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## **PROPERTIES OF THE POLYURETHANE (PU) LIGHT FOAMS**

### **ABSTRACT**

The report presents results of laboratory investigations made on the PU foams. Mechanical properties of foams have been measured in compression tests for two foams of 16 kg/m<sup>3</sup> and 62 kg/m<sup>3</sup> density, and in tension and shearing tests for foam of 62 kg/m<sup>3</sup> density. PU foams have shown anisotropic properties as measured in parallel and perpendicular direction to the foam rise. Three directional values of Poisson's ratios in tension have been determined for foam of 62 kg/m<sup>3</sup> density. The fatigue tests have been made for foam of 62 kg/m<sup>3</sup> density, at 10,000 cycles of loading and unloading of mass cargo barge. Reduction in buoyancy for both foams after 7 and 30 days of immersion in water has been shown to occur to some extent. The burning tests were performed for foam of 62 kg/m<sup>3</sup> density showing good behaviour.

**Key words:** *polyurethanes, properties*

### **INTRODUCTION**

The polyurethanes (PU) foams are widely used as insulating and core materials for furniture, cooling and freezing systems, in housebuilding, shipbuilding etc. The use of rigid foams is resulted from their low heat conduction coefficient, low density, low water absorption, relatively good mechanical strength [1,2]. The PU foams have been applied also as core materials of sandwich constructions with steel plates, in building the industrial houses, warehouses, sport houses, fruit stores, carrying freezers and cold stores, where they have to fulfill both insulating and mechanical requirements [3,4].

There is a number of references illustrating the effects of foam density on mechanical properties of PU foams [2,5]. The data are largely dependent on foam producer, as used substrates and production technology decide on intrinsic structure and foam density, and in such a manner - on capacity to carry mechanical loads. The data on fatigue properties of PU foams are generally lacking.

This project has been aimed at complex evaluation of various properties: static and dynamic mechanical properties, physical properties (density and water absorption) and chemical properties (flame spreading rate – burning test) of the foam EDULAN A/S produced by the Danish enterprise. Such foam is considered to be used as a core material in production of the light barges for shallow waters, designed in the framework of the UE INBAT project.

The PU foam created in situ between steel plates will undergo the mechanical stress of different form and level. Therefore, the various tests have been performed, including among others: fatigue tests simulating loading and unloading of coal and ore; Tests of water absorption as to measure the change in mechanical properties after damage of side and bottom plating of barge; burning tests to assess the danger for crew, resulting from possible fire.

## EXPERIMENTAL

Two kinds of foams were investigated: (a) polyurethane foam EW 045-45-20-K delivered as of  $62 \text{ kg/m}^3$  density, and (b) polyurethane foam EW 045-14-20-C delivered as of  $16 \text{ kg/m}^3$  density. Apparent density of PU foams was determined according to ISO 845 Standard.

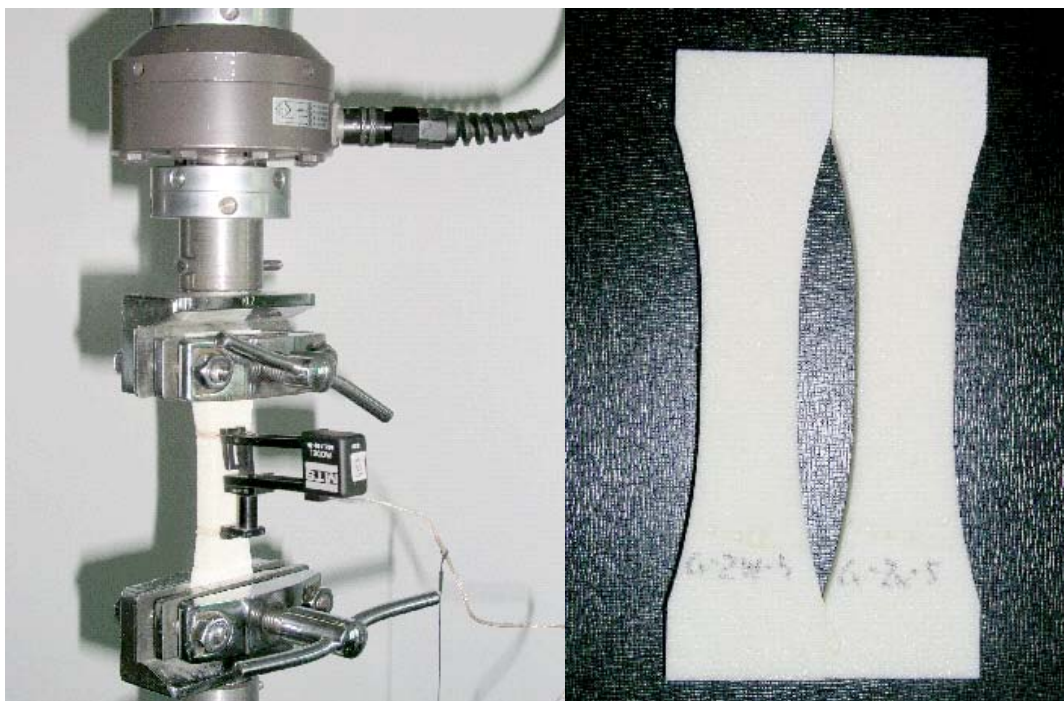
The compression, tensile, shearing and fatigue tests were performed with the MTS 810.12 No. 1012 machine. The force/deformation relation were computer-recorded and processed using ExMTS software developed by the Ship Design and Research Centre. The linear regression procedure was applied for determination of elasticity modules.

The compression tests were carried out according to ISO 844 Standard in parallel and perpendicular direction to the foam rise. Specimens' dimensions were  $100 \times 100 \times 50 \text{ mm}$ . The used equipment is shown in Photo 1. The compression strength and rigidity modulus were measured for both foams. For the foam of  $62 \text{ kg/m}^3$  density compressive properties were determined in a 10 kN force range, 15 mm displacement range and a testing speed of 5 mm/min. The modulus of elasticity was determined within the load range of  $0.75 \div 2.5 \text{ kN}$ . For the foam of  $16 \text{ kg/m}^3$  density compressive properties were determined in a 0.5 kN force range, 15 mm displacement range and at a testing speed of 5 mm/min. Approximate modulus of elasticity was determined within the load range of  $0.004 \div 0.01 \text{ kN}$ .



**Photo 1.** Equipment used in compression tests of foams

The tensile tests were performed according to ISO 1926 Standard in parallel and perpendicular direction to the foam rise. The equipment used and shape of specimens cut out from foam blocks are shown in Photo 2. The tensile strength and Young modulus were measured for foam of  $62 \text{ kg/m}^3$  density only. Tensile properties were determined in a 0.5 kN force range and at a testing speed of 5 mm/min. The strain was measured with an extensometer MTS 632.12C-20 of a 50 mm gauge length and a 12.5 mm strain range. The modulus of elasticity was determined within the strain range of  $0.1 \div 0.5\%$ .



**Photo 2.** Equipment (left) and specimens (right) used in tension tests

Shearing tests were performed according to ASTM C 273-94 Standard in parallel and perpendicular planes to the foam rise. Dimensions of specimens were 300x50x25 mm. The used equipment is shown in Photo 3. The shear strength and shear modulus were measured only for foam of  $62 \text{ kg/m}^3$  density. The test specimens were rigidly supported by steel plates bound to the foam with epoxy resin adhesive. The shear properties were determined at a 10 kN force range and a testing speed of 1 mm/min. The displacement of steel plates was measured with an extensometer MTS 632.12C-20 of a 50 mm gauge length and 1.25 mm strain range. The shear modulus was determined within the travel of an extensometer of  $0.1 \div 0.5 \text{ mm}$ . The extensometer was taken off when the displacement of plates had reached 1 mm and test was continued up to the moment of foam rupture, registering the force and displacement of piston of a testing machine (stroke).

The Poisson's ratios were performed for foam of  $62 \text{ kg/m}^3$  density, on the basis of EN ISO 527-1:1996 Standard. The specimens of dimensions 75x50x50 mm in parallel and perpendicular planes to the foam rise were cut out. The used flat-wise tension test setup according to the ASTM C 297-94 Standard is shown in Photo 5. The facings of the test specimen were bound to the loading blocks with epoxy resin adhesive. The Poisson's ratios were determined at a testing speed of 1 mm/min. The directional

deformations of PU foam during tensile were measured simultaneously by means of two extensometers fixed on the sides of specimen at the following parameters:

$\Delta_{\text{ext.l}}$  - travel of the extensometer 1, in a longitudinal direction, measured with an extensometer MTS 632.12C-20 of a 50 mm gauge length and a 1.25 mm strain range.

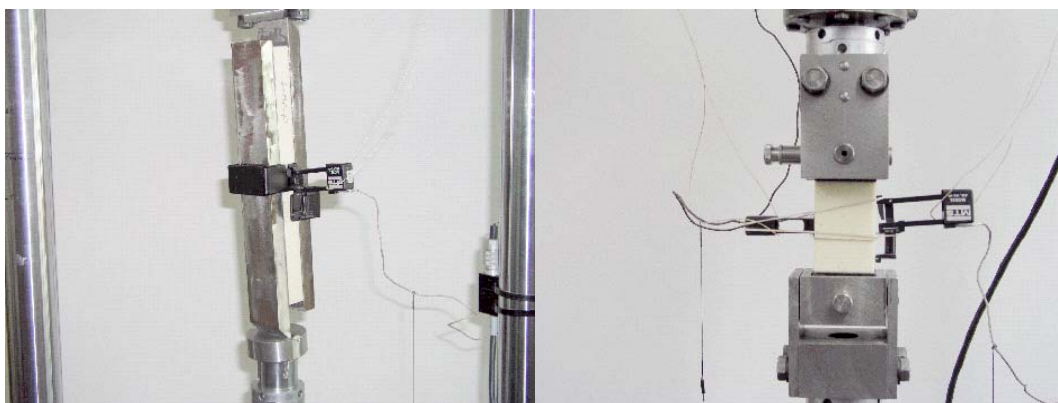
$\Delta_{\text{ext.t}}$  - travel of the extensometer 2, in a transverse direction, measured with an extensometer MTS 632.11C-20 of a 25 mm gauge length and a 1.00 mm strain range.

The relation of  $\Delta_{\text{ext.l}}/\Delta_{\text{ext.t}}$  was directly determined within strain range of  $0.03 \div 0.15$  mm, using the linear regression method and taking into account the data registered during the test by the extensometer 1 and 2. The following factors were determined for:

$v_{12}$  - longitudinal direction parallel to the foam rise and transverse direction perpendicular to the foam rise,

$v_{22}$  - longitudinal direction perpendicular to the foam rise and transverse direction perpendicular to the foam rise,

$v_{21}$  - longitudinal direction perpendicular to the foam rise and transverse direction parallel to the foam rise.



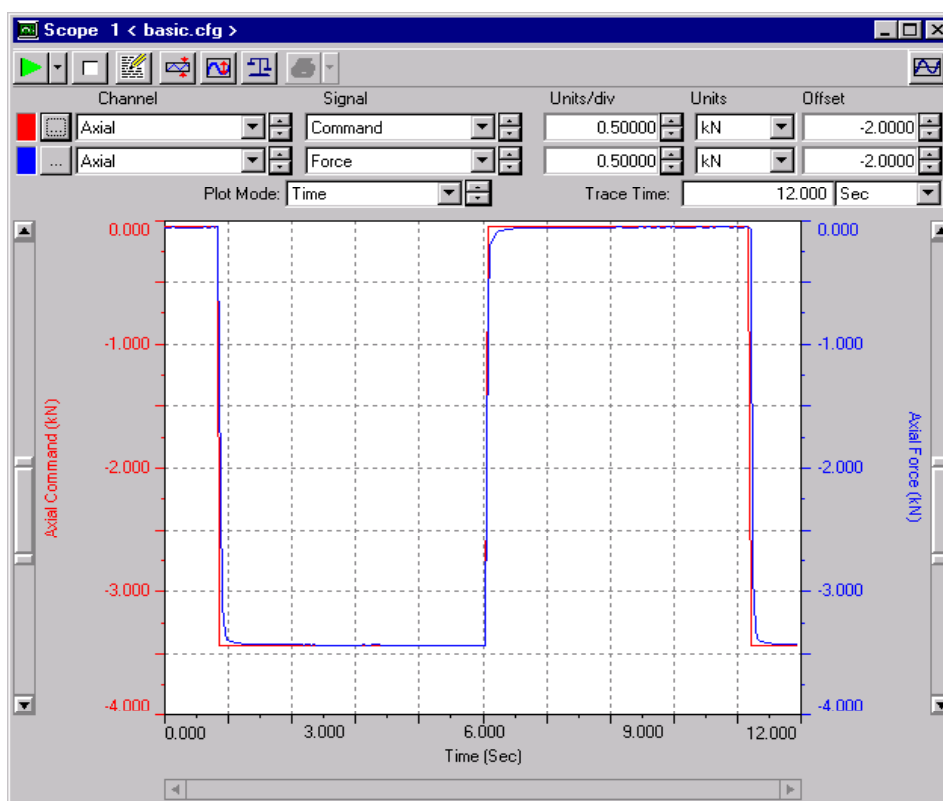
**Photo 3.** Equipment used in shearing tests (left) and for determining the Poisson's ratio (right)

The tests of reduction in buoyancy of foams after immersion in fresh water for a period of 7 and 30 days, 1 m under water level, were made according to IMO recommendations (IMO DE 41/11/11 Section 6.4 „Evaluation And Test Report For Buoyancy Material”). The dimensions of the specimens were 150x150x150 mm. The samples buoyancy was determined using an electronic balance having the 0.5 g accuracy of reading. The balance was equipped with a specimen clamping setup, designed in accordance with the ISO 2896 Standard. The setup was hung under the balance. The balance was calibrated after immersion in water. The foam specimen buoyancy was measured directly after placing it in the set.

The fatigue (loading – unloading) tests were carried out only for foam of  $62 \text{ kg/m}^3$  density. The dimensions of the specimens were 100x100x50 mm, and test temperature  $26 \pm 2^\circ\text{C}$ . It was assumed that specimens be loaded in the direction perpendicular to the foam rise, in the least beneficial direction concerning the strength aspect. Each specimen was subjected to the test at 10,000 load cycles number. The time of the fatigue test for one specimen approached ca 28 hrs.

The one-sided haversquare compressive cycles are applied: cycle duration 10 s,  $\sigma_{\text{min}} = 0.005 \text{ MPa}$ ,  $\sigma_{\text{max}} = 0.15 \div 0.35 \text{ MPa}$ . The fatigue properties were determined at a 10 kN force range and 15 mm displacement range. During the test, modulus of elasticity was automatically measured at compression before 1 cycle and after 2,000, 4,000, 6,000,

7,000, 8,000 and 10,000 cycles` number. The modules of elasticity were determined within the load range of  $0.75 \div 1.40$  kN. After 99, 1,000, 2,000, 3,000, 4,000, 5,000, 6,000, 7,000, 8,000, 9,000 and 10,000 cycles number, minimum and maximum specimens deformations were determined as well as the data necessary to draw the relationships for full loading/deformation relation (hysteresis loops) were registered. The used equipment was shown in Photo 1. Scheme of fatigue tests is shown in Photo 4.



**Photo 4.** Scheme of fatigue (loading – unloading) tests

The burning characteristics were tested according to the ISO 9772 standard. This standard specifies a small-scale laboratory screening procedure for comparing the relative burning characteristics of horizontally oriented, small plastic specimens having density lower than  $250 \text{ kg/m}^3$ . Specimens of dimensions  $150 \times 150 \times 13 \text{ mm}$  were cut out from block of PU foam in plane parallel to the foam rise.

## RESULTS AND DISCUSSION

The results of compression tests for foam of  $62 \text{ kg/m}^3$  density are shown in Figs. 1 ÷ 2, and for foam of  $16 \text{ kg/m}^3$  density in Figs. 3 ÷ 4. The carried force is about one half greater for heavier foam.

The results of tension tests are given in Figs 5 ÷ 6. The maximum tensile strength is very low, and scarcely depends on tension direction vs. foam rise direction. In the case of specimens cut out from foam where no bonding of two layers existed, almost all specimens fractured correctly at the necking of the section. In the case where border of

layers ran even at the wider part of specimen, fracture occurred at the foam interface boundary.

In Photo 5 two specimens are shown, before and after tension tests. As was here and generally observed, the specimens broke at the interface boundary, between two portions of foam, which solidified at different time.

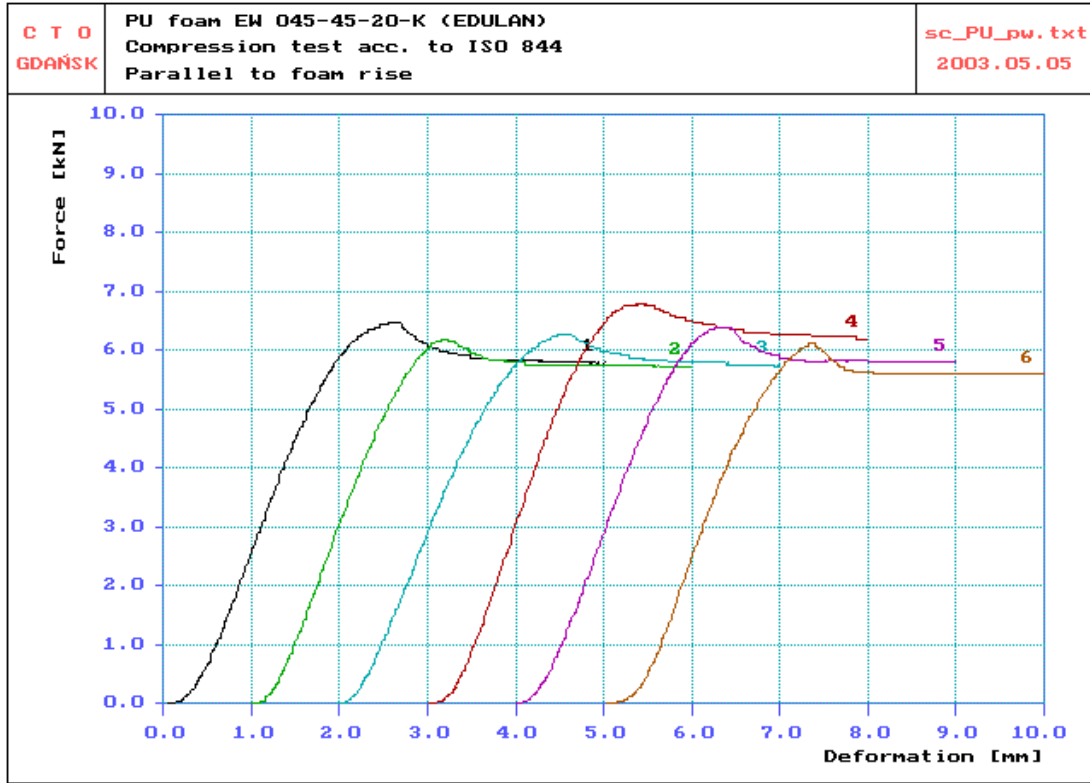


Fig. 1. Results of compression tests of the foam of  $62 \text{ kg/m}^3$  density, parallel to the foam rise

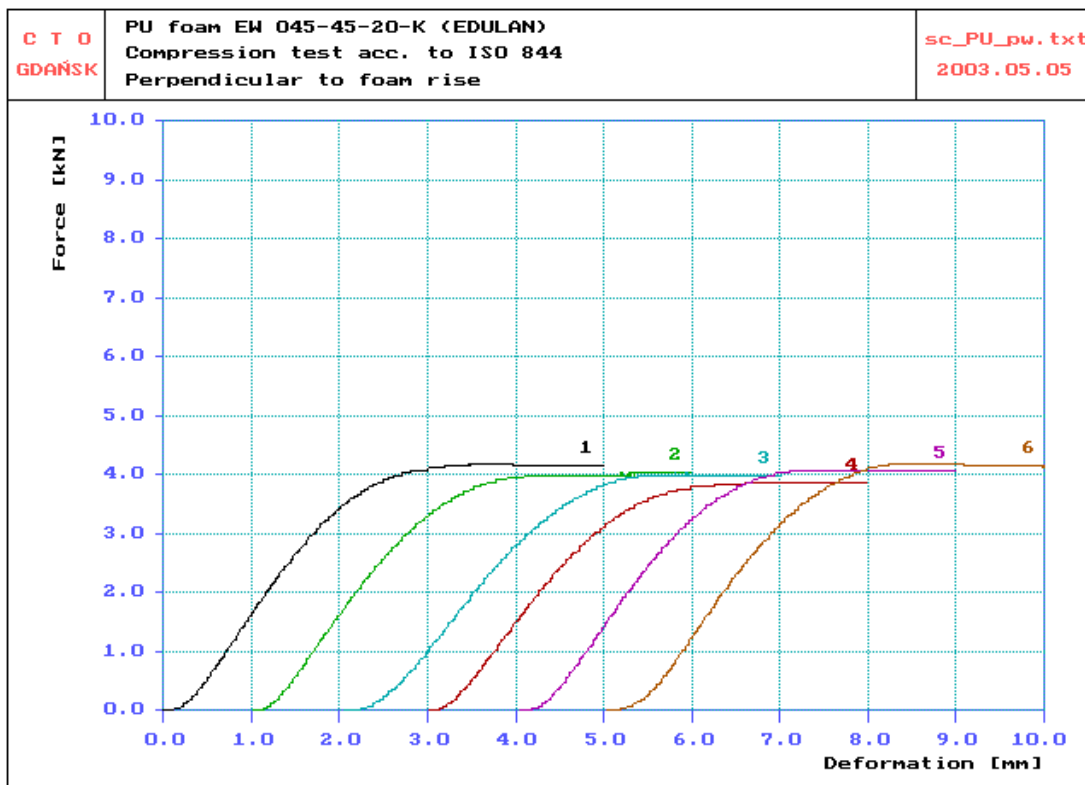


Fig. 2. Results of compression tests of the foam of 62 kg/m<sup>3</sup> density, perpendicular to the foam rise

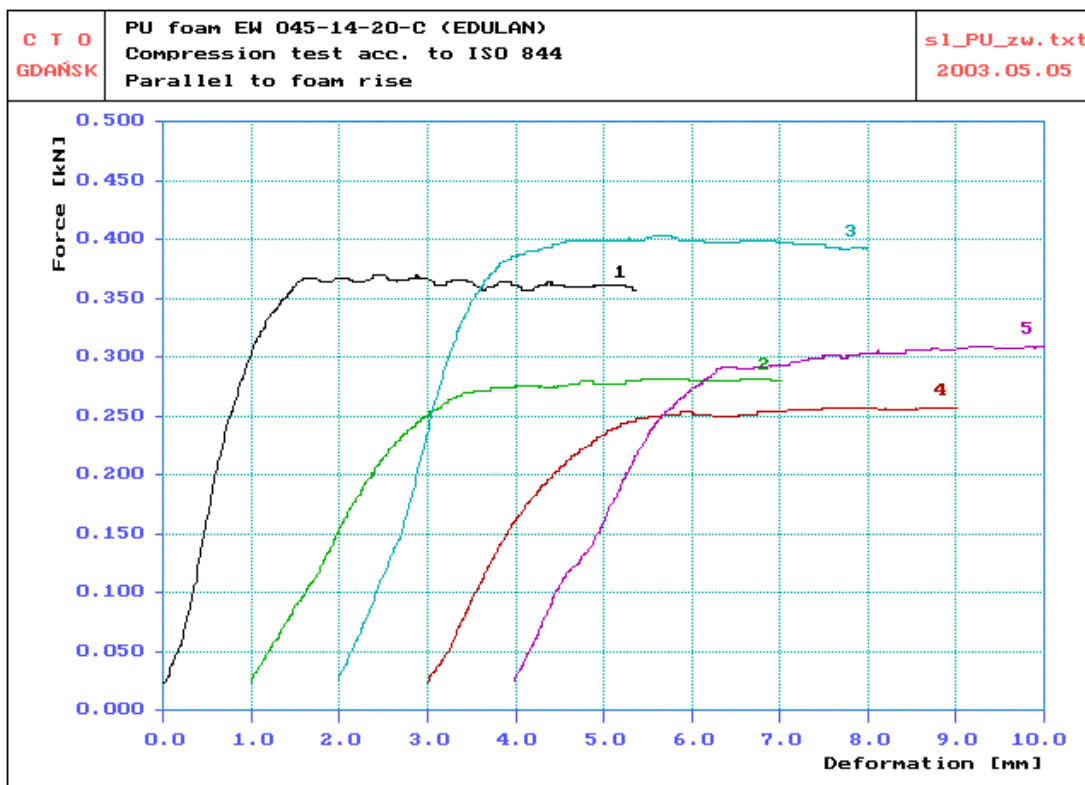


Fig. 3. Results of compression tests of the foam of 16 kg/m<sup>3</sup> density, parallel to the foam rise

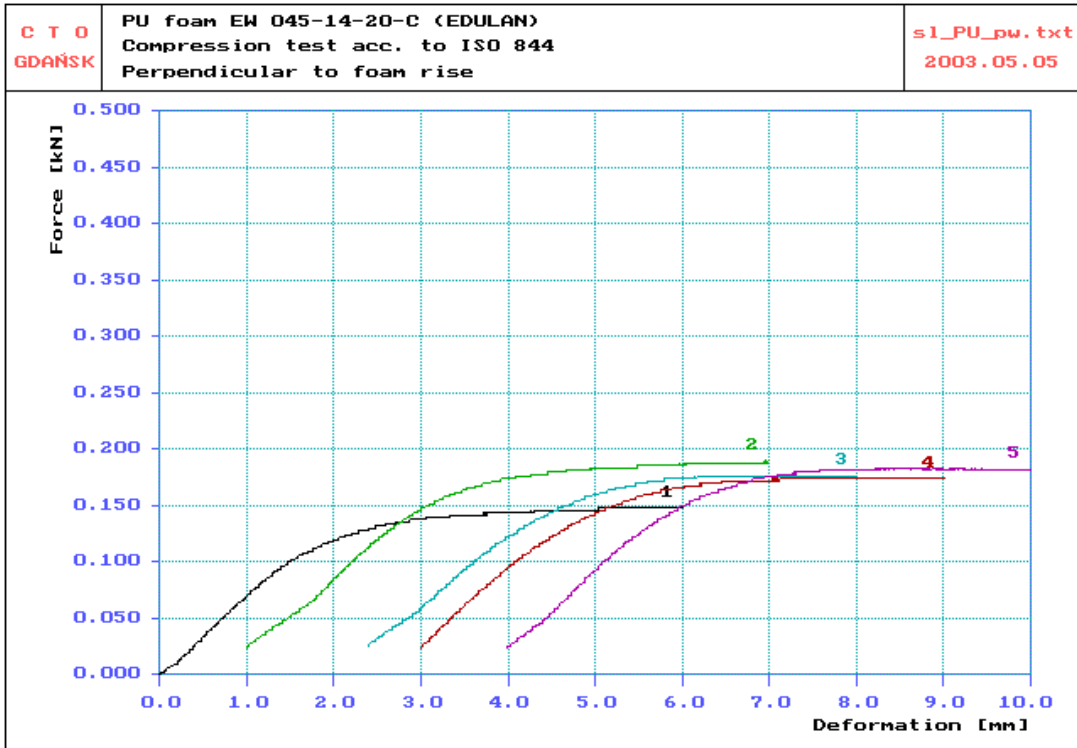


Fig. 4. Results of compression test of the foam of 16 kg/m<sup>3</sup> density, perpendicular to the foam rise

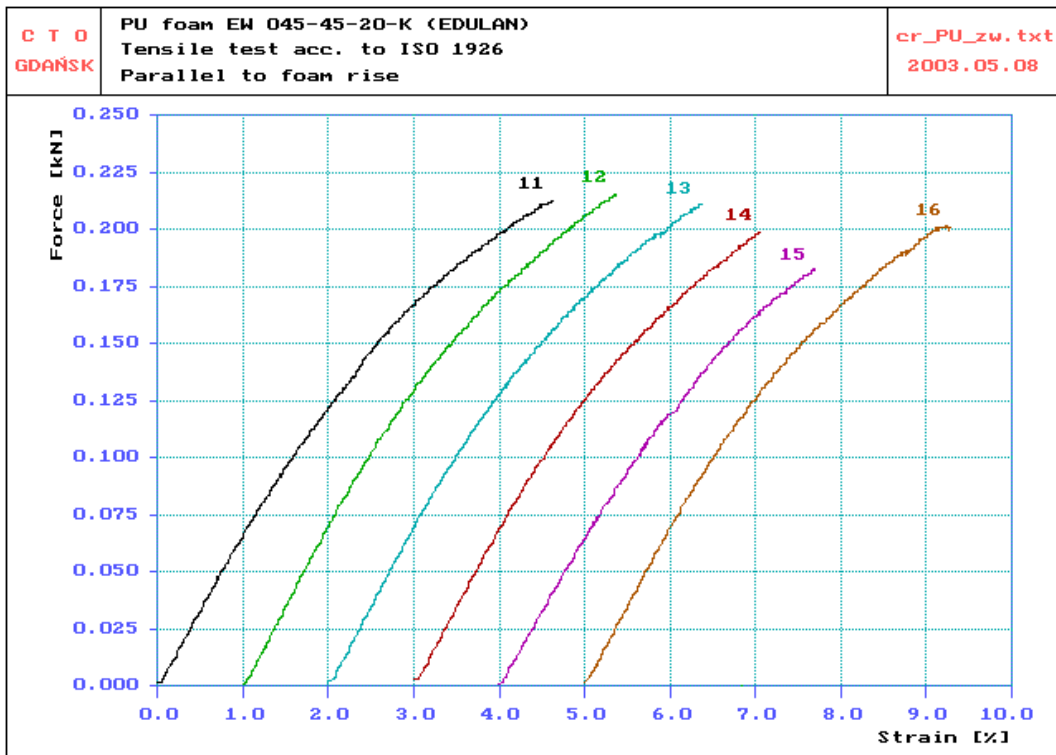


Fig. 5. Results of tension tests of the foam of 62 kg/m<sup>3</sup> density, parallel to the foam rise



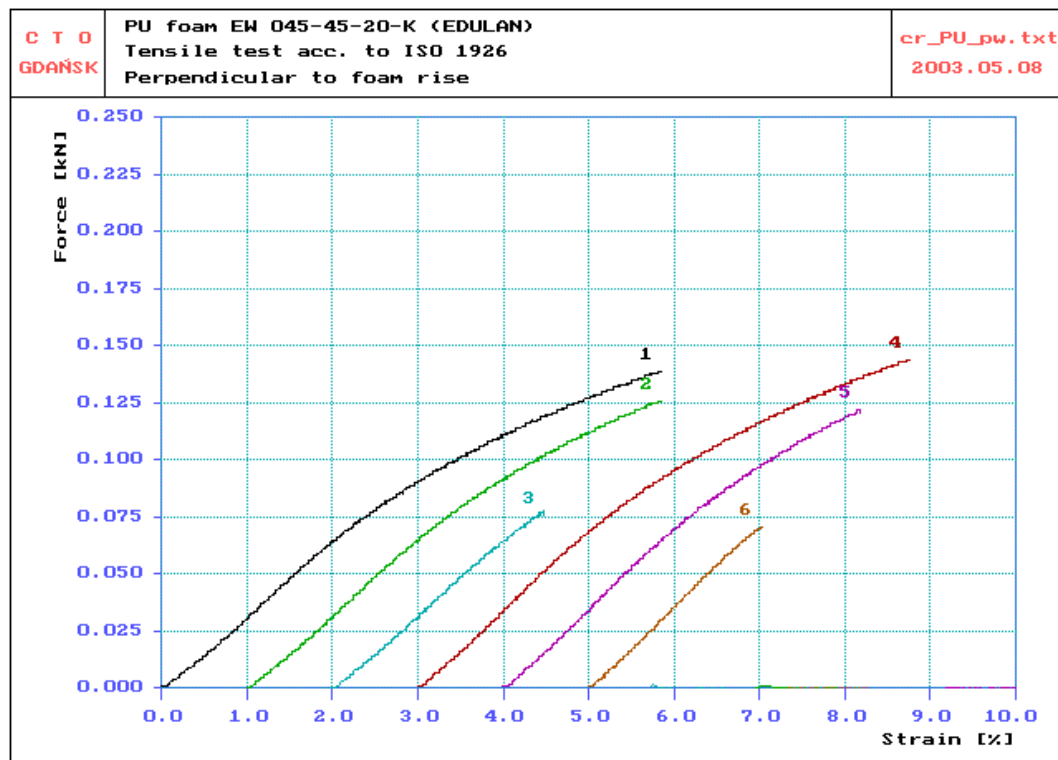


Fig. 6. Results of tension tests of the foam of  $62 \text{ kg/m}^3$  density, perpendicular to the foam rise

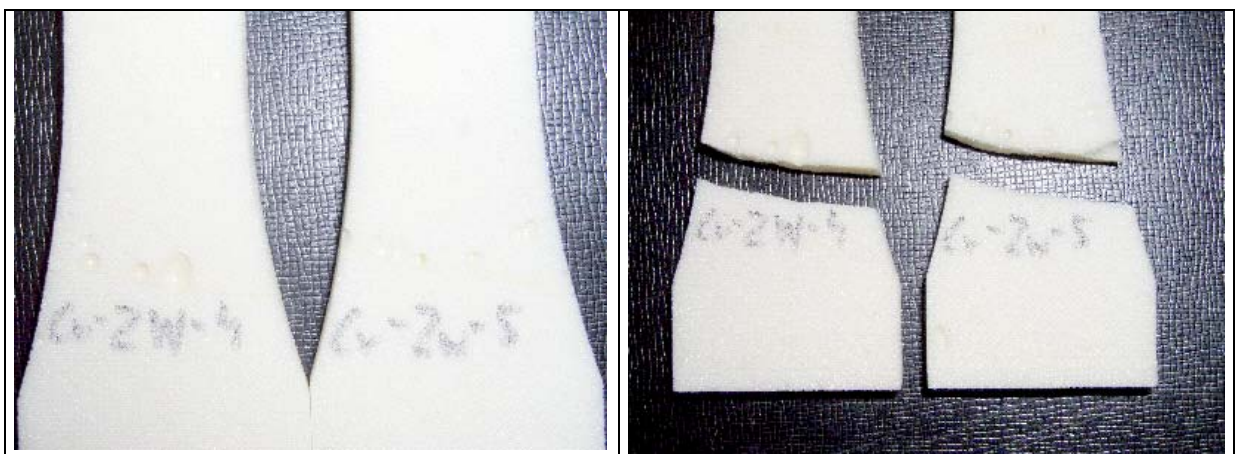
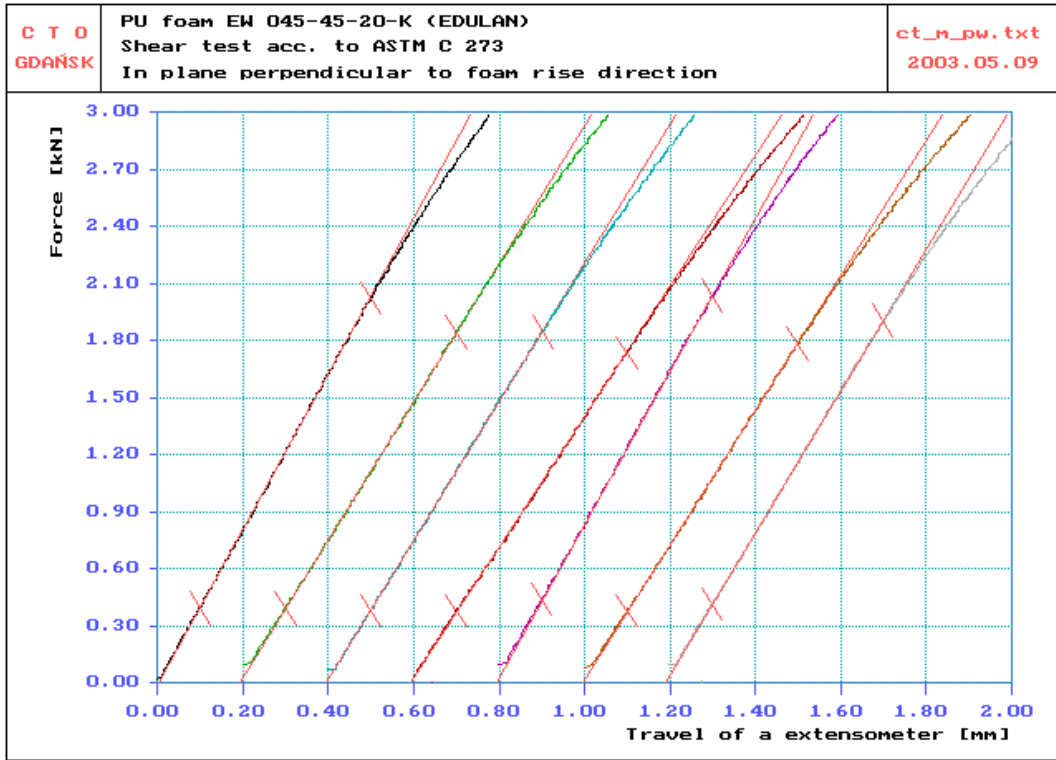


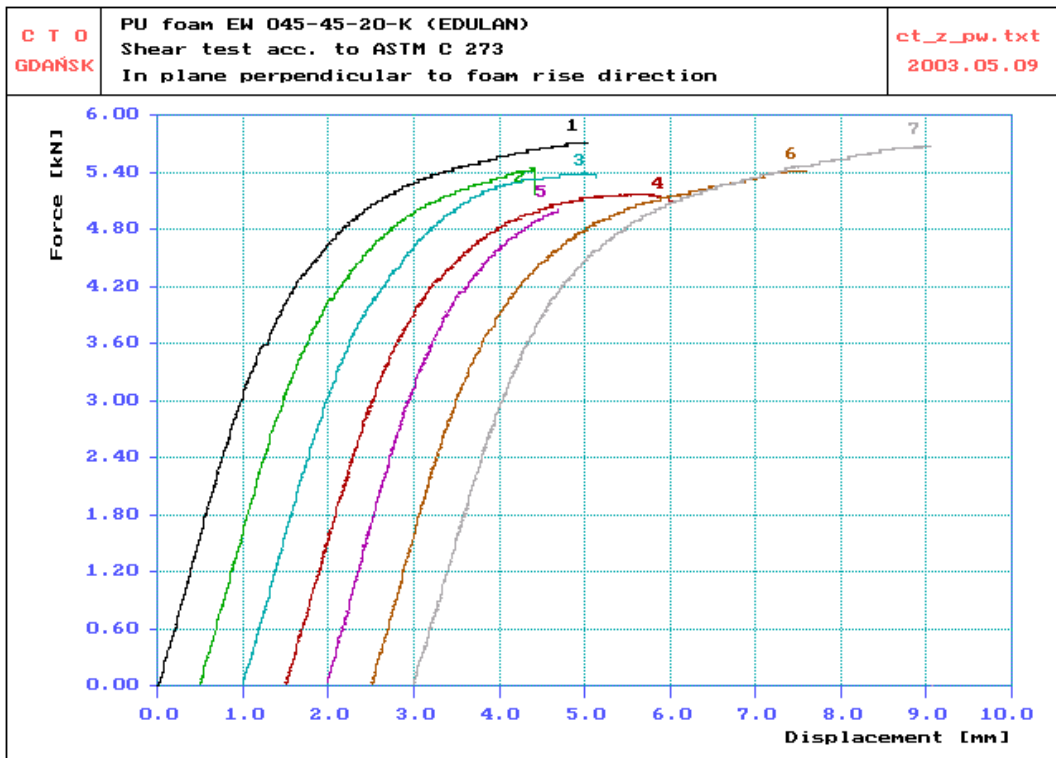
Photo 5. Specimens before (left) and after (right) tension test. The foam of  $62 \text{ kg/m}^3$  density

The results of shearing tests for foam of  $62 \text{ kg/m}^3$  density are demonstrated in Figs. 7 ÷ 9. Fig. 7 shows dependence of the force on displacement of steel plates measured with an extensometer and illustrates the way of shear modulus determining. At the displacement ca 1 mm, the extensometer was removed to avoid its destruction during shearing of the foam. Figs. 8 and 9 show dependence of the force on the displacement of a piston of a testing machine.

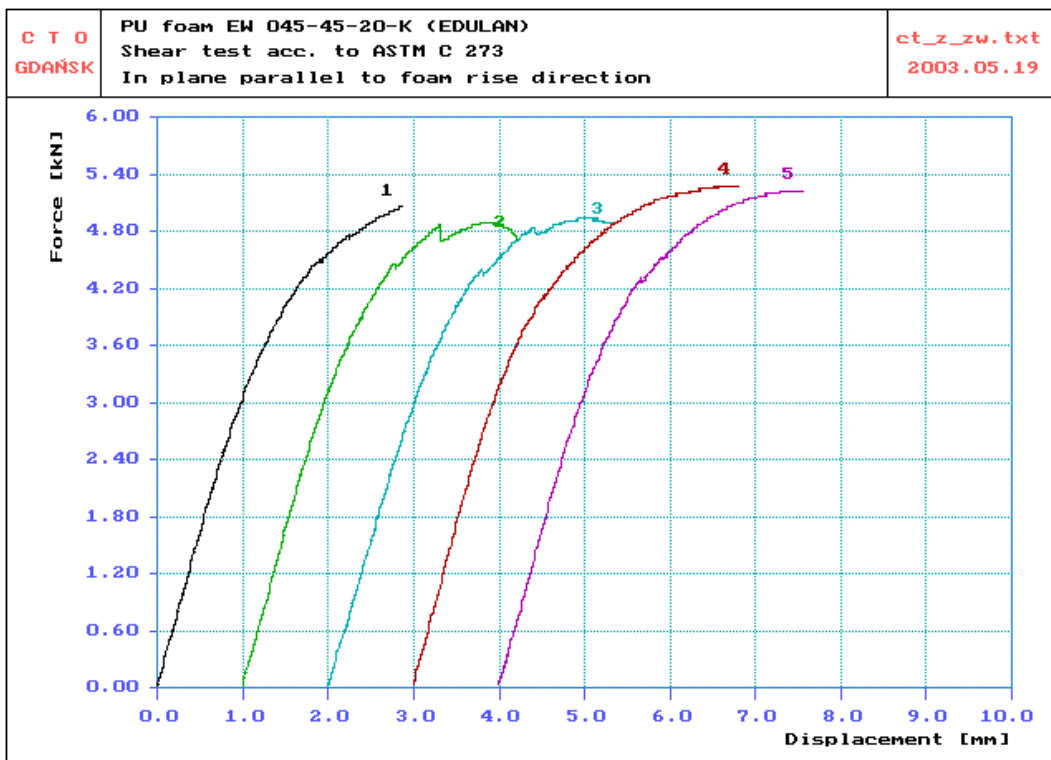
The Poisson's ratio data for the foam of  $62 \text{ kg/m}^3$  density are demonstrated in Fig. 10.



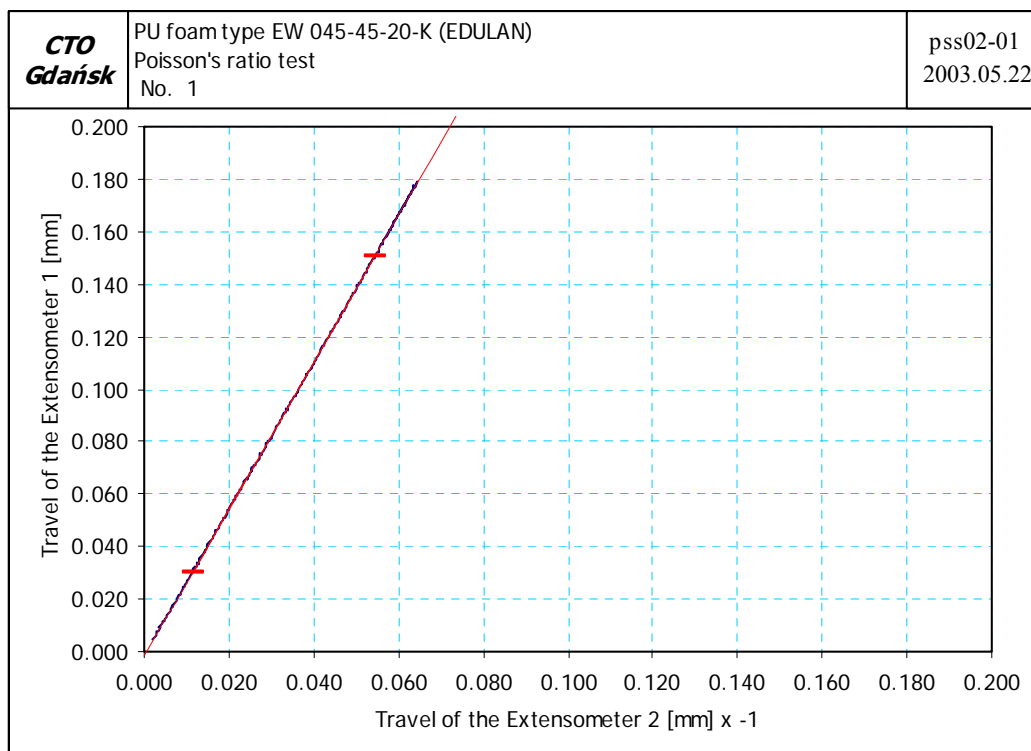
**Fig. 7.** Results of shearing tests on the foam of 62 kg/m<sup>3</sup> density, in perpendicular plane to the foam rise. Shear modulus determination



**Fig. 8.** Results of shearing tests on the foam of 62 kg/m<sup>3</sup> density. Shear strength determination in perpendicular plane to the foam rise



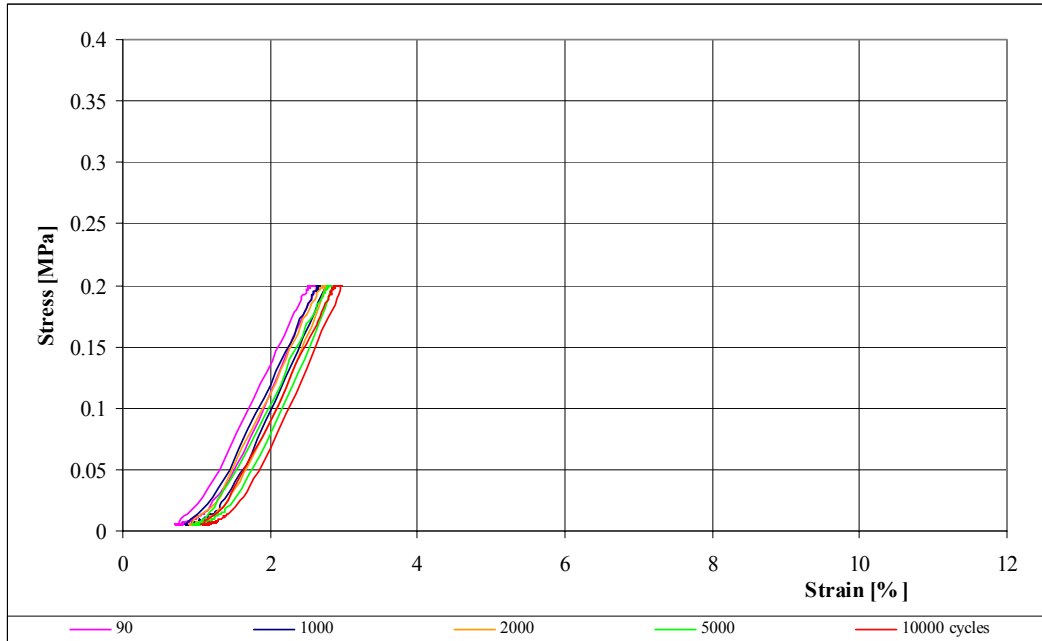
**Fig. 9.** Results of shearing test on the foam of 62 kg/m<sup>3</sup> density. Shear strength determination in parallel plane to the foam rise



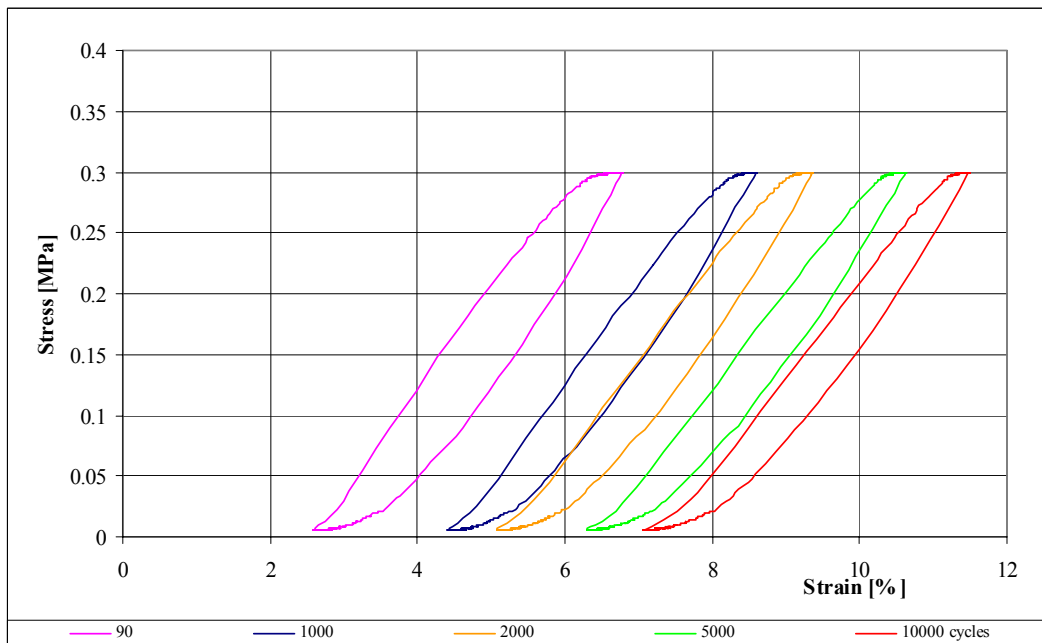
**Fig. 10.** Relationship used to determine the Poisson's ratio

The results of fatigue (loading – unloading) tests are demonstrated in Figs. 11-15. The relationships obtained under fatigue conditions at two values of maximum stress

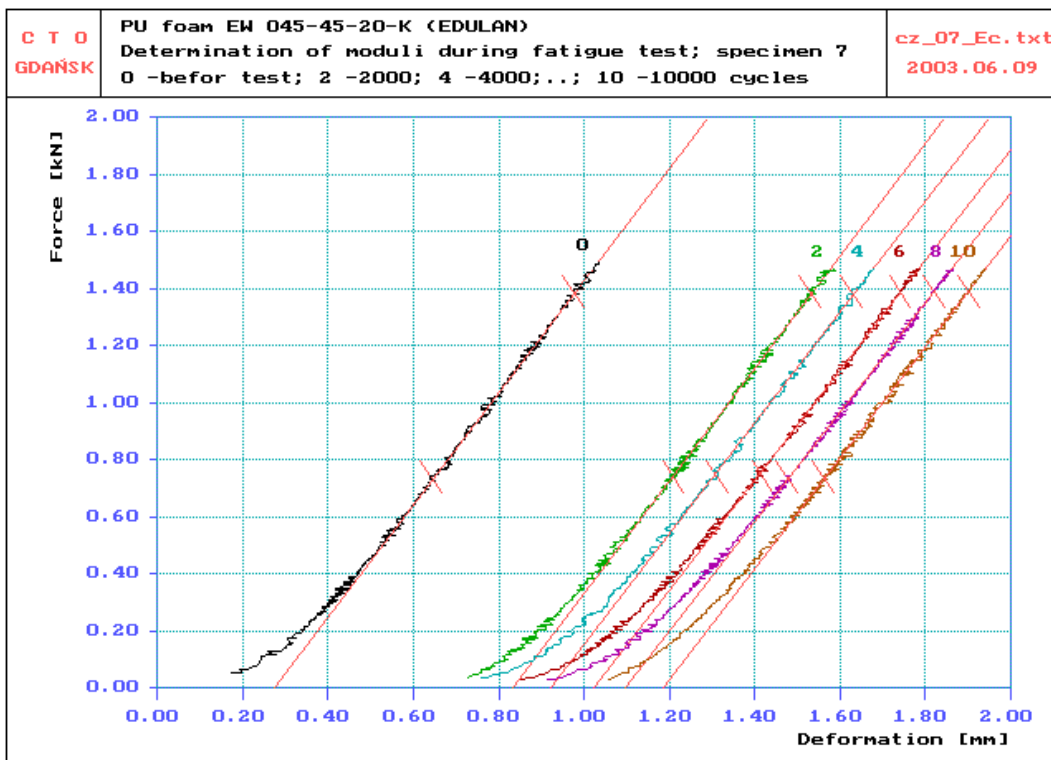
are presented in Figs. 11 and 12. Fig. 13 presents the force – deformation relationships recorded periodically before and during fatigue testing at a maximum stress 0.25 MPa (specimen No. 7). The tangent slopes to curves illustrate a method of elasticity modulus determination. In Fig. 14, the relations of deformation – cycles` number for six chosen values of a maximum stress are demonstrated. In Fig. 15, the relation maximum compressive stress – strain after 10000 cycles number is shown.



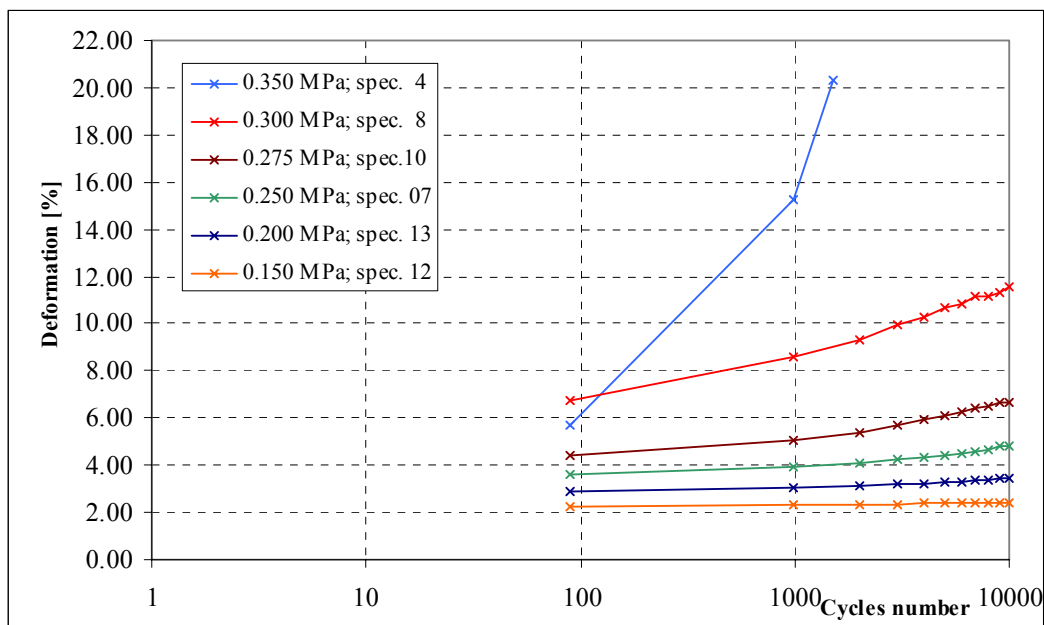
**Fig. 11.** Stress-strain relationship at fatigue testing of the foam of  $62 \text{ kg/m}^3$  density at maximum stress 0.2 MPa



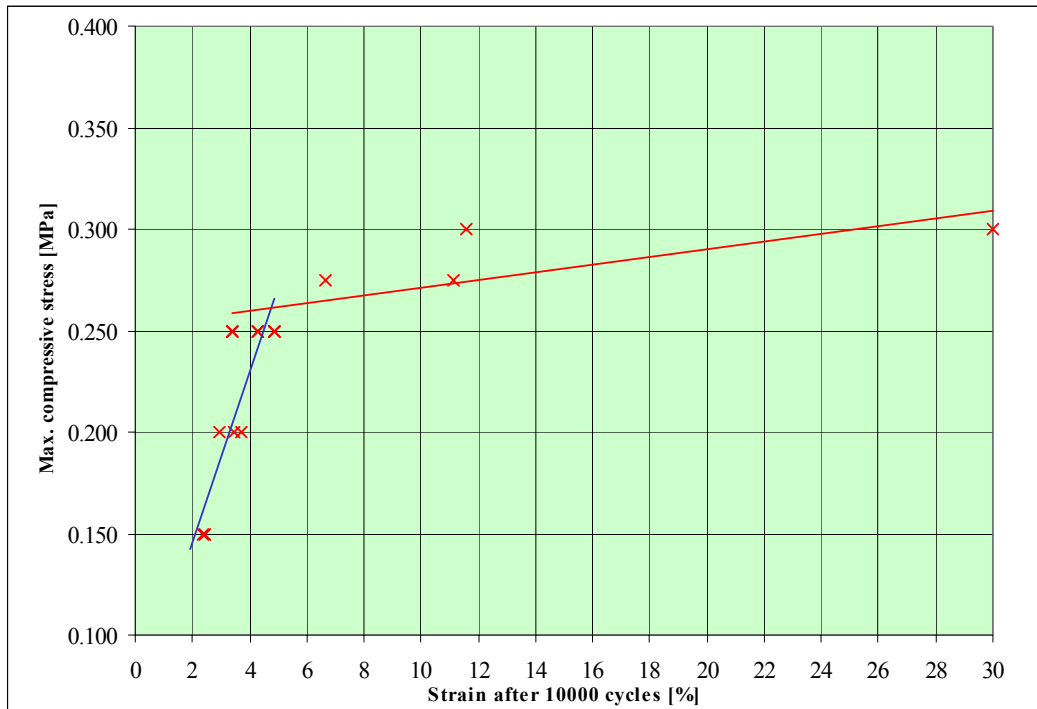
**Fig. 12.** Stress-strain relationship at fatigue testing of the foam of  $62 \text{ kg/m}^3$  density at a maximum stress 0.3 MPa



**Fig. 13.** Force-deformation relationships recorded periodically before and during fatigue testing at a maximum stress 0.25 MPa



**Fig. 14.** Deformation – cycles number relationships at fatigue testing of the foam of 62 kg/m<sup>3</sup> density at different maximum stress 0.15 ÷ 0.35 MPa



**Fig. 15.** Results of fatigue (loading – unloading) test of the foam of  $62 \text{ kg/m}^3$  density, perpendicular to the foam rise

The test results of horizontal burning for foam of  $62 \text{ kg/m}^3$  density are demonstrated in Table 1. Ten specimens were tested: 5 after conditioning for 48 hrs at  $23 \pm 2^\circ\text{C}$  and  $50 \pm 5\%$  as well as 5 after conditioning for 168 hrs at  $70 \pm 2^\circ\text{C}$ . Specimens after burning tests are shown in Photo 8.



**Photo 8.** Specimens after burning tests (after conditioning for 168 hrs at  $70^\circ\text{C}$ )

The reductions in buoyancy for foams 16 of 62 kg/m<sup>3</sup> density are demonstrated in Table 1..

**Table 1.** Physical, mechanical and chemical parameters of tested PU foams

Property	Test standard or specimens dimensions	Unit	Property at different foam density	
			62	16
Apparent density	ISO 845	kg/m <sup>3</sup>	62	16
Compressive strength parallel to foam rise	ISO 844	MPa	0.64	0.033
Compressive stress perpendicular to foam rise			0.41	0.018
Compressive modulus parallel to foam rise			19.5	0.92
Compressive modulus perpendicular to foam rise			10.1	0.34
Tensile strength parallel to foam rise	ISO 1926		0.79	
Tensile strength perpendicular to foam rise			0.44	
Tensile modulus parallel to foam rise			26.7	
Tensile modulus perpendicular to foam rise			12.3	
Poisson`s ratio $\nu_{12}$	75x50x50		0.72	
Poisson`s ratio $\nu_{22}$			0.32	
Poisson`s ratio $\nu_{21}$			0.30	
Shear strength in plane parallel to foam rise	ASTM C-273	MPa	0.34	
Shear strength in plane perpendicular to foam rise			0.36	
Shear modulus in plane parallel to foam rise			6.4	
Shear modulus in plane perpendicular to foam rise			6.2	
Reduction of buoyancy after 7 day immersion in water	150x150x150	pct.	0.62	8.05
Reduction of buoyancy after 30 day immersion in water			1.05	17.8
Maximum compressive stress no causing plastic deformation above 5% after 10,000 cycles, perpendicular to foam rise	ISO 844	MPa	1.24	
Average burning rate after exposure at 48 h for °C	ISO 9722	mm/min	45.80	
Average burning rate after exposure at 168 h for 70°C			54.90	

## DISCUSSION

The results of compression tests indicate that the foam of  $16 \text{ kg/m}^3$  density is not able to resist the mechanical force. The water absorption and reduction in buoyancy for this PU foam is high what indicates a significant number of open pores. The lighter foam shows various disadvantages: great discontinuities (cavities) at the border between portions of the foam, low compressive strength, high water absorption and loss in buoyancy caused by a number of open pores. It does not fulfil requirements of GL and IMO for buoyancy materials, according to DE 41/11/11 Section 6.4 „Evaluation and test report for buoyancy material” since loss in buoyancy after 7 days of exposure is higher than 5%. Therefore, this foam has been rejected from other tests, as it cannot carry any mechanical stresses expected for a barge.

The resistance to compression, tension and shear is quite high for the foam of  $62 \text{ kg/m}^3$  density and corresponds to the reference data for PU foams of this type. The polyurethane foam of EW 045-45-20-K type is an anisotropic material as regards its mechanical properties. The strength properties of the foam are higher in direction of the foam rise. It is true especially for elasticity modules at compression and tension and results from intrinsic structure.

In fatigue compression tests the resistance to imposed force is much lower than in static stress tests. The fatigue tests show that stress exceeding 0.25 MPa may be dangerous and cause fast failure of the foam, and at compressive stress as low as 0.30 MPa the irreversible relative deformation exceeds 10% at 10,000 cycles` number. On the other hand, during repeated loading up to 10,000 cycles, at maximum stress below 0.25 MPa, modulus of elasticity at compression practically does not change its values.

The water absorption and reduction in buoyancy for the foam of  $62 \text{ kg/m}^3$  density is not high and it indicates a presence of mainly of closed pores.

During burning tests the specimens generated a large quantity of smoke and soot. The highest burning rate was demonstrated by specimens previously subjected to conditioning for 168 hrs at an increased temperature ( $70^\circ\text{C}$ ).

A classification of PU foam was not made because obtained results of parameters did not meet any of three classes given in the ISO 9772 Standard (HF-1, HF-2, HFB).

## CONCLUSIONS

The PU foam of  $62 \text{ kg/m}^3$  density may be assumed as proper for its use in building the light weight barges for shallow waters in view of compression, tension and shearing static tests.

The low cycle fatigue compression tests simulating 10,000 loading-unloading cycles` demonstrate that in this case there is a limiting force value above which rapidly progressing permanent foam deformation is observed. For the PU foam of  $62 \text{ kg/m}^3$  density, produced in EDULAN S/A, at stress perpendicular to the foam rise and temperature  $26^\circ\text{C}$ , this value is about 0.25 MPa.

It is recommended that during the barge design a factor of safety should be included into strength calculations. This parameter results from differences of the particular PU foam portions, possibility of material heterogeneity occurrence (voids), decrease of the



foam strength at higher temperatures, creep effect of the material at long-lasting loads, different foam density, etc.

## REFERENCES

1. Randall D., Lee S.: *The Polyurethanes Book*, Wiley, New York, 2002.
2. Olczyk W.: *Poliuretany*. WNT, Warszawa, 1968.
3. [www.ruuki.com.pl](http://www.ruuki.com.pl)
4. [www.balex.com.pl](http://www.balex.com.pl)
5. [www.generalplastics.com/products/idasheets.php](http://www.generalplastics.com/products/idasheets.php)