minimum and maximum values) in the bottle wall were determined via a simple and elegant method using Laplace's theory of thin shells.

The results enable us to draw the general conclusion that an older bottle with a worn "sports cap" closure no longer gives a reliable seal, thus potentially causing damage (e.g. leakage may damage personal property, food items, clothing etc.). In older bottles there is an almost 100% probability of liquid leakage. In newer bottles (with a non-worn "sports cap" closure) the probability of leakage when containing carbonated beverages is 50% (only if the "sports cap" is properly closed).

The results indicate that plastic bottles with "sports cap" closures are unsuitable for carbonated beverages.

In the future, further testing could be conducted on different bottles; this may include cyclical loading (e.g. according to [4]) or more detailed solutions applying a probability-based method [5] or a complex numerical method [6].

References

[1] FOJTÁŠEK, K, DVOŘÁK, L. Measurement of Static Characteristics of Pneumatic Motors with Elastic Working Elements, In *Transactions of the VŠB – Technical University of Ostrava, Mechanical Series*, vol. LVIII, no. 1, 2012, pp. 53 – 56, ISSN 1210-0471

[2] FRYDRÝŠEK, K., DVOŘÁK, L., BAJTEK, V., MICHENKOVÁ, Š., SEJDA, F. *Measurement Report about the Measurement of Leaking of Bottles (Zpráva z měření - testování těsnosti lahví)*, VŠB–Technical University of Ostrava, Department of Applied Mechanics, Ostrava, 2014, pp. 1-31, written in Czech.

[3] TIMOSHENKO, S. WOINOWSKY-KRIEGER, S. *Theory of plates and shells*. 2nd ed., reissued. New York: McGraw-Hill, 1987. ISBN 0070647798.

[4] HALAMA, R., SEDLAK, J., ŠOFER, M., *Phenomenological Modelling of Cyclic Plasticity*. Numerical Modelling, InTech, Croatia, 2012, pp. 329-354, ISBN 978-953-51-0219-9.

[5] LOKAJ, A., VAVRUŠOVA, K., Application of laboratory tests results of dowel joints in cement-splinter boards VELOX into the fully probabilistic methods (SBRA method). *APPLIED MECHANICS AND CIVIL ENGINEERING*, Book Series: Applied Mechanics and Materials, Vol. 137, 2012, ISSN: 1660-9336, pp. 95-99.

[6] JANČO, R., KOVÁČOVÁ, M., Using Packages Mechanics Explorers 'Beam' in Program Mathematica for Solution of Euler-Bernoulli Beams. *APLIMAT 2005 - 4TH INTERNATIONAL CONFERENCE, PT II*, ISBN:978-80-969264-2-8, Bratislava, Slovakia, 2015, pp. 197-203.