

SWELLING BEHAVIOR OF NEW NANOPHOTONIC SOFT CONTACT LENSES BASED ON POLY (2- HYDROXYETHYL METHACRYLATE) AND FULLERENE

Aleksandra Mitrović^{1,a}, Vladimir Miljković^{1,2,b}

¹Kraljice Marije 16, 11000 Belgrade, Serbia University of Belgrade, Faculty of Mechanical Engineering,

²Neuhofstrasse 11, CH-4153 Reinach, Omya International AG, Switzerland

^aaleksandramitrovic1926@gmail.com, ^bv_miljkovic@yahoo.com

Abstract This work presents comparative research of characteristics of a basic and new nanophotonic materials, the latter of which were obtained by incorporation fullerene, C₆₀ and its derivatives in the basic material for soft contact lenses. Nanophotonic contact lens materials were obtained by adding fullerene C₆₀ and its derivatives: fullerene hydroxylate C₆₀(OH)₂₄ (fullerol) and fullerene metmorphene hydroxylate C₆₀(OH)₁₂(OC₄N₅H₁₀)₁₂ into the structure of the basic material, Polymacon, during the polymerization. New materials were obtained by addition of mentioned nanomaterials, which were derived by the technology in the production lab of the company Soleko (Milan, Italy). The materials were used for production of soft contact lenses in the company Optix (Belgrade, Serbia) for the purposes of this research. Fullerene was used due to its unique structure. For the purposes of materials characterization degree of swelling, diffusion in tested materials, swelling kinetics and network parameters were calculated. Results showed that the tested materials belong to a group of conventional hydrogels that swell slower than others. It was concluded that the incorporation of fullerene and its derivatives into the basic material does not affect significantly degree of swelling or the water content. The values of the diffusion exponent, n, close to 0.5 indicated Fick's kinetics corresponding to diffusion. The investigated hydrogels could be classified as non-porous hydrogels. Hence, new nanophotonic soft contact lenses could have potential application in this field.

Keywords: materials for nanophotonic soft contact lenses; PHEMA; fullerenes; swelling behavior.

1. INTRODUCTION

Soft contact lenses (SLCs) are made from hydrophilic polymers, which easily and quickly absorb water until they reach equilibrium. Swelling degree of SCLs is defined by external stimulants such as temperature, pressure, pH and other. The first hydrogel lenses were made from poly (2-hydroxyethyl methacrylate), pHEMA, hydrogel. A revolution in the world of contact lenses occurred when the production of thinner lenses with a large oxygen transmission became possible. The occurrence of such materials has initiated numerous research and development of physiologically more perfect materials for soft contact lenses [1,2]. The main advantage of SCLs monomer, 2-hydroxyethyl methacrylate (HEMA) is its ability to absorb water. The water content in this material can reach a value of 38%. This usually provides the necessary and sufficient elasticity and softness of the lens as well as the transmission of oxygen. However, the main disadvantage of this material is the limited transmission of oxygen compared to modern materials with higher water content. To increase the water content of the material, HEMA is combined with various monomers. HEMA-based polymers precisely differ in the amount and composition of the added monomers. All these agents have a different influence on the content of water in the lens, as well as on the electric charge and other physical properties of the polymer [3,4].

Soft contact lens materials can be synthesized to contain an optimal amount of water or biological fluids in the aqueous environment, to have appropriate mechanical properties, oxygen permeability, biocompatibility, the stability of the shape and softness similar to soft tissues [5-7]. Previous research in the field of biopolymers used for contact lenses was mainly related to material technology and also to the composition and morphology of polymers, with a special emphasis on oxygen permeability, bacterial adhesion, and resistance to protein and lipid deposits. Numerous research [8-13] had goal to develop and improve the characteristics of materials for soft contact lenses, all with purpose of achieving the highest quality vision correction, greater wearing comfort, providing sufficient amount of oxygen for the cornea and also to reduce medical complications wearing the soft contact lenses. Also, in the field of optics and materials for soft contact lenses, it is necessary to develop a new material which, after processing, should improve the optical properties such as transmission of visible and closely visible light.

One of the ways that can be used to improve the characteristics of the soft contact lens material is the application of nanotechnology. Immediately after the invention of the C_{60} , scientists and engineers examined methods for incorporating fullerene into the polymers. The primary goal was the production of processable materials that would have the usual characteristics of organic polymeric materials. Over the past several decades, polymers modified with nanoparticles have been of particular interest in the research and development of materials for making contact lenses [8,10,14,15].

The aim of this paper was to compare the properties of the basic and nanophotonic materials, synthesized in Soleko (Milan, Italy). Basic (SL38) and nanophotonic materials (SL38-A SL38-B and SL38-C) for soft contact lenses were obtained by radical polymerization of 2-hydroxyethyl methacrylate or 2-hydroxyethyl methacrylate and fullerene. From the obtained materials, soft contact lenses were made in Optix (Belgrade, Serbia). The swelling of the basic and nanophotonic materials in a buffer solution of pH 7.3 was studied. From the obtained results, the parameters of the network were calculated, as well as the molar mass between the two points of crosslinking and the pore size.

2. MATERIALS AND METHODS

2.1. Materials

Materials were obtained on the basis of the contract on scientific-technical-business cooperation between companies Optix (Belgrade, Serbia), Soleko (Milan, Italy) and the Faculty of Mechanical Engineering of the University of Belgrade. The polymerization of new nano-photonics materials for soft contact lenses was made by technology in the production labs of Soleko (Milan, Italy).

Nanophotonic contact lens materials were obtained by adding fullerene C_{60} (MER Corporation, USA, $\geq 99\%$) and its derivatives: fullerene hydroxylate $C_{60}(OH)_{24}$ (fullerol) and fullerene metamorphene hydroxylate $C_{60}(OH)_{12}(OC_4N_5H_{10})_{12}$ into the structure of the basic material Polymacon (SL38) during the polymerization. New materials were obtained by addition of mentioned nanomaterials, which were poorly dissolved in methacrylic acid. Individually, they were mixed with a monomer, which is incorporated into the composition of the SL38 material, prior to degassing the mixture. For the purpose of easier monitoring of all future measurements, the obtained materials were marked with

SL38-A or (SL38 + C₆₀), SL38-B respectively (SL38 + C₆₀(OH)₂₄) and SL38-C respectively (SL38 + C₆₀(OH)₁₂(OC₄N₅H₁₀)₁₂). The fullerene derivatives for SL38-B and SL38-C samples were previously dissolved in water. The fourth polymerization was carried out under the same conditions, without nanomaterials, in order to obtain a reference sample SL38. From the obtained materials, soft contact lenses were made.

2.2. Methods

2.2.1. Equilibrium swelling studies

For the investigation of the swelling, network parameters and reaction kinetics, the basic material (SL38), and nanophotonic materials for soft contact lenses SL38-A, SL38-B, and SL38-C were used. The density of the basic and nanophotonic materials was determined with the pycnometer.

The synthesized materials were in the discs form with dimensions: SL38 (R = 12.16 mm, h = 3.830 mm) and SL38-A (R = 12.50 mm, h = 3.730 mm), SL38-B (R = 12.42 mm, h = 3.680 mm) and SL38-C (R = 12.57 mm, h = 3.790 mm). For swelling study, a buffer solution (pH = 7.3): sodium chloride (Sigma Aldrich, BioXtra, ≥99.5%), boric acid (Sigma Aldrich, 4%) and borax disodium tetra borate (Sigma Aldrich, 50 g / l) was used.

Dry, measured samples were immersed in a 50 ml buffer solution pH 7.3 (pH value of the tear film). The average weight of the samples was: 0.1055 g (sample SL38), 0.1155 g (sample SL38-A), 0.1097 g (sample SL38-B) and 0.1059 g (sample SL38-C). The swelling process was gravimetrically monitored at 25 °C. At certain time intervals, the gels were extracted from the solution and after removal of an excess of buffer solution from the surface of the gel, the mass of the swollen gel was measured, and the degree of swelling q_t was calculated according to the equation [16-18]:

$$q_t = (w_t/w_o) \quad (1)$$

where:

w_o is the mass of dry sample,

w_t is the mass of swollen gel at the moment t .

Equilibrium degree of swelling was determined as the ratio of the mass of the swollen gel after the equilibrium and mass of the dry gel:

$$q_e = w_e/w_o \quad (2)$$

where:

w_e is the mass of swollen gel after reaching the equilibrium.

The obtained experimental results represent the mean value of three independent measurements. In order to keep the temperature constant during the measurement, all measurements were made in a dryer that was adjusted to the appropriate temperature. In this way, the influence of the temperature and pH of the solution as characteristic external factors affecting the swelling of the hydrogels was determined.

3. RESULTS AND DISCUSSION

3.1. Swelling behavior of hydrogels

3.1.1. Determination of the equilibrium degree of swelling

One of the most important properties of the soft contact lens is swelling due to water absorption. Due to this effect, volume of the SCL increases. When the dry sample is immersed in water, water molecules first hydrate the most polar hydrophilic groups, ionic groups (if they are present) and groups that can form the hydrogen bonds. The water content in soft contact lenses can reach a value between 38% and 79%. Absorbed water makes the lens soft and flexible. Figure 1 shows the time dependence of the swelling degree of the synthesized lenses at pH 7.3, which corresponds to the pH of the tear film.

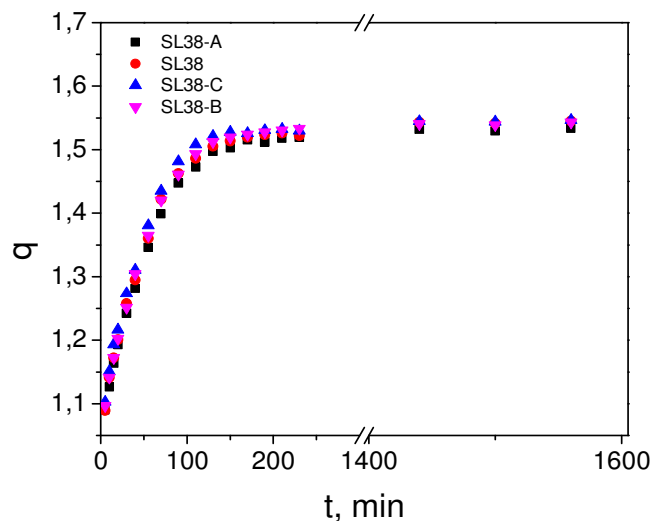


Figure 1. Degree of swelling of the tested materials for soft contact lenses SL38, SL38-A, SL38-B, and SL38-C.

The content of water in the basic material, SL38 was determined in the company Soleko (Milan, Italy) and it was 38%. Based on the diagram shown in Figure 1, it can be seen and concluded that all curves of the swelling have a similar shape and that crosslinking has been successfully performed because the hydrogels were not dissolved, but swollen in the water reaching the equilibrium degree of swelling. By comparing curves in Figure 1, for the SL38, SL38-A, SL38-B and SL38-C samples, it can be concluded that the incorporation of fullerene and its derivatives into the basic material does not affect significantly onto swelling degree or water content. The tested materials belong to a group of conventional hydrogels that swell slower than others. Based on the obtained results, it is assumed that synthesized nanophotonic materials can provide necessary and sufficient elasticity and softness of the lens as well as the basic material.

3.1.2. Diffusion in basic and nanophotonic materials

It is well known that diffusion in hydrogels is associated with the physical properties of the network and the interactions between the polymer and the penetrating medium [17]. When dry sample comes in contact with water, the water molecules diffuse into the polymeric network, and these water molecules are placed in spaces between the polymeric chains, causing their separation and swelling of the network. Time dependent water transport mechanism, when the equilibrium is reached, can be described and monitored using the semi-empirical equation (Eq.3):

$$\frac{w_t}{w_e} = k \cdot t^n \quad (3)$$

where:

w_t is the mass of water that absorbed by hydrogel after time t ,

w_e is the mass of water absorbed by hydrogel in an equilibrium state (when it reaches the equilibrium degree of swelling),

k is swelling constant,

n is diffusion exponent.

The Eq.3 is valid for the condition when $w_t/w_e < 0.6$. Based on the value of the diffusion exponent, information about the water absorption mechanism was obtained. If the value of the diffusion exponent is $n \leq 0.5$, the transport of liquids into the hydrogel follows the Fick law, or the water diffusion controls the swelling because it is a slower process than the relaxation of polymer chains. When $n = 1$, relaxation of the polymer chains controls the swelling process (so-called Type II, Case II). For values of n in the interval $0.5 < n < 1$, the swelling mechanism is not followed by the Fick's law, and fluid diffusion and relaxation of polymer chains control the swelling process. For values of $n > 1$, the mechanism corresponds to type III (super case II).

Figure 2 shows the graph of the linear dependence between $\ln(w_t / w_e)$ and $\ln(t)$. Table 1 represents the parameters and coefficients of dependence $\ln(w_t / w_e)$ and $\ln(t)$.

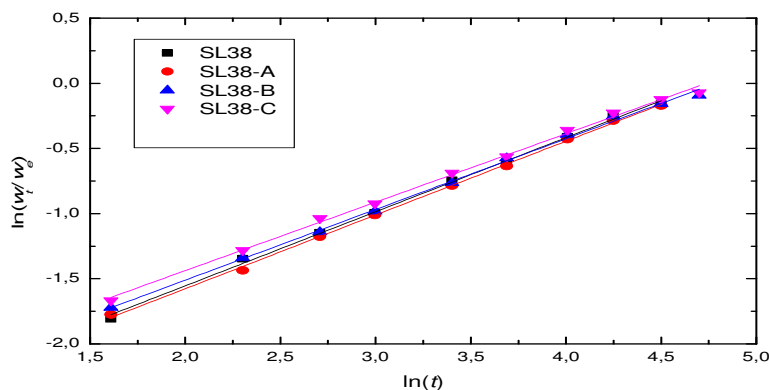


Figure 2. Linear dependence between $\ln(w_t/w_e)$ and $\ln(t)$ of the tested materials for soft contact lenses.

Table 1: Parameters and coefficients of logarithmic dependence $\ln(w_t/w_e)$ and $\ln(t)$ of the tested materials for soft contact lenses.

Sample	Functional dependence		Correlation coefficient (R)	Determination coefficient (R ²)
	$\ln\left(\frac{w_t}{w_e}\right) = a + b \cdot \ln(t)$			
	Coefficients			
	a	b		
SL 38	-2,69	0,569	0,9992	0,9981
SL 38-A	-2,71	0,566	0,9995	0,9989
SL 38-B	-2,60	0,542	0,9990	0,9977
SL 38-C	-2,49	0,526	0,9988	0,9973

The values of the constant k and the exponent n for the initial phase of the swelling process for the SCL materials were calculated from the intersection and slope when the dependence of the swelling degree over time had been linear. This is the time for which the hydrogel absorbs 60% of the total absorbed water or buffer solution. The obtained results are shown in Table 2.

Table 2: Kinetic parameters of the swelling.

Sample	$k \cdot 10^2, \text{min}^{-1/2}$	n	R ²
SL 38	6,77	0,57	0,9981
SL 38 - A	6,66	0,57	0,9989
SL 38 - B	7,45	0,54	0,9977
SL 38 - C	8,29	0,53	0,9973

Based on these data, it can be concluded that the value of the diffusion exponent was not significantly greater than 0.5 so that the transport of the fluid through the samples can be considered close to the Fick's diffusion ie. water diffusion controls the swelling process. It can also be noticed that the addition of the fullerene and its derivatives did not significantly change the value of the diffusion exponent. The advantage of Fick diffusion is reflected in the homogeneity of the fluid by volume. The SL38-C material had the closest diffusion exponent value of 0.5.

3.1.3. Swelling kinetics

Based on the normalized degree of swelling and normalized equilibrium degree of swelling, as well as the equations describing the first and second order of reaction, it is possible to determine the order of reaction by which the swelling of the hydrogels is carried out.

The normalized swelling degree was calculated using the equation [19]:

$$Q_t = \frac{w_t - w_0}{w_0} \quad (4)$$

The value of the normalized equilibrium degree of swelling was obtained from the value of the normalized degree of swelling in the equilibrium state.

If it was assumed that the swelling process, ie reaching an equilibrium state, followed the first-order reaction, then the following equation was applied [19]:

$$\frac{Q_t}{Q_e} = 1 - \exp(-k_1 \cdot t) \quad (5)$$

where:

k_1 is the rate constant of the first-order reaction, h^{-1} ,

t is the time, h,

Q_t is the normalized swelling degree, and

Q_e is the normalized equilibrium swelling degree.

The logarithm of the equation (5) and its arrangement yields the following dependence:

$$\ln\left(1 - \frac{Q_t}{Q_e}\right) = -k_1 \cdot t \quad (6)$$

If it was assumed that the kinetics of the swelling process take place according to the second order of reaction, the following equation was used [20]:

$$Q_t = \frac{k_2 \cdot Q_e^2 \cdot t}{1 + k_2 \cdot Q_e^2 \cdot t} \quad (7)$$

where :

k_2 is the constant for the second order reaction, h^{-1} .

By linearizing, the Eq. 7 was reduced to the following form [19]:

$$\frac{t}{Q_t} = \frac{1}{k_2 \cdot Q_e^2} + \frac{t}{Q_e} \quad (8)$$

The results shown in Table 3 indicated that the swelling of the lens deviated considerably from the first order of the reaction. However, the dependence t/Q_t - t was rectilinear for all samples. It was also shown that the experimentally determined and calculated values of normalized equilibrium degree of swelling of the hydrogel, $Q_{e,exp}$ and $Q_{e,calc}$ coincide, which confirms that the swelling of the lenses was following the second order reaction.

Table 3: The values of the experimentally obtained and calculated normalized equilibrium degree of swelling of the lens, parameters of the first and second order of reaction.

Sample	$Q_{e, \text{exp}}$	I order of reaction		II order of reaction			
		k_1, h^{-1}	R^2	$Q_{e, \text{calc}}$	k_2, h^{-1}	R^2	$Q_{e, \text{calc}}$
SL-38	0,54	0,0033	0,5650	3,57	0,083	0,9996	0,55
SL 38-A	0,53	0,00028	0,2107	2,07	0,082	0,9995	0,54
SL 38-B	0,54	0,00045	0,6427	2,58	0,0903	0,9996	0,55
SL 38-C	0,55	0,00038	0,7022	2,35	0,0991	0,9997	0,55

3.1.4 Network parameters

In order to characterize a polymeric network, it is necessary to determine the molar mass of the polymer chains between the two adjacent crosslinking points (M_c), the pore size (ξ), the bulk fraction of the polymer in the swollen state (v_{2s}), the polymer solvent interaction parameter (χ) and the effective crosslinking density (V_e). The molar mass between the two crossing points was calculated using the Flory-Rehner equation [21]. The values of the parameters of the hydrogel network (bulk fraction of the polymer in the swollen hydrogel, the molar mass of the polymeric chains between the two adjacent crosslinking points, the effective crosslinking density and the pore size) are shown in Table 4 [1, 22-23].

Table 4: Network parameters of tested materials for the soft contact lenses obtained by application of the equilibrium swelling theory.

Sample	q_e	$d_p, \text{g/cm}^3$	v_{2m}	χ	$M_c \cdot 10^{-3}, \text{g/mol}$	$V_e \cdot 10^{-22}, \text{mol/cm}^3$	$\xi \cdot 10^{-10}, \text{nm}$
SL 38	1,54	1,36	0,72	0,85	0,0367	0,23	0,365
SL 38 - A	1,53	1,24	0,73	0,88	0,0297	0,25	0,324
SL 38 - B	1,54	1,40	0,72	0,84	0,0386	0,22	0,376
SL 38 - C	1,55	1,35	0,72	0,85	0,0361	0,23	0,362

Based on the shown values of the network parameters, it was observed that the SL38-A nanophotonic material had a lower molar mass between the two points of crosslinking, and the pore size compared to SL38, while the nanophotonics SL38-B and SL38-C had approximately same values of the same parameters as the basic material, SL38. The effective crosslinking density and the polymer solvent interaction parameter for SL38-A were greater than the SL38 basic material (Table 4). SL38-B and SL38-C nanophotonic materials also in this case have values similar to the basic material, SL38. The results obtained were consistent with the results of swelling. Low values for M_c were expected due to the small equilibrium degree of swelling of the observed synthesized materials. The smaller is the molar mass between the two points of crosslinking, the effective crosslinking density is greater, and the swelling is lower. The values of the interaction parameter were in accordance with the swelling results.

Therefore, from the obtained results, it can be concluded that the SL38-A nanophotonic material has slightly different values of the network parameters compared to the other three tested samples. Results indicated that SL38-A formed a more compact material compared to the basic material, SL38. Such results can be explained by the fact that incorporation of the fullerene into the polymer matrix increases the number of polymer-fullerene interactions, as it can be seen through the increase in the interaction parameter, χ . In addition, fullerene, unlike its derivatives, does not dissolve in water and in certain organic solvents. There is a different sensitivity to dissolution [15]. Unlike the SL38-A material, the SL38-B and SL38-C materials have similar values with the basic material, SL38, so it was assumed that a certain amount of nanomaterials did not interact with the polymer but remained trapped in the polymer matrix and did not significantly affect the changes of some properties of synthesized materials. According to the calculated pore size values, tested hydrogels can be classified as non-porous since the pore size is less than 10 nm [20, 24].

The further research direction would be the synthesis of existing hydrogels with improved characteristics in terms of swelling properties. The swelling process in hydrogels mostly depends on the elasticity of the polymer network, from the presence of hydrophilic functional groups (such as hydroxide, carboxyl, amide, sulfide) in the polymer chain, from the degree of crosslinking and porosity of the polymer. Furthermore, the swelling may also be affected by the balance of forces between charged particles and nature of the solvent. When the dry hydrogel has contact with water, water molecules firstly hydrate the most polar hydrophilic groups, as well as the ionic groups and they can form a hydrogen bond. Due to the rigid structure of crystalline zones and low elasticity, conventional hydrogels slowly swell and therefore the time they need to reach an equilibrium swelling degree is much longer (for few hours or days).

Although this, slower swelling mode is beneficial in many areas of their application, there are situations when a much shorter time is required to reach the maximum degree of swelling of hydrogel. Thus, the development of a new generation of hydrogels is in progress, and one of the most important properties is significantly reduced time for reaching the maximum degree of swelling. These type of gels are commonly referred as super absorbable hydrogels (SAH) [3]. These polymers will achieve an equilibrium swelling degree in just a few minutes. There are three ways [25] that can affect the improvement of the swelling speed of the hydrogels. One approach is the synthesis of a copolymer where a second component is inserted into the hydrogel by grafting. The rate of swelling of hydrogel obtained by grafting is higher than for the hydrogel obtained by homopolymerization due to the increased mobility of the tained chain. Another possibility is to reduce the size of the hydrogel particles. The third way is to synthesize the hydrogel with porous structure.

4. CONCLUSION

In this paper, the properties of basic and new nanophotonic materials were examined and compared. It was concluded that the incorporation of fullerene and its derivatives into the basic material does affect significantly degree of swelling or the water content. It has been shown that the transport of liquids through synthesized materials follows the Fick's diffusion law and that these synthesized materials can be classified into a group of non-porous hydrogels.

On the basis of the obtained results, the investigated nanophotonic materials for soft contact lenses could have a potential application for the production of soft contact lenses.

Acknowledgements

This research has been partially funded by Ministry of Science and Technological Development of Republic of Serbia, through Project III 45009. Authors wish to express their sincere gratitude to company Optix (Belgrade, Serbia) for technical assistance.

References

- [1] Lowman A.M., and Peppas, N.A., 1999, Hydrogels, In: Mathiowitz E. (Ed.), *Encyclopedia of Controlled Drug Delivery*, pp. 397-418, John Wiley & Sons, New York.
- [2] Bajpai S.K., 2001, Swelling–deswelling behavior of poly(acrylamide-co-maleic acid) hydrogels, *Journal of Applied Polymer Science*, Vol. 80, pp. 2782-2789.
- [3] Karadağ E., Üzümlü Ö.B., and Saraydin D., 2002, Swelling equilibria and dye adsorption studies of chemically crosslinked superabsorbent acrylamide/maleic acid hydrogels, *European Polymer Journal*, Vol. 38, pp. 2133-2141.
- [4] Torres-Lugo M., and Peppas N.A., 1999, Molecular Design and in vitro Studies of Novel pH-Sensitive Hydrogels for the Oral Delivery of Calcitonin, *Macromolecules*, Vol. 32, pp. 6646-6651.
- [5] Safrany A., 1997, Radiation processing: Synthesis and modification of biomaterials for medical use, *Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials and Atoms*, Vol. 131, pp. 376–381.
- [6] Rosiak J.M., and Yoshii F., 1999, Hydrogels and their medical applications, *Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials and Atoms*, Vol. 151, pp. 56–64.
- [7] Yu T., and Ober C.K., 2003, Methods for the Topographical Patterning and Patterned Surface Modification of Hydrogels Based on Hydroxyethyl Methacrylate, *Biomacromolecules*, Vol. 4, pp. 1126–1131.
- [8] Ahmed R.M., and El-Bashir, S.M., 2011, Structure and Physical Properties of Polymer Composite Films Doped with Fullerene Nanoparticles, *International Journal of Photoenergy*, 6 p.
- [9] Howard A. Ketelson, David L. Meadows, and Ralph P. Stone, 2005, Dynamic wettability properties of a soft contact lens hydrogel, *Colloids and Surfaces B: Biointerfaces*, Vol. 40, pp. 1-9.
- [10] Opdahl A., Kim S.H., Koffas T.S., Marmo C., and Somorjai G.A., 2003, Surface mechanical properties of PHEMA contact lenses: Viscoelastic and adhesive property changes on exposure to controlled humidity, *Journal of Biomedical Material Research Part A*, Vol. 67, pp. 350-356.
- [11] Kim S.H., Opdahl A., Marmo C., and Somorjai G.A., 2002, AFM and SFG studies of PHEMA-based hydrogel contact lens surfaces in saline solution: adhesion, friction, and the presence of non-crosslinked polymer chains at the surface, *Biomaterials*, Vol. 23, pp. 1657-1666.
- [12] Tranoudis I., Efron N., 2004, Water properties of soft contact lens materials, *Eye and Contact Lens*, Vol. 27, pp.193–208.
- [13] Kopeček J., 1993, Hydrogels: From Soft Contact Lenses and Implants to Self-Assembled films, *Journal of Applied Physics*, Vol. 743, pp. 669-672.
- [14] Stamenkovic D., Kojic D., Matija L., Miljkovic Z., Babic B., 2010, Physical Properties of Contact Lenses Characterized by Scanning Probe Microscopy and Optomagnetic Fingerprint, *International Journal of Modern Physics*, Vol. 24, 825-834.
- [15] Debeljković A.D., Matija L.R., Koruga Đ.Lj., 2013, Characterization of nanophotonic soft contact lenses based on poly (2-hydroxyethyl methacrylate) and fullerene, *Hemjska industrija*, Vol. 67, pp. 861-870.
- [16] Bell C.L., Peppas N.A., 1996, Water, solute and protein diffusion in physiologically responsive hydrogels of poly(methacrylic acid-g-ethylene glycol), *Biomaterials*, Vol. 17, 1203-1218.

- [17] Milosavljević N.B., Milašinović N.Z., Filipović J.M., Kalagasidis Krušić M.T., 2011, Sinteza i karakterizacija kopolimernih hidrogelova hitozana, itakonske kiseline i N-izopropilakrilamida, *Hemijska Industrija*, Vol. 65, pp. 657–666.
- [18] Valencia J., Pierola I., 2001, Equilibrium swelling properties of poly(N-vinylimidazole-co-sodium styrenesulfonate) hydrogels, *European Polymer Journal*, Vol. 37, pp. 2345-2352.
- [19] Wu F.C., Tseng R.L., Juang R.X., 2000, Comparative adsorption of metal and dye on flake- and bead-types of chitosans prepared from fishery wastes, *Journal of Hazardous Materials*, Vol. 73, pp. 63–75.
- [20] Omidian H., Rocca J.G., Park K., 2005, Advances in superporous hydrogels, *Journal of Controlled Release*, Vol. 102, pp. 3-12,.
- [21] Kopeček J., 2003, Smart and genetically engineered biomaterials and drug delivery systems, *European Journal of Pharmaceutical Sciences*, Vol. 20, pp. 1-16.
- [22] Peppas N.A., Bures P., Leobandung W., Ichikawa H., 2000, Hydrogels in Pharmaceutical Formulations, *European Journal of Pharmaceutics and Biopharmaceutics*, Vol. 50, pp. 27-46.
- [23] Narasimhan B., Peppas N.A., 1997, Molecular Analysis of Drug Delivery Systems Controlled by Dissolution of the Polymer Carrier, *Journal of Pharmaceutical Sciences*, Vol. 86, pp. 297-304.
- [24] Chen J., Blevins W.E., Park H., Park K., 2000, Gastric retention properties of superporous hydrogel composites, *Journal of Controlled Release*, Vol. 64, pp. 39-51.
- [25] Zhang J., Wang L., Wang A., 2006, Preparation and Swelling Behavior of Fast-Swelling Superabsorbent Hydrogels Based On Starch-g-Poly(acrylic acid-co-sodium acrylate), *Macromolecular Materials and Engineering*, Vol. 291, pp. 612-620.