MECHANICAL TESTING OF ELASTOMERS FOR SENSOR AND ACTUATOR APPLICATIONS

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Abstract: *Mechanical testing of soft materials, such as polymers, elastomers and bio-materials, presents considerable challenges that do not arise when characterizing metals and ceramics. Soft elastomers, mostly silicones and acrylics, are interesting candidates as dielectric materials in electroactive polymer (EAP) actuator technology [1]. In this paper we investigated the elastic properties of poly(dimethylsiloxane)-based elastomer films using various mechanical tests. Uniaxial tensile and compression tests were performed in room conditions in order to determine the elastic modulus that showed to have similar values for both tests. In order to investigate the membrane behavior, biaxially stress tests were performed by indentation of freestanding circular films with various spherical indenter sizes at loads up to 1 N. The load–deflection measurements showed a non-linear elastic response, typically for elastomers, that depends on span length and indenter size. Also, the load-displacement measurements of indentation of flat films showed a strong non-linearity. In this case, classical Hertz solution is not valid, so other constitutive models that account for non-linear elastic contact needed to be considered.*

Keywords: *elastomers, mechanical tests, elastic modulus, EAP actuators*

1. Introduction

Polymers have many advantages such as low manufacturing cost, lightweight, compliant nature, fracture tolerant, can be made in different shape or size, easy handling etc. They are used in various applications including toys, footwear, electronics, coatings, paints, adhesives, tires, packing and encapsulating materials etc.

It was showed that polymers can change their shape or size in response to various stimuli including chemical, thermal, pneumatic, optical, electric and magnetic. Recently, much attention has been paid to soft elastomers, mostly silicone and acrylic, as dielectric electroactive polymers (EAPs) in the field of novel actuator technology [1].

Dielectric elastomers (DEs) consist of a thin polymer film sandwich between two compliant electrodes. When a voltage is applied across the electrodes, the electrostatic forces from the opposite electric charges create a pressure, called Maxwell stress, which squeeze the film in thickness direction and expand it in area. Dielectric elastomer actuators (DEAs) showed good overall actuator performance such as linear and circular electric field-induced strain responses beyond 200%, high stress (up to 7.2 MPa), high elastic energy density of 3.4 J/cm^3, good efficiency and high response speed in order of milliseconds [2],[3],[4]. DEs have also showed the capability to be used in sensors and generators applications [5],[6],[7].

The specific requirements for DE materials depend on the actuator type and its foreseen applications. Elastomer materials for sound generation, for instance, require primarily materials with fast response speed at high frequencies without large strains [8,9]. In contrast, for pumps, materials with a relatively low response speed may also be sufficient, but large strains are obligatory [10,11,12,13]. Furthermore, for both cases high efficiency is required, which means that the actuator should have low mechanical and electrical losses [14].

Elastomers are hyperelastic materials with a nonlinear stress-strain behavior. Measuring the mechanical properties of thin elastomer films, and understanding the effects of scale, microstructure, and process parameters on their mechanical behavior, is essential for designing and modeling of dielectric elastomer actuators and sensors with high performance and sufficient reliability [15,16,17].

In this paper we present a set of mechanical tests performed on poly(dimethylsiloxane)-based elastomer films in order to determine the elastic properties and validate with those reported in literature. These tests are very important in characterizing elastomers suitable for electromechanical actuators.

2. Experimental part

2.1 Uniaxial tensile tests

Elastomer films from PDMS/SiO_2/TiO_2 composites with different thickness were synthesized by sol-gel technique at "P. Poni" Institute of Macromolecular Chemistry, Iasi, Romania [18]. Dumbbell-shaped specimens were prepared according to ISO 37 [19,20] and test on a TIRA 2161 apparatus, Germany, at room temperature. Specimens were subjected to uniaxial stresses at extension rates of 50 and 20 mm/min until mechanically broken. The elastic tangent modulus was calculated from the slope of stress-strain curve at small strains (10%) where Hooke's law is still valid. Details about the experimental setup and tests procedure can be found in Ref. [21].

Rubber-like materials such as elastomers show viscous properties which appear as creep or stress relaxation. In this concern, uniaxial stress relaxation tests were performed at a strain rate of 20 mm/min for a maximum strain of 100%.

2.2 Uniaxial compression tests

Uniaxial compression tests were realized on circular specimens with 7 mm diameter at loads up to 15 N and velocity of 0.6 mm/min in room conditions. The compressive measurements were performed on a universal mechanical tester UMT2-CETR, USA. The specimens were horizontally arranged and pressed with an indenter that has a circular cooper disk attached to the tip. The surfaces of the specimens were lubricated with oil in order to reduce the friction forces that can influence the measurements. The surface roughness of films and cooper disk are about 10 nm [22] and 0.13 µm, respectively. However, we have previously reported that the friction coefficient between the film surfaces and copper disk is drastically reduced when lubricant oil is used [23]. The experimental setup for compressive measurements is illustrated in Figure 1. The compressive elastic modulus was calculated from the stress-strain data obtained with UMT2 tribometer.

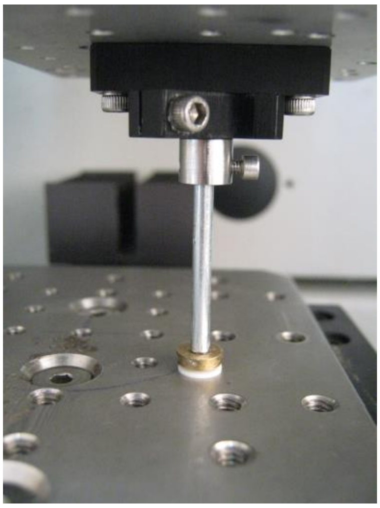

Figure 1: *Uniaxial compression of small PDMS circular specimens*

2.3 Indentation of freestanding circular films

Testing polymer membranes has many problems associated with traditional uniaxial testing of thin, compliant films. The biaxial properties of thin membranes are commonly measured using a bulge test wherein a circular membrane is circumferentially clamped and a uniform pressure is applied to one side using an incompressible fluid [24]. This can be applied also to dielectric elastomer membranes with compliant electrodes [25]. However, this test method requires custom equipment that can be quite cumbersome to set up and conduct. Problems also arise in sealing the gripping region especially at high applied pressures.

The proposed test geometry subjects the polymer membrane to a biaxial stress state by displacing the center of a clamped circular specimen with a spherical indenter (Figure 2). This method was also applied by other researchers that studied the film response – plate or membrane regime - accounting for indenter radius (*R*), load (*F*), span radius (*a*) and film thickness (*h*) [26,27,28,29,30].

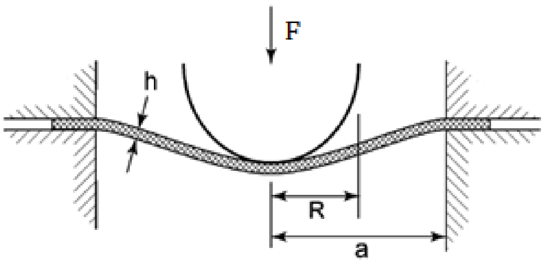

Figure 2: *Schematic diagram of the indentation test for freestanding films [28]*

The elastomer films were cut in circular form and fixed between two circular metallic rings with an inner diameter (span) of 27 mm. This assemble was then fixed on the UMT's table using a holding system with screws. The loads were vertically applied with a resolution of 1 mN and a velocity of 12 mm/min. Load-deflection measurements were recorded for various *R/a* ratios. The indenter consisted of a 440-C stainless steel ball (hardness RC 58-62) with different diameters glued on the tip of a pin. Figure 3 shows the experimental setup used for indentation measurements of freestanding circular films.

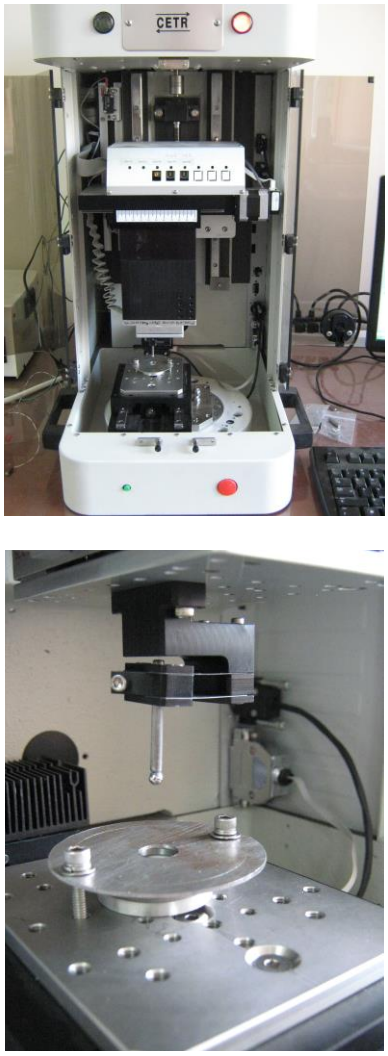

Figure 3: *Equipment for indentation of freestanding films*

2.4 Indentation of flat films

In order to study the elastic contact between a rigid spherical indenter and a hyperelastic material, we performed indentation tests on flat elastomer films. The measurements were made on UMT2-CETR equipment with a spherical indenter of 8 mm in diameter and velocity of 0.6 mm/min. A piece of specimen was put on linear table and indented with loads up to 10 N. The load-displacement data for different specimen thicknesses were obtained in room conditions. Figure 4 illustrates the indentation of a PDMS specimen at high loads.

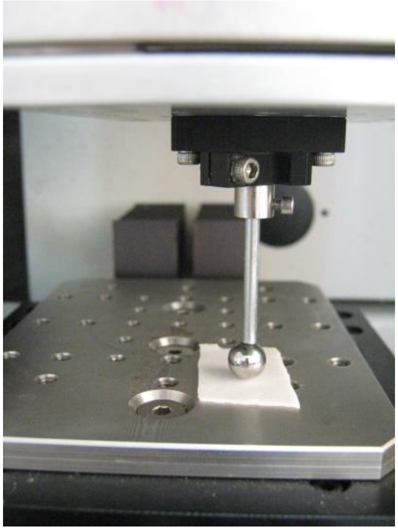

Figure 4: *Experimental setup for indentation of flat films*

3 Results and Discussions

3.1 Uniaxial tensile tests

The stress-strain data from the uniaxial tensile measurements showed a non-linear elastic response of specimens. The Young modulus was calculated for each specimen at small strains as tangent modulus. The values ranging from 0.1 to 0.9 MPa are in agreement with those reported in literature for PDMS [15,28]. The elastic modulus of PDMS depend on several factors such as geometry and thickness of the specimen, manufacturing technology, test conditions (humidity, temperature, strain rate) and the strain at which the modulus is calculated. Figure 5 illustrates the stress-strain measurements performed at two strain rates in room conditions for one PDMS specimen. It can be observed that the tangent elastic modulus does not vary significantly with the strain rate.

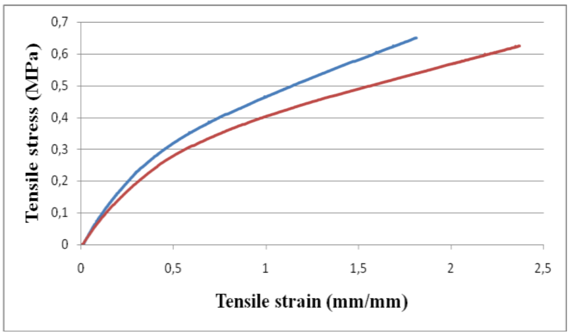

Figure 5: *Stress-strain measurements at a strain rate of 50 mm/min (red) and 20 mm/min (blue)*

Viscoelastic properties of specimens were investigated by performing stress relaxation tests at a strain of maximum 100%. Figure 6 shows the stress relaxation measurements for one specimen performed at a strain rate of 20 mm/min for 5 cycles.

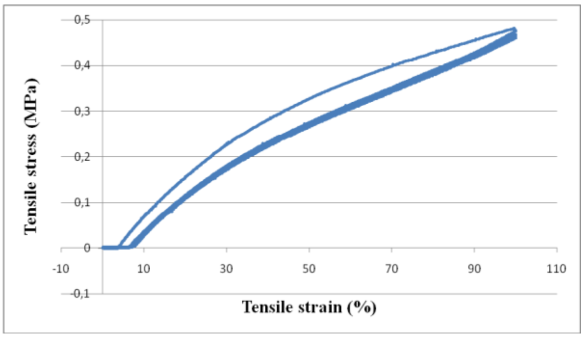

Figure 6: *Stress relaxation data for 5 cycles at a maximum strain of 100%*

It can be observed that the hysteresis is relatively small in the first load-unload cycle and almost inexistent in the other cycles. These observations are in agreement with low viscoelastic effects reported in literature for silicone elastomers. The uniaxial tensile data were used as input in a finite element analysis (FEA) and fitted with hyperelastic models (Arruda-Boyce, Mooney-Rivlin, Yeoh, Ogden).

3.2 Uniaxial compression tests

Compression measurements were made on small circular specimens at load up to 15 N and velocity of 0.6 mm/min. The stress-strain data under uniaxial compression showed also a nonlinear elastic behavior of specimens (Figure 7).

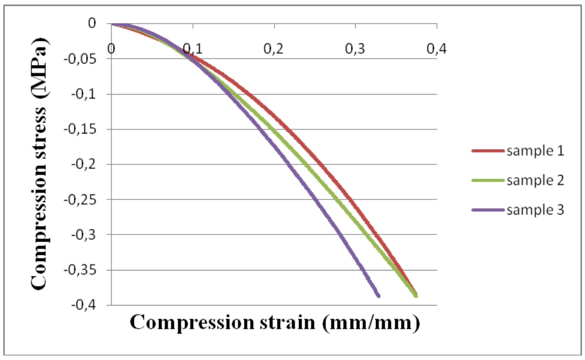

Figure 7: *Uniaxial compressive stress-strain curves*

Compressive elastic modulus was calculated at small strains and was found to be in accordance with uniaxial tensile modulus. A similar compressive modulus was also measured by [31] on Sylgard 184 (Dow Corning Corp., USA) with UMT-CETR machine.

3.3 Indentation of freestanding films

Figure 8 illustrates the load-deflection measurements for various indenter sizes, span radius of 13.5 mm and a film thickness of 0.8 mm. Noted that viscoelastic effects for this type of material can be neglected for the low strain rates used.

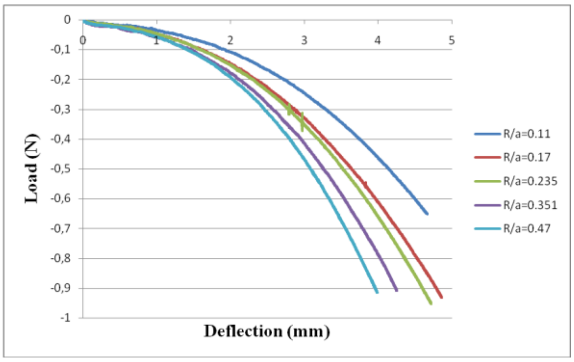

Figure 8: *The effect of indenter size on a PDMS specimen*

The *R/a* ratio for the indentation tests keeps the strain rates small even for relatively fast loading rates. Higher strain rates have been used for both indentation testing and uniaxial testing with little change in load–deflection behavior. Thus, the difference in measured modulus between the uniaxial test and indentation method is solely a function of the indentation strain and are not sensitive to the rate at which the tests are performed.

Linear and non-linear load-deflection response corresponding to plate and membrane regime can be discussed in context of point-load plate models and finite-contact membrane models, respectively. It is possible to extract the elastic modulus from indentation tests. However, connections between tangent modulus over a given strain range and the load–deflection behavior of plate/membrane tests have yet to be established [Scott]. These approaches will be discussed in details in a following paper.

3.4 Indentation of flat films

The results of indentation of flat films showed a non-linear load-displacement behavior as the previous tests. The contact between spherical indenter and specimens cannot be solved with classical Hertz solution [32] because the penetration is largest when films are flat compare to freestanding one. Figure 9 shows the load-displacement measurements of several specimens with a spherical indenter of 8 mm in diameter.

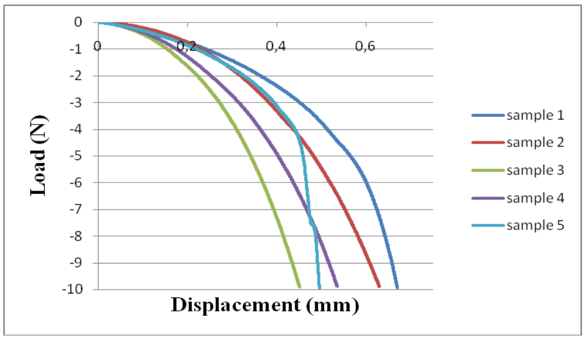

Figure 9: *Load-displacement curves of PDMS specimens under indentation with a 8 mm spherical indenter*

4 Conclusions

This paper reveals some mechanical tests used to investigate the elastic properties of soft materials. PDMS-based elastomer films showed to have an elastic modulus ranging from 0.1 to 1 MPa similar for both uniaxial tensile and compression tests. These values are typically for silicone elastomers. The Young's modulus was shows to depend on several factors including the strain rates at which the measurements are performed. Viscoelastic properties were investigated by stress relaxation tests that showed a relatively small hysteresis, in accordance with literature. Indentation of freestanding films measurements showed a non-linear membrane behavior that depends on indenter size and film thickness. The indentation of flat films showed that the penetration is largest then freestanding films.

These tests are very promising methods for characterization of soft materials like polymers, elastomers and biological materials.

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