Compression Properties of Hydrogels Synthesized from Diepoxy-terminated Poly(ethylene glycol)s and Aliphatic Polyamines

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The compression properties of a novel family of hydrogels prepared from diepoxy-terminated poly(ethylene glycol)s of approximate molecular weights 600, 1000, 2000 and 4000 Daltons and various aliphatic polyamines of different chain length and functionality (ethylenediamine, 1,4-diaminobutane, hexamethylenediamine, 1,8-octanediamine, diethylenetriamine, triethylenetetramine, tris(2-aminoethyl)amine) were determined by uniaxial compression. It was shown that both elastic and compression moduli, and compression strength of the fully swelled hydrogels depended on the molecular weight of the PEG oligomer, structure and functionality of the aliphatic amine employed as crosslinker, and mole ratio between the reacting groups, as a consequence of the different crosslinking degree of the resulting networks.

*Keywords**:** hydrogels; poly(ethylene glycol), epoxy groups, aliphatic polyamines, uniaxial compression*

Hydrogels are crosslinked polymer structures able to absorb and retain large amounts of water [1]. Since the initial works of Wichterle and Lim [2] on 2-hydroxyethyl methacrylate-based hydrogels, the field has continuously expanded as hydrogels have found numerous and important applications in medicine and pharmacy [3-6], as well as agriculture [7], and many other fields. The main biomedical applications of hydrogels are in the area of biosensors, controlled drug delivery and tissue regeneration and repair, while the agricultural ones include soil conditioners and controlled release of agrochemicals.

Most applications of hydrogels are based on their water absorption, expressed as the amount of water absorbed by 1 g of dry polymer (xerogel) at equilibrium, i. e. the equilibrium swelling degree. This is one of the most important factors affecting the functionality and quality of a hydrogel. In addition, for many applications the large swelling degree should be accompanied by good mechanical properties, which can be adjusted through several parameters like comonomer composition, crosslinking density or polymerization conditions [8]. Therefore, besides the swelling properties, the determination of the mechanical properties of a hydrogel is also important when a certain application is targeted. Many methods, including uniaxial tensile testing [9], uniaxial compression [10-14], dynamic mechanical analysis [15], etc, have been employed to test the mechanical properties of hydrogels.

In the present study we report on the mechanical properties of a novel family of hydrogels prepared from diepoxy-terminated poly(ethylene glycol)s of different molecular weight and various aliphatic polyamines of different chain length and functionality (ethylenediamine, EDA, 1,4-diaminobutane, DAB, hexamethylenediamine, HMDA, 1,8-octanediamine, ODA, diethylenetriamine, DETA, triethylenetetramine, TETA, tris(2-aminoethyl)amine, TREN, fig. 1) [16], whose characteristics can be tailored through the variation of available parameters, like molecular weight of PEG oligomer, number of carbon atoms and functionality of the amine, molar ratio of the reactants. Uniaxial compression has been employed to determine the elastic (E) and compression (G) moduli, and compression strength of the fully swelled hydrogels.

Experimental part

Materials

α,ω-Dihydroxy poly(ethylene glycol) with an approximate molecular weight of 600 mol/g (DHPEG$_{600}$), DHPEG$_{1000}$, DHPEG$_{2000}$ and DHPEG$_{4000}$ (DHPEG$_{X}$, Fluka) were used as received. Their hydroxyl numbers, determined by the phthalic anhydride/pyridine method, were 185.52, 114.44, 54.55 and 27.99 mg KOH/g, respectively, corresponding to the number average molecular weights ($M_{n,PEG}$) of 605 D, 982 D, 2060 D and 4010 D, calculated assuming the presence of two hydroxy groups within each PEG macromolecule. Diepoxy-terminated PEGs (DEPEG$_{X}$)

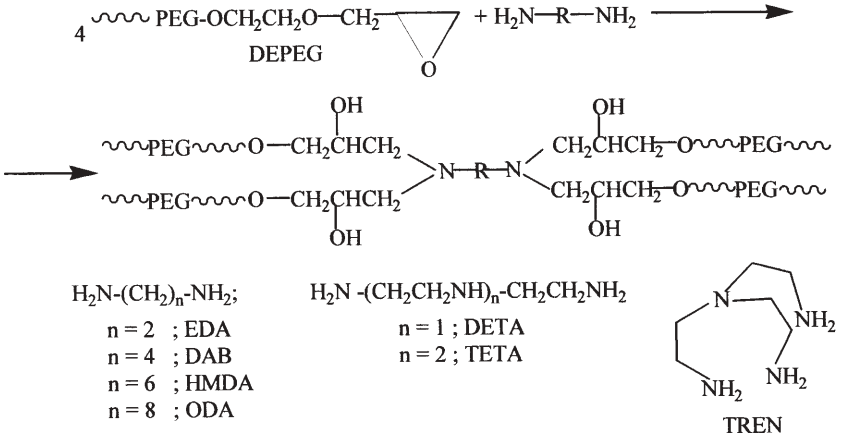

Fig. 1. Synthesis scheme of the hydrogels investigated

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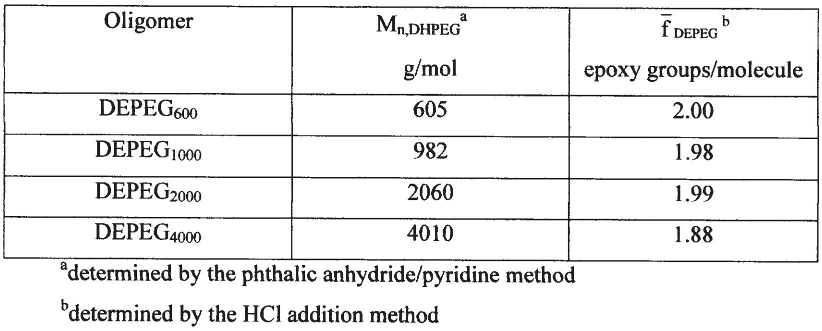
Table 1

THE FUNCTIONALITY OF THE DEPEG$_X$ PREPARED



Oligomer	$M_{n,DHPEG}$[a] g/mol	$\bar{f}_{DEPEG}$[b] epoxy groups/molecule
$DEPEG_{600}$	605	2.00
$DEPEG_{1000}$	982	1.98
$DEPEG_{2000}$	2060	1.99
$DEPEG_{4000}$	4010	1.88

[a]determined by the phthalic anhydride/pyridine method

[b]determined by the HCl addition method

were synthesized from the corresponding DHPEG$_X$ and epichlorohydrin (ECH), in benzene, in the presence of NaOH, as previously described [16]. Their functionality (f) is shown in table 1. EDA (Scharlau, 99%), DAB (ACROS, 99%), HMDA (Merck, 99%), ODA (ACROS, 99%), DETA (99%, Alfa Aesar), TETA (Fluka, 97%), TREN (96%, ACROS), ECH (Aldrich, 99%), benzene (Fisher, 99.9%), ethanol (Riedel-de-Haën, 99.8%) and all the other reagents were employed without further purification. Amine solutions of known concentrations were prepared in volumetric flasks by employing bidistilled water.

Hydrogel preparation

A 30 wt.-% DEPEG$_X$ solution was prepared by dissolving 3.0 g oligomer into the appropriate amount of bidistilled water, followed by the addition of the calculated volume of the aliphatic polyamine aqueous solution of known concentration. The reaction mixture was very well stirred and transferred by means of syringe and needle into the space between two parallel glass plates separated by a 3 mm-thick circular rubber gasket (fig. 2), in order to obtain plate-shaped hydrogels of uniform thickness.. The reactor was then introduced into a constant temperature oven and kept at 60°C for 6 days. At the end of the reaction time, the reactor was opened, the hydrogel plate was taken out and placed into excess bidistilled water for 7 days at room temperature. The water was changed daily in order to remove unreacted amine and oligomer. The hydrogel was then cut into 15 mm . 15 mm square-shaped pieces, which were kept into bidistilled water for one more week to reach the equilibrium swollen state, and then mechanically tested.

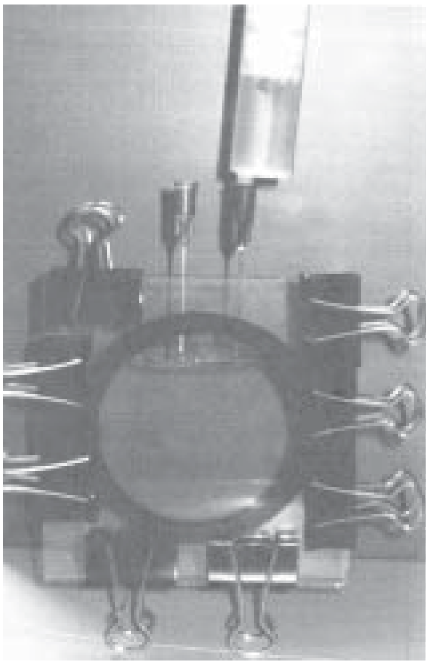


Fig. 2. The reactor employed to synthesize the plate-shaped hydrogels

Equilibrium swelling degree (ESD) determination

A swollen hydrogel piece was removed from the water bath, wiped superficially with filter paper and weighed (W$_h$). The hydrogel was then thoroughly dried (constant weight) at room temperature, under air and in a desiccator over anhydrous calcium chloride, and the resulting xerogel was weighed (W$_x$). ESD, expressed as amount of water absorbed by 1 g of xerogel under equilibrium conditions, was calculated according to:

$$ESD\ (g\ water/g\ dry\ polymer) = \frac{W_h - W_x}{W_x} \qquad (1)$$

Characterization

The functionality ($\bar{f}$) of the synthesized DEPEG$_X$ was titrimetrically determined by the addition of HCl to the epoxy ring, in dioxane, at room temperature [17]. The mechanical properties of the water-swollen hydrogels were measured on an Instron 3382 instrument, equipped with a 2 kN cell at room temperature (25 ± 1 °C) and 50 ± 10 % relative humidity. The square - shaped (15 mm . 15 mm) gel samples of 4-5 mm thickness were placed on the lower plate and compressed by the upper plate at a constant compression rate of 2 mm/min until fragmentation of the hydrogel occurred. As the compression period was no more than 1 – 1.5 min , no water loss was noticed during the experiment. Measurements were done 4 times for each sample and the average value was calculated and reported. For clarity reasons, the plots displayed within the Results and discussion section show only one curve from each set, the one having the closest parameters to the mean values.

Results and discussion

Hydrogels with different crosslinking and equilibrium swelling degrees were prepared through the reaction between diepoxy-terminated PEGs of various molecular weights and aliphatic polyamines with different number of carbon atoms, structure and functionality (scheme 1), in various mole ratios, and their compression properties as a function of these molecular and synthesis parameters were determined. The crosslinking reaction was carried out in solution, in the reactor shown in figure 2 in order to obtain plate-shaped hydrogel pieces, with parallel faces. After extracting the unreacted polyamine and oligomer, the elastic (Young's) modulus, compression (shear) modulus and compression strength of the fully swollen gels were obtained from uniaxial compression measurements. The elastic modulus (E) was obtained as the slope in stress (τ) - strain (λ-1) plots, according to equation (2):

$$\tau = E(\lambda - 1) \qquad (2)$$

where τ corresponds to the applied force per unit area of swollen hydrogel, $\lambda = l/l_0$ is the compression ratio, l and l_0 are the instantaneous and initial thickness of the gel, respectively [15].

The compression modulus (G) was determined from the stress τ vs. (λ-λ^{-2}) plots, according to equation (3) [18]:

$$\tau = G(\lambda - \lambda^{-2}) \qquad (3)$$

The slopes of the stress - strain plots, i. e. E and G, were calculated for small strains, on the interval where the plots are linear [11] (fig. 3). The curvature noticed at the beginning of the stress – strain plots was due to the fact that the two faces of the sample which come into contact with the plates of the measuring instrument are not perfectly parallel.

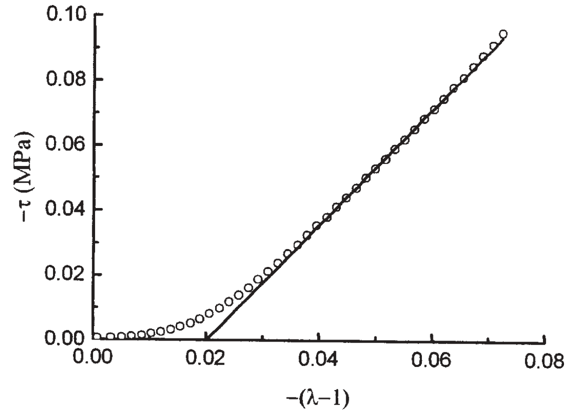


Fig. 3. Example of E modulus determination. $DEPEG_{600}$ – EDA; H_{amine}/epoxy groups = 1/1 mole ratio

The fracture stress (τ_{max}), i.e. the stress value right before the fragmentation of the hydrogel occurred, was taken as a measure for compression strength.

Influence of PEG molecular weight onto the compression properties of the hydrogels

Diepoxy-terminated poly(ethylene glycol)s of approximate molecular weights 600, 1000, 2000 and 4000 D were reacted with equimolar amounts of EDA, i.e. H_{amine}/ epoxy groups = 1/1 mole ratio, to obtain hydrogels whose compression properties were determined (fig. 4, table 2).

As the molecular weight of the oligomer increased, networks with lower degrees of crosslinking resulted, leading to hydrogels with increasing capacity of water absorption, as proven by the ESD values shown in table 1. Also, higher molecular weight DEPEG led to hydrogels with lower elastic and compression moduli, and compression strength, due to the lower density of the resulting network, which is in agreement with the general knowledge that the mechanical properties of polymer networks depend on the length of the chains which form the network [19]. The E values obtained (0.3 – 1.8 MPa) were according to those reported for similar hydrogels prepared from dihydroxy PEGs and polyisocyanates (0.39 – 4.8 MPa) [20].

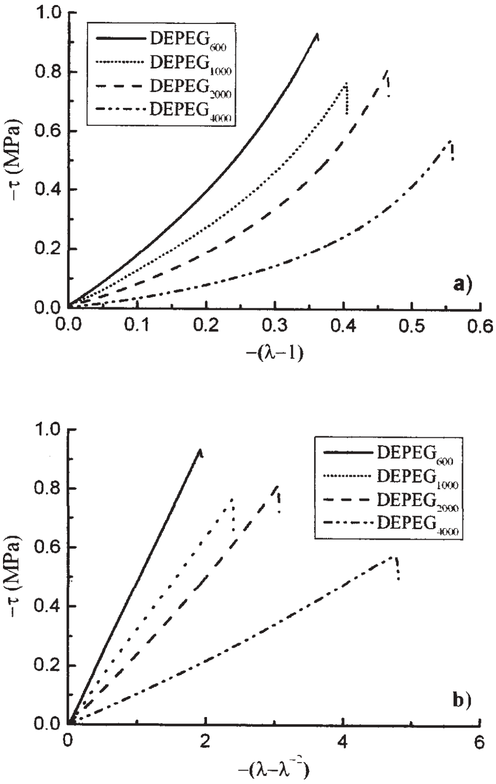


Fig. 4. The compression behavior of hydrogels synthesized from equimolar amounts of DEPEG of various molecular weights and EDA. a) stress vs. (λ-1); b) stress vs. (λ- λ^{-2})

Influence of amine structure and functionality

The amine functionality equals the number of hydrogen atoms contained by the amine and involved in the addition reaction to the epoxy ring. For example, the functionality of EDA equals 4 as it contains 4 hydrogen atoms. In order to investigate the influence of amine functionality upon the compression properties of our hydrogels, $DEPEG_{1000}$ was

Table 2

THE DEPENDENCE OF COMPRESSION PROPERTIES OF HYDROGELS SYNTHESIZED ON $DEPEG_X$ MOLECULAR WEIGHT*

Oligomer	E MPa	Compression strength MPa	G MPa	E/G	ESD g water/g dry polymer
$DEPEG_{600}$	1.83	0.914	0.518	3.53	4.90
$DEPEG_{1000}$	1.33	0.763	0.373	3.56	5.90
$DEPEG_{2000}$	0.77	0.804	0.218	3.55	7.52
$DEPEG_{4000}$	0.34	0.572	0.096	3.53	10.99

*crosslinking agent = EDA; H_{amine}/epoxy groups = 1/1 mole ratio

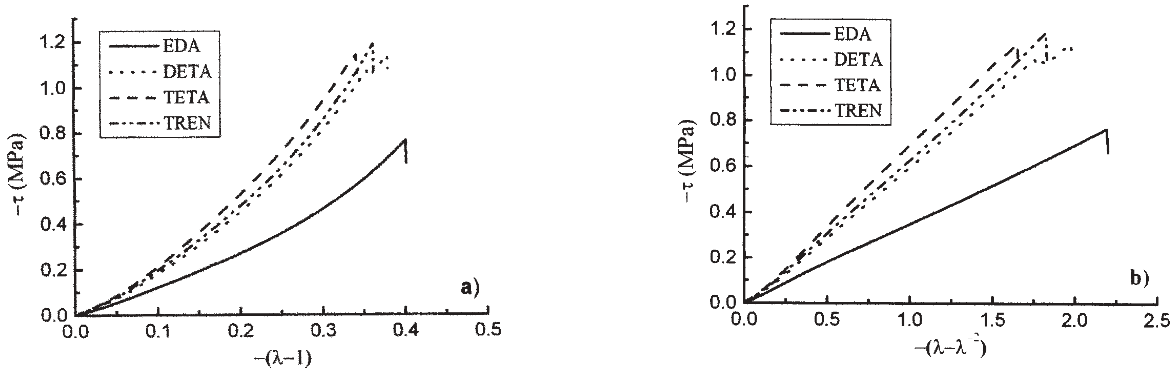


Fig. 5. The compression behavior of hydrogels synthesized from equimolar amounts of $DEPEG_{1000}$ and amines with various functionalities. a) stress vs. (λ-1); b) stress vs. (λ- λ^{-2})

Table 3

THE DEPENDENCE OF COMPRESSION PROPERTIES OF HYDROGELS SYNTHESIZED ON AMINE STRUCTURE AND FUNCTIONALITY*

Amine	E MPa	Compression strength MPa	G MPa	E/G	ESD g water/g dry polymer
EDA	1.33	0.763	0.373	3.56	5.90
DETA	2.202	1.166	0.617	3.56	5.43
TETA	2.615	1.145	0.732	3.57	5.10
TREN	2.255	1.196	0.633	3.56	5.00

* $DEPEG_{1000}$; H_{amine}/epoxy groups = 1/1 mole ratio

crosslinked with equimolar amounts of EDA, DETA and TETA, whose functionality is 4, 5 and 6, respectively (scheme 1). As amine functionality increases, the crosslinking degree of the resulting hydrogels increases as well, leading to lower ESD values. The results of both compression and swelling degree measurements are displayed in table 3 and figure 5.

As expected, as the crosslinking degree increased, both elastic and compression moduli, and compression strength increased. It can be noticed that both elastic and compression moduli doubled as the functionality of the amine increased from 4 to 6 (i. e. EDA to TETA) (table 3).

TREN is an aliphatic polyamine having the same functionality as TETA, but a different structure (scheme 1). The results showed that the amine structure may influence in a certain degree the compression properties of the hydrogels synthesized, as can be seen from the values of the elastic modulus (table 3), although ESD is practically the same in both cases. The lower elastic modulus in the case of TREN may be rationalized through a slightly increased flexibility of the network crosslinked with this polyamine as compared to the one crosslinked with TETA, due to the larger distance between the oligomer chains at the crosslinking point (fig. 6).

Influence of amine chain length

Aliphatic diamines with increasing chain length were also employed for the synthesis of $DEPEG_{1000}$ - based hydrogels (scheme 1). As previously shown [16], by employing an amine with a higher number of carbon atoms the hydrophobic character of the hydrogel increases, leading to a lower ESD, especially for longer chain amines (ODA), whose water solubility is lower (table 4). In the case of amines with high water solubility, like EDA, DAB and HMDA, ESD is practically constant.

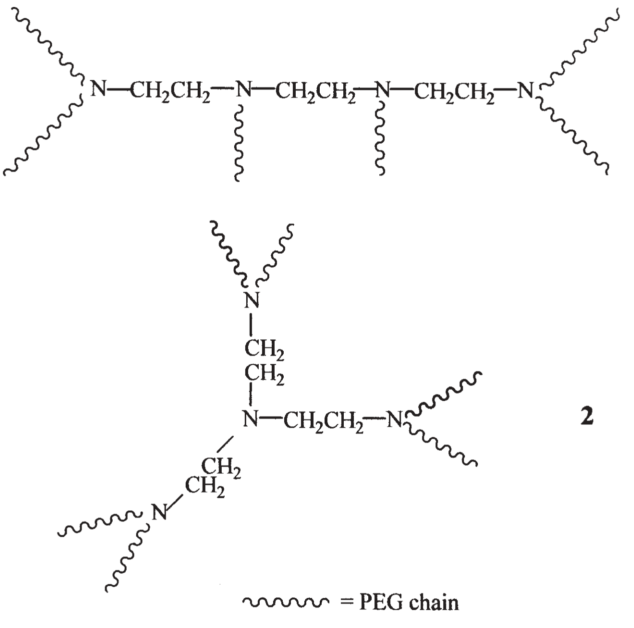


Fig. 6. The structure of crosslinking points in the case of (1) TETA and (2)(TREN)

In addition to this, the increase of the hydrophobic character of the hydrogel is expected to lead to an increase of the mechanical properties of the gel, due to the formation of additional physical crosslinking points through the hydrophobic interactions amongst the amine hydrocarbon chains [13]. Indeed, as the number of amine carbon atoms increased from 2 to 8, the elastic modulus

Table 4
THE DEPENDENCE OF COMPRESSION PROPERTIES OF HYDROGELS SYNTHESIZED ON AMINE CHAIN LENGTH*

Amine	E MPa	Compression strength MPa	G MPa	E/G	ESD g water/g dry polymer
EDA	1.33	0.763	0.373	3.56	5.90
DAB	1.42	1.068	0.399	3.56	5.87
HMDA	1.58	1.099	0.460	3.44	5.86
ODA	1.745	1.129	0.492	3.55	5.44

* $DEPEG_{1000}$; H_{amine}/epoxy groups = 1/1 mole ratio

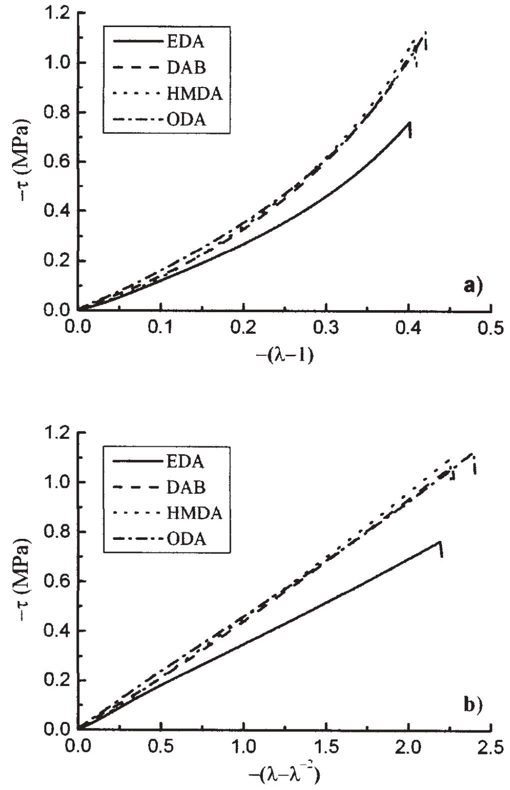


Fig. 7. The compression behaviour of hydrogels synthesized from equimolar amounts of $DEPEG_{1000}$ and amines with various chain lengths. a) stress vs. (λ-1); b) stress vs. ($\lambda-\lambda^{-2}$)

increased from 1.33 MPa to 1.745 MPa, as well as the compression modulus from 0.373 MPa to 0.492 MPa and the compression strength from 0.763 MPa to 1.129 MPa (table 4, fig. 7).

Influence of the amine/epoxy groups mole ratio

Hydrogels with different network structures, obtained at three different H_{amine}/epoxy groups (EG) mole ratios, i.e. 1/1, 1/0.7 and 1/1.3 were also tested from the compression properties point of view (table 5, fig. 8). For the same PEG chain length, excess of any of the reacting functional groups resulted in higher ESD by comparison to the hydrogel formed under stoichiometric conditions (table 5), as already reported [16]. Excess amine leads to a lower degree of crosslinking due to the formation of larger meshes within the hydrogel network, while in the case of excess epoxy groups several effects contribute to an ESD increase even larger than that for excess amine: i) formation of a network with larger meshes; ii) formation of grafts; iii) incomplete conversion of diepoxy-terminated PEG, leading to pore formation within the hydrogel after the removal of the unreacted oligomer during the purification step [16].

The different structure of the hydrogel networks, obtained as a result of the different H_{amine}/EG mole ratios, led to different compression properties, as expected (table 5, fig. 8). Thus, excess of any of the reactants determined a decrease of both elastic and compression moduli, and compression strength due to the formation of a lower crosslinking degree network. The reduction was more significant in the case of excess DEPEG, very likely due to the presence of pores within the hydrogel structure.

Table 5
THE DEPENDENCE OF COMPRESSION PROPERTIES OF HYDROGELS SYNTHESIZED ON H_{amine}/EPOXY GROUPS MOLE RATIO*

H_{amine}/epoxy groups mol/mol	E MPa	Compression strength MPa	G MPa	E/G	ESD g water/g dry polymer
1/0.7	0.75	0.706	0.214	3.51	9.74
1/1	0.77	0.804	0.218	3.55	7.54
1/1.3	0.375	0.320	0.106	3.54	12.11

* $DEPEG_{2000}$; crosslinking agent = EDA

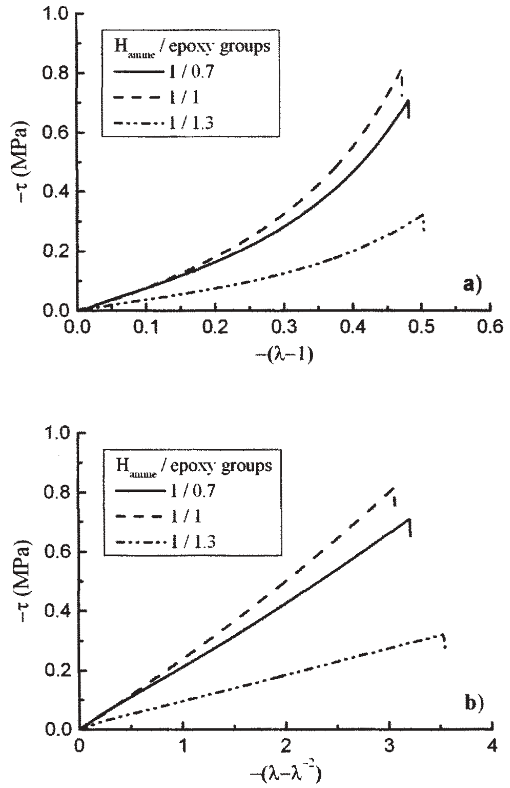


Fig. 8. The compression behaviour of hydrogels synthesized from $DEPEG_{2000}$ crosslinked with various amounts of EDA.
a) stress vs. (λ-1); b) stress vs. ($\lambda - \lambda^{-2}$)

Comments on the compression modulus values obtained

For a rubbery material, the ratio of E to G should equal 3. However, in the case of rubbery hydrogels the E/G value determined by compression measurements are usually higher than 3, depending on the λ values for which G was determined, as predicted by equation 4 [21]:

$$G = E/(1 + 2\lambda^{-3}) \qquad (4)$$

In the case of extremely small deformations, when $\lambda \rightarrow 1$, $E/G \rightarrow 3$ according to eq. 4 [21].

In our case, the E/G values obtained in all cases were around 3.5, because we determined E and G at higher deformations λ = 0.92 - 0.97), due to the curvature of the stress – strain plots (see above). Therefore, the G values shown in tables 2 – 5 are overestimated by about 15 %, but their correlation with the structure of the hydrogels still keeps as the multiplication factor was the same in all cases (E/G = constant). The constant E/G value obtained in all cases, although higher than 3, proves that all the synthesized hydrogels exhibit a rubbery character.

Conclusions

The compression properties of a novel family of hydrogels prepared from diepoxy-terminated PEGs of different molecular weights and various aliphatic polyamines were determined by uniaxial compression. It was shown that both elastic and compression moduli, and compression strength of the fully swelled hydrogels depended on the molecular weight of the PEG oligomer, the structure and functionality of the aliphatic amine employed as crosslinker, and the mole ratio between the reacting groups. Thus, the compression properties of the hydrogels synthesized increased as the molecular weight of the oligomer decreased and the functionality of the amine increased, due to the formation of a network with a higher crosslinking degree. A similar effect was noticed when the amine chain length increased, due to the formation of additional physical crosslinking points through the hydrophobic interactions amongst the amine hydrocarbon chains. Also, excess of any of the reactants determined a decrease of both elastic and compression moduli, and compression strength due to the formation of a lower crosslinking degree network, as compared to the stoichiometric conditions.

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