International Journal of Biological Macromolecules 92 (2016) 220–224

Contents lists available at ScienceDirect

International Journal of Biological Macromolecules

journal homepage: www.elsevier.com/locate/ijbiomac

Surfactant and metal ion effects on the mechanical properties of alginate hydrogels

Hakan Kaygusuz [a,b], Gülşen Akın Evingür [c], Önder Pekcan [d], Regine von Klitzing [b], F. Bedia Erim [a,*]

[a] Istanbul Technical University, Faculty of Science and Letters, Maslak 34469 Istanbul, Turkey
[b] Stranski-Laboratorium für Physikalische und Theoretische Chemie, Institut für Chemie, Technische Universität Berlin, Strasse des 17. Juni 124, 10623 Berlin, Germany
[c] Piri Reis University, Faculty of Science and Letters, Tuzla 34940 Istanbul, Turkey
[d] Kadir Has University, Faculty of Science and Letters, Cibali, 34083 Istanbul, Turkey

ARTICLE INFO

Article history:
Received 25 March 2016
Received in revised form 4 June 2016
Accepted 1 July 2016
Available online 2 July 2016

Keywords:
Alginate
Surfactant
Mechanical properties

ABSTRACT

This paper addresses the controlled variation of the mechanical properties of alginate gel beads by changing the alginate concentration or by adding different surfactants or cross-linking cations. Alginate beads containing nonionic Brij 35 or anionic sodium dodecyl sulfate (SDS) surfactants were prepared with two different types of cations (Ca^{2+}, Ba^{2+}) as crosslinkers. Compression measurements were performed to investigate the effect of the surfactant and cation types and their concentrations on the Young's modulus of alginate beads. The Young's modulus was determined by using Hertz theory. For all types of alginate gel beads the Young's modulus showed an increasing value for increasing alginate contents. Addition of the anionic surfactant SDS increases the Young's modulus of the alginate beads while the addition of non-ionic surfactant Brij 35 leads to a decrease in Young's modulus. This opposite behavior is related to the contrary effect of both surfactants on the charge of the alginate beads. When Ba^{2+} ions were used as crosslinker cation, the Young's modulus of the beads with the surfactant SDS was found to be approximately two times higher than the modulus of beads with the surfactant Brij 35. An ion specific effect was found for the crosslinking ability of divalent cations.

1. Introduction

Alginate is a material of interest due to its unique and useful properties. Being extracted from marine brown algae, alginates are non-toxic and edible polysaccharides. This polymer is a copolymer of 1–4 linked β-D-mannuronate (M) and α-L-guluronate (G) homopolymeric blocks. This polyelectrolyte forms crosslinked hydrogels with divalent cations, and this hydrogel structure is used in many applications. Applications of crosslinked alginates have a wide range, including controlled release, drug delivery formulations and waste removal agents [1–5].

Addition of various dopants to alginate formulations may increase the chemical and mechanical stability of the gels. One of the candidates for dopants is surfactants. Previously, the effect of cationic surfactant cetyltrimethylammonium bromide (CTAB) on viscosity and the effect of SDS on aggregation of alginate solution were studied by Yang et al. [6,7]. Rheological and turbidity measurements were carried out in aqueous mixtures of hydrophobically modified alginates with cationic, anionic and nonionic surfactants were also reported before[8].

The effect of different crosslinking cations on Young's modulus values of alginate beads [9], the effect of compression speed [10], the effects of M/G ratio of alginate and of the crosslinking cation type [11] on mechanical behavior have been reported before. Recently the effects of the crosslinking ion and polyamino acid coating on the mechanical properties of alginate beads were reported [12]. Besides beads, the effect of the crosslinking ion on the mechanical properties of disc-shaped alginates are also reported, such as the recent study by Kaklamani et al. [13].

The importance of the alginate materials in biomedical applications such as drug release studies and scaffolds for tissue engineering requires mechanical strength of these gels. Surfactants play an important role for the uptake and release of drugs. According to our knowledge, so far the effect of surfactant on the mechanical properties of alginate gel beads hasn't been studied. This paper reports for the first time, the effect of surfactant incor-

* Corresponding author.
E-mail address: erim@itu.edu.tr (F.B. Erim).

http://dx.doi.org/10.1016/j.ijbiomac.2016.07.004
0141-8130/

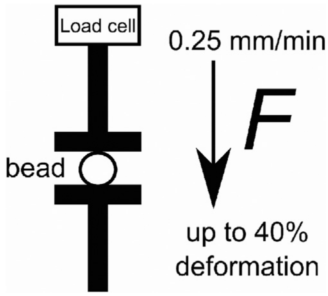

Fig. 1. Schematic representation of the unaxial compression measurement.

poration into alginate gels on the Young's modulus of alginate beads. Two different types of surfactants (nonionic: Brij 35 and anionic: sodium dodecyl sulfate) were used. Surfactant added alginates were crosslinked by calcium or barium ions. The effect of crosslinking ions on Young's modulus was also studied.

2. Materials and methods

Alginic acid sodium salt (viscosity of 2% solution ~250 cps) was from Sigma-Aldrich. This alginate is extracted from *Macrocystis pyrifera* and has a M/G ratio around 1.6 [14]. Calcium chloride dihydrate was purchased from J.T. Baker. Brij® 35, sodium dodecyl sulfate (SDS) and barium chloride dihydrate were obtained from Merck. All reagents were used without further purification. The critical micelle concentration (cmc) of Brij® 35 is about 0.09 mmol/L and about 8 mmol/L for SDS. In the present study both surfactants were used well above their respective critical micelle concentrations (cmc).

Accurately weighed alginate was dissolved in deionized water and necessarily amounts of surfactants were added into the alginate solutions. The solutions were stirred carefully in order to prevent bubble formation. The pH of the 1% alginate solution was around 6.7. Addition of SDS into alginate did not change the pH significantly. On the other hand, incorporation of Brij 35 into alginate solutions decreased the pH slightly to around 6.45. After complete dissolution, the mixture of alginate and surfactant were added dropwise to the gelling solution (e.g. $CaCl_2$ or $BaCl_2$) using a syringe of 0.8 cm inner diameter. The concentration of the crosslinking solutions was selected as 3% of $CaCl_2$ or $BaCl_2$ (w/v) in the experiments dealing with the effect of surfactants. For the effect of crosslinker ion experiments, the concentrations were 2, 3 and 5% of $CaCl_2$ or $BaCl_2$ (w/v). Formed beads were transferred into storage vessels and kept in the gelling media for 12 h at room temperature in order to complete gelation.

Compression measurements were carried out using an Instron 3345 testing machine attached with a 10 N force transducer. The diameter of each bead was measured using a digital caliper and all of the measurements were conducted at least in triplicate. A single bead was placed onto a platform, as shown in Fig. 1. A probe with a flat end was used to compress the bead. Compression measurements were performed at a speed of 0.5 mm/min and up to 40% deformation ratio at 25 °C.

In order to clarify the statistical significance of the results, single factor analysis of variance (ANOVA) tests were conducted for each data set. The level of statistical significance was assumed as 0.05 and statistical calculations was done using R statistical software v. 3.02 [15].

3. Results

The effect of crosslinker cation, alginate and surfactant concentrations on bead size is shown on Table 1. Barium alginate

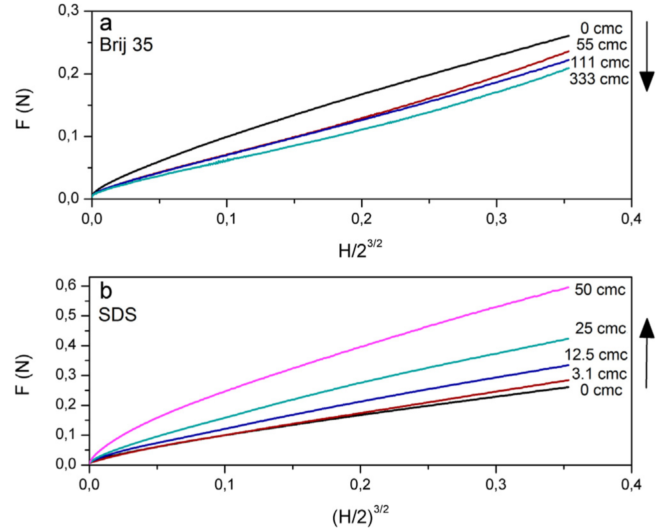

Fig. 2. The Force F (N) and $(H/2)^{3/2}$ curves of 4% (w/v) alginate beads crosslinked with 3% (w/v) $BaCl_2$ containing (a) 0, 5, 111 and 333 times cmc Brij 35 and (b), 0, 3.1, 12.5, 25 and 50 times cmc SDS. The arrows indicate the direction of increasing surfactant concentration.

beads have bigger diameter than calcium alginate beads. The sizes increased with increasing alginate concentrations for all formulations. Incorporating both types of surfactants into formulations decreases the sizes of the beads initially, then the sizes increase with increasing surfactant concentrations. For 333 cmc of Brij 35 (i.e. the molar concentration of Brij 35 has 333 times of cmc of Brij 35) and 50 cmc of SDS, the sizes became almost equal to formulations without any surfactant for each crosslinker concentration.

The force (F) versus displacement (H) data was generated from the compression measurements. Hertz Theory [16] was used to determine the Young's modulus, as shown below:

$$F = \frac{4R^{0.5}}{3}\frac{E}{1-\upsilon^2}\left(\frac{H}{2}\right)^{3/2} \quad (1)$$

where R is the radius of a bead, E is the Young's modulus, H is the displacement, and υ is the Poisson's ratio. First, the force (F) was plotted against the displacement $(H)^{3/2}$. The Poisson ratio was taken as 0.5 for 0.5 mm/min compression speed applied. This value is compatible with literature values [10,17]. In the literature, for the compression speed range between 0.075 mm/min [17] and 60 mm/min, [10] the Poisson ratio was selected as 0.5. The Young's modulus was then determined from the slope of linear region using the least square regression of the plot of F versus $(H/2)^{3/2}$.

Two examples of force versus $(H)^{3/2}$ curves for 4% (w/v) alginate beads crosslinked with 3% (w/v) $BaCl_2$ are shown in Fig. 2(a) and (b). Fig. 2(a) corresponds to the 4% (w/v) alginate beads containing 0, 55, 111 and 333 times cmc of Brij 35. Fig. 2(b) shows the curves of 4% (w/v) alginate beads containing 0, 3.1, 12.5, 25 and 50 times cmc of SDS. From comparing Fig. 2(a) with Fig. 2(b), the larger concentrations of SDS surfactant required larger force values to produce a given degree of deformation. On the other hand, the nonionic surfactant Brij 35 shows the opposite effect. The same trend was observed for calcium alginate beads, with smaller slope values. For each formulation, the Young's modulus of at least three different beads were calculated from the linear region of the force versus $(H)^{3/2}$ curves.

Statistical significance of Young's modulus values among changing surfactant concentrations at each alginate concentration was investigated using one way ANOVA tests at $p = 0.05$. Except the 1% and 2% (w/v) alginate beads crosslinked with barium, all series resulted in $p < 0.05$. Thus, incorporation of Brij 35 shows no effect