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Controlled production of alginate nanocomposites with incorporated silver nanoparticles aimed for biomedical applications

JASMINA STOJKOVSKA, JOVANA ZVICER, ŽELJKA JOVANOVIĆ[#], VESNA MIŠKOVIĆ-STANKOVIĆ[#] and BOJANA OBRADOVIĆ*[#]

Faculty of Technology and Metallurgy, University of Belgrade, Karnegijeva 4, 11000 Belgrade, Serbia

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Abstract: The production of nanocomposite alginate microbeads with electrochemically synthesized silver nanoparticles (AgNPs) based on the electrostatic extrusion technique was investigated with respect to their potentials for utilization in pharmaceutical and biomedical applications. It was shown that electrochemical synthesis of AgNPs results in the reduction of practically all the Ag^+ present in the initial solution, yielding stable Ag/alginate colloid solutions that were demonstrated to be suitable for sterilization, manipulation, and electrostatic extrusion with retention of the AgNPs. The presence of AgNPs in the alginate colloid solutions had negligible effects on the size of the produced Ag/alginate microbeads, which was mainly determined by the electrostatic potential applied during the extrusion. On the other hand, the incorporation of AgNPs within the alginate hydrogel induced slight changes in biomechanical properties of the microbeads determined in a biomimetic bioreactor. Thus, packed beds of nanocomposite Ag/alginate microbeads exhibited a slightly higher dynamic compression modulus as compared to that of control alginate microbeads (154±4 and 141±2 kPa, respectively). On the other hand, the equilibrium unconfined compression modulus was significantly lower for the nanocomposite microbeads as compared to that of the controls (34±2 and 47±1 kPa, respectively).

Keywords: electrochemical synthesis; electrostatic extrusion; sterilization; biomechanical properties.

INTRODUCTION

The antimicrobial properties of silver have been known for centuries, so that silver pots were utilized for water preservation while silver-based compounds

* Corresponding author. E-mail: bojana@tmf.bg.ac.rs
[#] Serbian Chemical Society member.
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found applications in traditional medicine.[1–3] Today, silver as an antimicrobial agent has gained renewed attention due to the increasing problem of antibiotic-resistant bacterial strains.[4] There is a range of silver-containing medical products such as antimicrobial wound dressings, ointments, and coatings.[5,6] Furthermore, silver nanoparticles (AgNPs) were reported to be even more potent than silver ions acting by attachment and interactions with the bacterial cell membrane, release of Ag^+ ions and, potentially, by penetration into the cell interior.[7] Different methods for the production of AgNPs made them also attractive for exploring possibilities for the development of novel bioactive biomaterials aiming at combining the relevant function of the biomaterial with the antimicrobial properties of the nanoparticles.[5]

However, one of the main problems for utilization of AgNPs is a strong tendency of these nanoparticles to agglomerate due to the large specific surface area and high surface energy. Polymers as capping agents in solutions and as hydrogels were shown to be viable options for achieving nanoparticle stabilization.[8] One of the widely investigated polymers for biomedical applications in general as well as in combinations with AgNPs, is alginate, a natural polysaccharide that easily forms hydrophilic, biocompatible and bioresorbable hydrogels. Alginates are already used in pharmacy and medicine as excipients for drugs, dental impression materials, wound dressings and carriers of drugs and transplanted cells.[9] Supplementation of alginate hydrogels with silver offers the additional feature of antimicrobial activity. Thus, a number of wound dressing products based on alginate fibers with incorporated silver ions have been produced.[10] However, incorporation of AgNPs within alginate solutions and/or hydrogels provides possibilities for controlled and prolonged release of Ag nanoparticles and/or ions and production of variety of formulations with different compositions and forms. AgNPs have been produced in alginate solutions supplemented with silver salts (*e.g.* nitrate, sulfate) by reduction of Ag^+ using sodium borohydride as the reductant,[11–13] by gamma irradiation[14] or simply by heating of the solution where alginate served as both a reducing agent and a stabilizer.[15]

It was recently shown that electrochemical synthesis can also be used for the production of AgNPs in alginate solutions and that the obtained colloid solutions could be further utilized to obtain nanocomposite Ag/alginate hydrogels.[16–18] Electrochemical synthesis is particularly advantageous for potential use in biomedicine and pharmacy due to precise control of particle size achieved by adjusting current density or applied potential and high purity of the obtained nanocomposite hydrogels containing only gelling cations, alginate and AgNPs. Furthermore, nanocomposite hydrogels in the form of microbeads (<1 mm in diameter) are suitable for controlled release of AgNPs and/or ions due to the large specific surface area and short internal diffusion distances. Alginate microbeads

were shown to be suitable for immobilization of variety of cell types, such as insect and mammalian cells[19] as well as brewing yeast cells.[20] It was previously shown that alginate microbeads could also be used for cartilage tissue engineering as supports for chondrogenic cells (*e.g.* bone marrow stromal cells[21,22] and bovine calf chondrocytes[23,24]) coupled with biomimetic bioreactors that imitate physiological conditions in articular cartilage. Supplementation of AgNPs within alginate microbeads could potentially provide an additional feature of prolonged sterility of engineered implants.

One of the techniques for controlled production of uniform hydrogel microbeads is electrostatic droplet generation based on extrusion of an alginate solution under the action of electrostatic forces that disrupt the liquid filament at the capillary/needle tip to form a charged stream of small droplets collected in a gelling bath.[25,26] As Na^+ are exchanged with Ca^{2+} from the gelling solution, the droplets solidify forming microbeads down to 50 μm in diameter.[26,27] The process of electrostatic droplet formation is a complex function of a number of parameters,[28,29] while for a chosen electrode set-up and polymer, the applied electrostatic potential was shown to be the key determinant of the droplet and, consequently, also the microbead size.[28] As the electrostatic potential, U, is increased, the droplet size decreases gradually at first and then sharply at a critical potential value, U_c, after which microscopic charged droplets are formed, the size of which does not vary with further increase in U.[28] Relationship between the applied potential, U, and the droplet radius, r, can be derived by balancing the forces acting on the droplet,[28,29] which for a positively charged needle resulted in:[30]

$$U^2 = \frac{[\ln(4H/r)]^2(c - dr^3)}{2\varepsilon_0} \quad (1)$$

with

$$c = r_0\gamma \quad (2)$$

and

$$d = \frac{2}{3}\rho g \quad (3)$$

where H is the distance between the electrodes (*i.e.*, the needle tip and the surface of the gelling solution), ε_0 is the permittivity of air ($\varepsilon_0 = 8.85\times10^{-12}$ C^2 $N^{-1}m^{-2}$), r_0 is the internal radius of the needle, γ is the surface tension, ρ is the liquid density, and g is the gravitational acceleration. Eqs. (1)–(3) were shown to agree qualitatively with the experimental data.[30]

For potential biomedical utilization of nanocomposite hydrogels, it is required that the production procedure is simple, precisely regulated and scalable, while the final products are pure, sterile and with controlled properties. The aim of this study was to characterize comprehensively the production of nanocompo-

site Ag/alginate microbeads based on electrochemical synthesis of AgNPs in alginate solutions followed by electrostatic extrusion of the obtained colloid solutions. Specifically, the possibilities for sterilization and manipulation of Ag/alginate colloid solutions with retention of AgNPs as well as the production of nanocomposite microbeads regarding the effects of electrostatic extrusion parameters on the microbead size and AgNP concentration were investigated. In addition, the effects of AgNP incorporation in alginate hydrogels on biomechanical properties of packed beds of microbeads were studied in a biomimetic bioreactor with dynamic compression that imitates *in vivo* conditions in native articular cartilage.

EXPERIMENTAL

Materials

Low viscosity sodium alginate (A-2158) was purchased from Sigma (St. Louis, MO). Sodium citrate was bought from Himedia (Mumbai, India), $AgNO_3$ from M. P. Hemija (Belgrade, Serbia), KNO_3 from Centrohem (Stara Pazova, Serbia) and $Ca(NO_3)_2 \cdot 2H_2O$ from Alkaloid (Skopje, Macedonia). Water from Milli-Q system (Millipore, Billerica, MA, USA) was used in all experiments and N_2 gas (Messer Tehnogas a.d., Belgrade, Serbia) was of high purity (99.5 %).

Production of alginate colloid solutions with AgNPs

Sodium alginate solutions with AgNPs were produced by electrochemical synthesis as described previously.[16] Briefly, electrochemical synthesis was performed galvanostatically in an electrochemical cell containing 50 cm^3 of an aqueous solution containing 0.1 M KNO_3, 3.9 mM $AgNO_3$ and 2 % w/v Na-alginate. Two Pt plates functioned as the working and counter electrodes and a saturated calomel electrode (SCE) as a reference electrode using Gamry Reference 600 Potentiostat/Galvanostat/ZRA (Gamry Instruments, Warminster, PA). The synthesis was performed under continuous stirring at the current density of 50 mA cm^{-2} and implementation time of 10 min. N_2 was passed through the solution for 20 min prior to the synthesis, followed by continuous N_2 flow over the solution during the synthesis. Gravimetric analysis showed that the final Ag/alginate colloid solution contained 1.9 % w/v alginate due to slight polymer deposition on the counter electrode.[18]

A series of colloid solutions with different concentrations of AgNPs was obtained by dilution of the initially synthesized colloid solution with 1.9 % w/v Na-alginate solution. Sterilization of the obtained Ag/alginate colloid solutions was realized by transferring the solution into a sterile, covered glass vessel and boiling for 30 min under magnetic stirring.

Production of nanocomposite alginate microbeads with incorporated AgNPs

Sodium alginate colloid solutions with AgNPs were used to produce Ag/alginate microbeads by electrostatic droplet generation as described previously.[16-18] In brief, Ag/alginate colloid solutions with different AgNP concentrations were extruded through a positively charged blunt edge, stainless steel needle (23 gauge) using a 5 or 10 cm^3 syringe and a syringe pump (Racel, Scientific Instruments, Stamford, CT, USA). The electrode distance between the needle tip and the grounded gelling bath (1.5 % w/v $Ca(NO_3)_2 \cdot 2H_2O$) was kept constant in all experiments at 2.5 cm. After extrusion, the microbeads remained in the gelling bath for an additional 30 min in order to complete their gelling, and thereafter were washed in H_2O to remove the residual silver ions. In order to investigate the effects of the extrusion parameters,

the initially synthesized Ag/alginate colloid solution with a silver concentration of 3.9 mM was extruded in two experimental series. In the first experimental series, the applied electrostatic potential was varied in the range 0–7.5 kV at a flowrate of 25.2 cm^3 h^{-1}, while in the second series, the flowrate ranged from 5.1 to 25.2 cm^3 h^{-1} at a constant potential of 6.6 kV. For biomechanical characterization, four experimental series of microbeads were produced at a flowrate of 39.3 cm^3 h^{-1} and an electrostatic potential of 6.8 kV using the initially synthesized Ag/alginate colloid solution (3.9 mM silver concentration), and colloid solutions diluted with 1.9 % w/v Na-alginate to yield silver concentrations of 2 and 1.5 mM, and 1.9 % w/v Na-alginate as a control.

The effects of the electrostatic extrusion on the further reduction of Ag^+ possibly remaining in the alginate solution after the electrochemical synthesis were examined by extrusion of the Ag/alginate colloid solution at different applied electrostatic potentials in the range 0–7.5 kV and measurements of the absorbance at 405 nm.

Characterization of Ag/alginate nanocomposites

UV–Vis Spectroscopy. The presence of AgNPs in alginate colloid solutions and nanocomposite microbeads upon dissolution in 0.05 M sodium citrate (0.1 g of microbeads in 1 cm^3 of sodium citrate) was confirmed using a UV-3100 spectrophotometer (Mapada, Japan). In addition, the possible effects of Na-citrate on the AgNP concentration were examined by measuring the absorbance at a wavelength of 405 nm of a mixture of the initially synthesized Ag/alginate colloid solution (3.9 mM silver concentration) and 0.05 M sodium citrate in the volume ratio 1:9 every 10 min during 1 h.

Silver concentration. The concentration of silver in the Ag/alginate microbeads was determined after oxidation of all the AgNPs by addition of excess concentrated nitric acid (65 %) (10–15 cm^3 of the acid per 1 g of microbeads). Concentration of Ag^+ in the solutions was then determined at a four-digit accuracy by atomic absorption spectrometry (AAS) using a Perkin Elmer 3100 instrument (Perkin Elmer, MA, USA).

Optical microscopy. Diameters of microbeads were determined from measurements of at least 20 microbeads using an optical microscope (Olympus CX41RF, Tokyo, Japan) with the image analysis program "CellA" (Olympus, Tokyo, Japan).

Biomechanical characterization of the Ag/alginate microbeads under bioreactor conditions

Biomechanical properties of packed beds of Ag/alginate microbeads prepared from colloid solutions with silver concentrations of 1.5, 2, and 3.9 mM were investigated in a biomimetic bioreactor with dynamic compression[31] as described previously.[24] Packed beds of 1.9 % w/v Ca-alginate microbeads served as a control. The compression tests were performed simultaneously in 3 cartridges loaded with microbeads (≈0.6 g in each) at 3 mm initial bed height, filled with distilled water and repeated at least 3 times for each microbead group. The tests were performed at 10 % strain in two regimes: at a loading rate of 337.5 μm s^{-1} and at sequential increments of 50-μm displacement every 30 min. Compression and equilibrium unconfined compression moduli were determined from the slopes of the best linear fits of the obtained stress–strain relationships.

RESULTS AND DISCUSSION

Production of alginate colloid solutions with AgNPs

Alginate colloid solutions with AgNPs were successfully produced by electrochemical synthesis as described previously.[16–18] In the present work, the pos-

sibilities for sterilization and dilution of the obtained colloid solution with retention of AgNPs, required for potential biomedical uses, were investigated. The initially synthesized Ag/alginate colloid solution with 3.9 mM concentration of silver was diluted with 1.9 % w/v Na-alginate yielding colloid solutions with different concentrations of AgNPs. Sterilization by boiling for 30 min of the initial and a diluted colloid solution (silver concentration of 1 mM) was shown to stabilize even further the nanoparticles, as indicated by the UV-vis absorption spectra. Specifically, the absorption spectra of all the corresponding samples exhibiting surface plasmon absorption band maxima at the wavelength of ≈405 nm were not significantly different (Fig. 1). Maximal absorbance at this wavelength corresponds to AgNPs with the diameter of about 20 nm based on theoretical predictions of the surface plasmon absorption band for spherical AgNPs suspended in water.[32] Indeed, the diameters of the electrochemically synthesized AgNPs in alginate solutions were in the range 10 to 30 nm as determined previously by transmission electron microscopy.[18] Furthermore, the maximum absorbance value slightly increased by about 10 % upon sterilization, implying a slight further reduction of Ag^+ and/or nanoparticle stabilization (Fig. 1). These results are consistent with the method of AgNP synthesis by reduction of Ag^+ in alginate solutions by heating at 90 °C for 1 h, where alginate was shown to be not only a nanoparticle stabilizer, but also a reducing agent.[15]

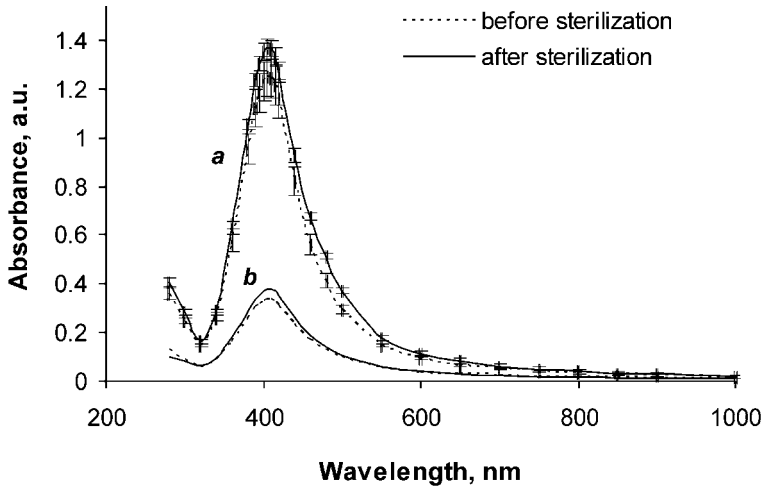

Fig. 1. Absorption spectra of a) initial Ag/alginate colloid solution (3.9 mM silver concentration) and b) 3.9-fold diluted Ag/alginate colloid solution (1 mM silver concentration) before and after sterilization by boiling for 30 min (the data represent the average of $n = 3$; standard deviations (<10 %) are omitted from the graph for data b in order for the spectra to be distinguishable).

Furthermore, dilution of the Ag/alginate colloid solution did not affect the AgNPs as confirmed by the UV-vis spectra that showed unchanged surface plasmon absorption band maxima at ≈405 nm (Fig. 1). In addition, the absorbance values at a wavelength of 405 nm of a series of diluted colloid solutions showed a linear dependence on the concentration of silver nanoparticles/ions ($r^2 > 0.99$), indicating preservation of the AgNPs (Fig. 2).

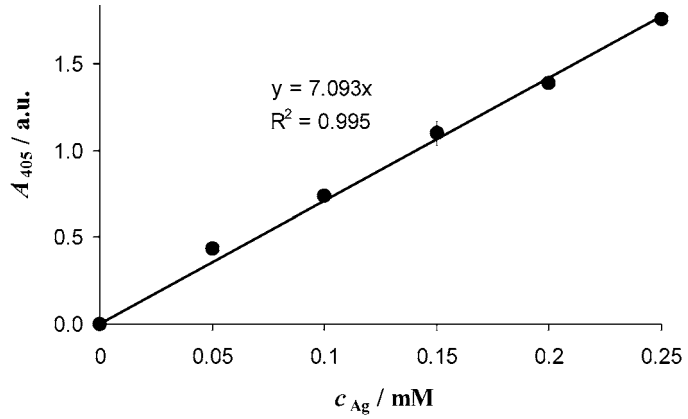

Fig. 2. UV–Vis Spectrometric analysis of Ag/alginate colloid solutions diluted with 1.9 % w/v Na-alginate: absorbance at a wavelength of 405 nm, A_{405}, as a function of the concentration of silver nanoparticles/ions in diluted solutions, c_{Ag} (the data represent an average of $n \geq 3$).

Production of nanocomposite alginate microbeads with incorporated AgNPs

Effects of the electrostatic extrusion parameters. Nanocomposite alginate microbeads with incorporated AgNPs were produced by electrostatic extrusion of Ag/alginate colloid solutions having different silver concentrations. The AgNPs were retained during the microbead production process as revealed by UV–Vis spectrometry as described earlier[18] (Fig. 3, inset). The value of the absorbance maximum positioned at ≈405 nm was even higher for the nanocomposite microbeads as compared to that of the initial colloid solution, implying a higher concentration of AgNPs. In this study, this result and the possibility that Ag^+ ions possibly retained in the Ag/alginate colloid solution were reduced during the electrostatic extrusion process and dilution of the microbeads in sodium citrate were examined. However, the absorbance values at a wavelength of 405 nm determined for Ag/alginate colloid solution extruded at different electrostatic potentials up to 7.5 kV remained constant (1.0±0.1). Moreover, the addition of sodium citrate to Ag/alginate colloid solution was shown to induce negligible effects on the absorbance measured at 405 nm (≈2 %). However, measurements of the concentration of silver nanoparticles/ions in the microbeads by AAS confirmed higher concentrations in the microbeads as compared to the corresponding source Ag/alginate solutions (Fig. 3). It can be seen that concentration of silver nanopar-

ticles/ions in Ag/alginate microbeads was on average ≈20 % higher than that in the corresponding source colloid solution with the exception of the lowest initial concentration of 0.5 mM, for which the measured concentration in the microbeads was significantly lower (0.3±0.1 mM). These results could be explained by the combined effects of mass losses during the extrusion, which were measured in this study to be up to 35 %, and contraction of the alginate gel during gelation, as reported in the literature[33] inducing higher silver concentrations in microbeads as compared to the source colloid solutions. Yet, it should also be noted that some experimental errors are introduced during sampling of the microbeads due to the very rapid water evaporation from the bead surfaces.

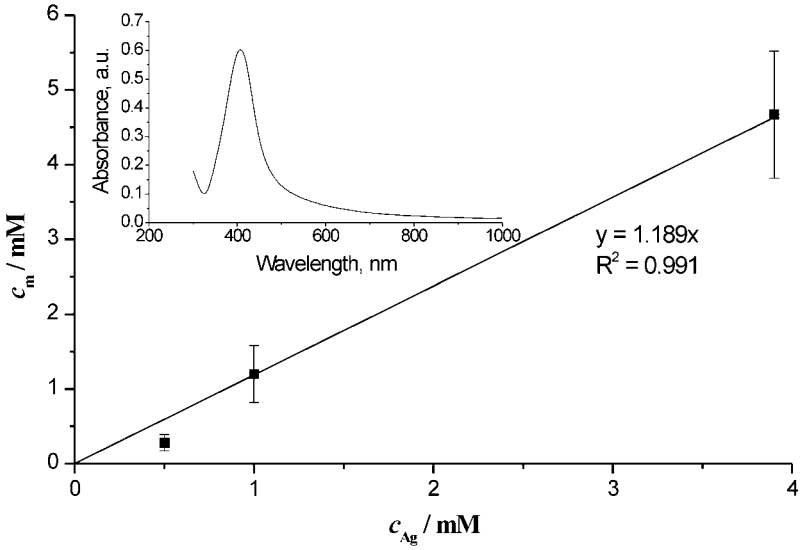

Fig. 3. Concentration of silver nanoparticles/ions in microbeads, c_m, as a function of the concentration in the corresponding source Ag/alginate colloid solutions, c_{Ag}; inset: absorption spectrum of dissolved Ag/alginate microbeads showing the absorbance maximum at a wavelength of ≈405 nm (the data represent an average of $n \geq 3$).

Overall, these results convincingly demonstrate that practically all the initial Ag^+ ions were reduced during the electrochemical synthesis of AgNPs, which were further retained during the electrostatic extrusion.

An investigation of the effects of the electrostatic extrusion parameters on the size of the obtained Ag/alginate microbeads showed the strong effects of the electrostatic potential (Fig. 4). Simultaneously, the effects of the variation of the flowrate, in the investigated experimental range, were negligible (*STD* < 4 %, data not shown). The dependence of the microbead diameter on the applied potential was modeled by Eqs. (1)–(3) using the determined value for the density of the Ag/alginate colloid solution of 1026±2 kg m^{-3} and for the surface tension

of 0.074 N m^{-1},[30] and a needle diameter of 0.337 mm (for a 23 gauge needle). The model predictions were in qualitative agreements with the experimental data (Fig. 4) but predicting a to some extent sharper decrease in the microbead diameter in the region of the critical electrostatic potential (approximately in the range 4–5 kV, Fig. 4). The modeling results could be explained by the hypothesis regarding the surface tension changes during the extrusion process, as reported previously.[30] In the region of applied potentials lower than the critical value ($U < U_c$), the surface tension of the liquid decreases due to repulsion of the charged molecules at the droplet surface that causes a decrease in the droplet diameter as well. However, in the region of the higher potential values ($U > U_c$), the increased liquid velocity may induce an increase in the surface tension and consequently, an increase in the droplet size as compared to the model predictions based on a constant surface tension value, which is consistent with the results presented herein (Fig. 4).

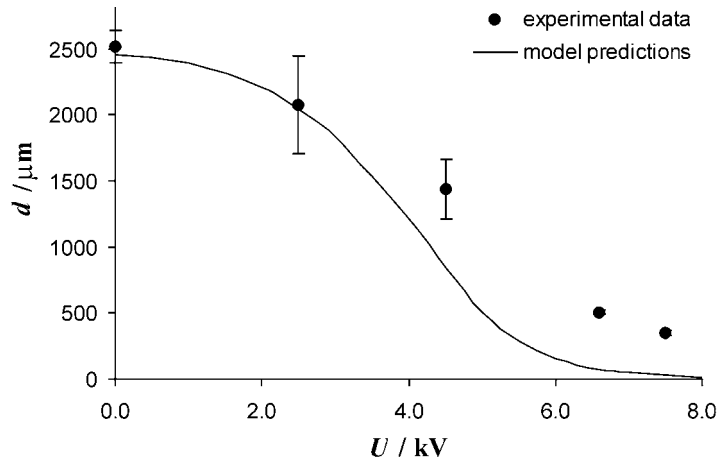

Fig. 4. Diameter of Ag/alginate microbeads as a function of the applied electrostatic potential: experimental data and model predictions.

It should be added that under the same electrostatic extrusion conditions used for production of microbeads for biomechanical characterization, the presence of AgNPs in Ag/alginate colloid solutions in the concentration range up to 3.9 mM did not influence the microbead diameter as compared to the control 1.9 % w/v Na-alginate solution amounting to ≈600 μm (600±40 μm).

Biomechanical characterization of Ag/alginate microbeads under bioreactor conditions

Biomechanical properties of packed beds of nanocomposite microbeads with different concentrations of incorporated AgNPs (1, 1.5 and 3.9 mM concentrations in the source colloid solutions) were examined in a biomimetic bioreactor

while packed bed of 1.9 % w/v Ca-alginate microbeads served as a control. The experiments were performed under dynamic compression at 10 % strain in two regimes: at a loading rate of 337.5 μm s^{-1} and at sequential increments of 50-μm displacement every 30 min. All microbeads exhibited similar approximately linear responses to the dynamic loading although the values determined for the control microbeads were slightly lower than those of Ag/alginate microbeads (Fig. 5a). Values of compression moduli determined from the slopes of the best stress–strain linear fits were 141±2 and 154±4 kPa, for packed beds of the control and of the Ag/alginate microbeads, respectively. On the other hand, the equilibrium stresses determined at sequential strains after 30 min pauses were significantly different for the control and Ag/alginate microbeads (Fig. 5b), yielding equilibrium unconfined compression moduli of 47±1 and 34±2 kPa, respectively.

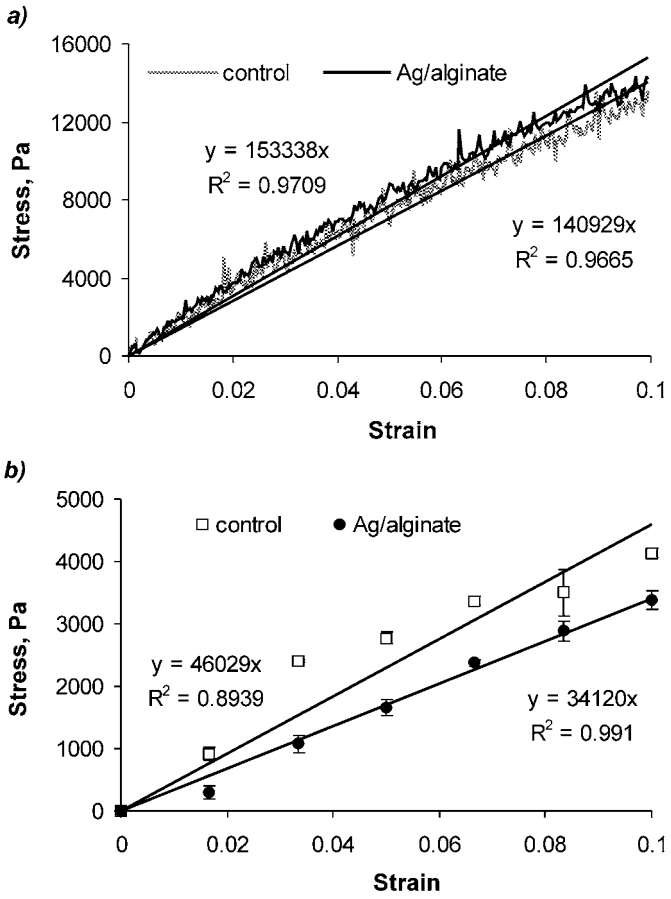

Fig. 5. Stress–strain relationships for packed beds of Ag/alginate and control alginate microbeads: a) at a loading rate of 337.5 μm s^{-1}; b) for sequential increments of 50 μm (the data represent an average of $n = 3$).

The values of compression moduli determined in this study for packed beds of the control alginate microbeads (1.9 % w/v Ca-alginate) were slightly higher than those determined in a previous study for packed beds of 2 % w/v Ca-alginate microbeads (compression modulus of 141±2 *vs.* 111±8 kPa, respectively, and equilibrium unconfined compression modulus of 47±1 *vs*. 32±0.4 kPa, respectively).[24] These result can be attributed to the significantly smaller microbeads used in the present study (600±30 μm) as compared to those used in the previous study (780±30 μm), which is consistent with the influence of entrapped water within a packed bed, as reported previously.[24] It could be assumed that the packed bed of smaller microbeads retains water more efficiently in the smaller interstitial channels, which contributes to the mechanical properties of the bed.

The slight effects of the presence of AgNP on mechanical properties of alginate microbeads are consistent with weak interactions of the nanoparticles with the polymer chains. Thus, the phase transition, thermosensitivity and viscoelasticity of the polymer gel were reported to remain unchanged.[34] The presence of AgNPs in the alginate microbeads apparently induced a slight increase in the dynamic compression modulus but a decrease in the equilibrium unconfined compression modulus (Fig. 5). These results imply that under dynamic conditions, the AgNPs induced a higher retention of water within the hydrogel matrix, while when the hydrogels were provided with time to relax, negative effects of the AgNPs on the hydrogel strength were revealed. In addition, although the influence of the presence of nanoparticle could be distinguished with respect to the control alginate hydrogel, effects of the AgNP concentration in the investigated range (1.5–3.9 mM) could not be perceived. These results are in agreement with reported effects of AgNPs at low concentrations (< 1 wt. %) incorporated within poly(vinyl alcohol) (PVA) hydrogels.[35] Specifically, the addition of AgNPs was shown to induce an abrupt increase in the elastic modulus of the hydrogel, which then remained constant as the AgNP concentration was increased up to 0.8 wt. %. On the contrary, during the stress relaxation, Ag/PVA nanocomposites exhibited reduced stability as compared to pure PVA hydrogels. These results were explained by interactions of nanoparticles with polymer chains inducing immobilization of interfacial regions and enhanced stiffness during loading. However, loading also induced debonding of the nanoparticles, which allowed easier structural rearrangements of polymer chains during the stress relaxation,[35] which is consistent with the lower equilibrium unconfined compression modulus determined in the present study for nanocomposite microbeads as compared to that of the controls.

CONCLUSIONS

Silver nanoparticles were successfully produced in alginate solutions by electrochemical synthesis resulting in stable colloid sols, which were shown in

this study to be suitable for sterilization, dilution and electrostatic extrusion to obtain nanocomposite alginate microbeads. It was demonstrated that practically all Ag^+ added to the alginate solution are reduced during the electrochemical synthesis, indicating the high efficiency of this production method. Furthermore, AgNPs were preserved during manipulation and gelation of the Ag/alginate colloid sol, yielding even higher concentrations in the nanocomposite microbeads by about 20 % as compared to the source colloid solutions. Incorporation of AgNPs in alginate microbeads slightly affected the biomechanical properties of the packed beds determined in a biomimetic bioreactor, strengthening the gel under dynamic compression (by about 9 %) but inducing easier polymer restructuring during relaxation and a lowering of the equilibrium unconfined compression modulus (by about 27 %). Results of these studies imply that Ag/alginate nanocomposite microbeads as well as the production method based on the electrochemical synthesis of AgNPs and electrostatic extrusion of the obtained colloid solutions are suitable for utilization in pharmaceutical and biomedical applications.

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И З В О Д

КОНТРОЛИСАНО ДОБИЈАЊЕ АЛГИНАТНИХ НАНОКОМПОЗИТА СА ИНКОРПОРИСАНИМ НАНОЧЕСТИЦАМА СРЕБРА У ЦИЉУ БИОМЕДИЦИНСКЕ ПРИМЕНЕ

ЈАСМИНА СТОЈКОВСКА, ЈОВАНА ЗВИЦЕР, ЖЕЉКА ЈОВАНОВИЋ, ВЕСНА МИШКОВИЋ-СТАНКОВИЋ и БОЈАНА ОБРАДОВИЋ*

Технолошко–металуршки факултет, Универзитет у Београду, Карнегијева 4, 11000 Београд

У овом раду је испитиван процес добијања електростатичком екструзијом нанокомпозитних алгинатних микрочестица са инкорпорисаним електрохемијски синтетисаним наночестицама сребра у погледу потенцијала за примену у фармацији и биомедицини. Показало се да током електрохемијске синтезе наночестица долази до практично потпуне редукције Ag јона присутних у почетном раствору, дајући на тај начин стабилне Ag/алгинатне колоидне растворе. Показано је затим, да су ови раствори погодни за стерилизацију, манипулацију, као и електростатичку екструзију уз задржавање и очување наночестица. Присуство наночестица сребра у колоидним растворима није имало утицај на величину добијених Ag/алгинатних микрочестица која је претежно била одређена вредношћу примењеног електростатичког напона током екструзије. Са друге стране, инкорпорација наночестица сребра унутар алгинатног хидрогела је узроковала мале промене биомеханичких карактеристика које су одређене у биомимичном биореактору. Наиме, модул еластичности пакованих слојева нанокомпозитних Ag/алгинатних микрочестица одређен при динамичкој компресији је био нешто већи него код пакованог слоја контролних алгинатних микрочестица (154±4 и 141±2 kPa, редом) док је равнотежни модул еластичности слојева нанокомпозитних микрочестица био значајно мањи (34±2 и 47±1 kPa, редом).

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