



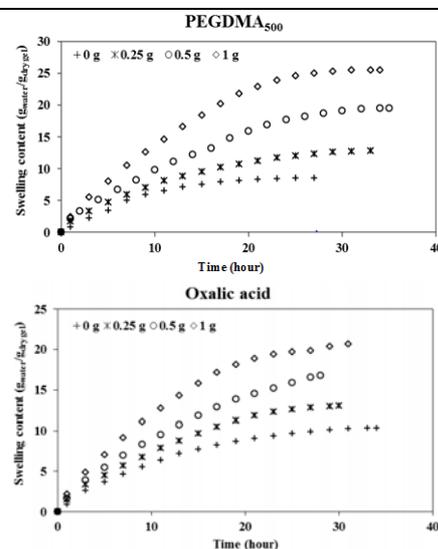
## MODELLING OF AAm-co-ALGINATE HYDROGELS SWELLING KINETICS

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In this study, cross-linked acrylamide-co-alginat hydrogels were synthesized by free radical polymerization in aqueous solutions of acrylamide and of acrylamide with sodium alginate as comonomer. For each copolymerization, four different compositions were used and in all systems a concentration of a crosslinker such as oxalic acid and polyethylene glycol dimethacrylate (PEGDMA<sub>500</sub>) was employed. As a result of swelling tests, the influence of crosslinkers and the relative content of sodium alginate on the swelling properties in the hydrogels were examined and modeled. Acrylamide-co- alginat hydrogels were swollen in the range 12.72–25.52 g<sub>water</sub>/g<sub>dry gel</sub> in water, while acrylamide hydrogels swelled in the range 8.5–10.37 g<sub>water</sub>/g<sub>dry gel</sub>. The swelling capacity was found to increase significantly with increase in alginate concentration. The diffusion coefficients (*D*) of acrylamide-co-alginat hydrogels was calculated in the range  $3.39 \times 10^{-10}$ – $4.34 \times 10^{-10}$  m<sup>2</sup> s<sup>-1</sup>. The experimental swelling data was fitted to three models. The first order swelling kinetic model showed the best fit for all acrylamide-co-alginat hydrogels.



### INTRODUCTION

Hydrogels are polymers characterized by hydrophilic and water insolubility. The swelling properties of hydrogels are mainly related to the network elasticity, the presence of hydrophilic functional groups, the cross-link density, and porosity. Many materials, both naturally occurring and synthetic, fit the definition of hydrogels. Their water absorption capacity, softness, and smartness make them unique materials.<sup>1</sup>

Extensive employment of these products in industrial and environmental applications is of primary importance. As expected, natural hydrogels were gradually replaced by synthetic hydrogels which has long service life, high capacity of water

absorption, and high gel strength. Synthetic polymers usually have well-defined structures that can be modified to yield tailor able degradability and functionality. Hydrogels can be synthesized from purely synthetic components. Many materials, both naturally occurring and synthetic, fit the definition of hydrogels.<sup>2-3</sup>

The IPN hydrogels based on ionically crosslinked alginate and covalent poly(acrylamide) network strongly attract interest of many investigators due to the advanced mechanical properties, water adsorption ability and biocompatibility.<sup>4</sup> Alginates are unbranched polysaccharides which are important components of some algae such as kelp, and also an exopolysaccharide of bacteria, including *Pseudomonas aeruginosa*.<sup>5</sup>

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The swelling kinetics are important parameters to characterize the swelling polymers. The characterization of swelling behaviors of hydrogels has been studied with several types of models in the literature.<sup>6,7</sup> However, there is no current model that fully describes the complex physical processes in hydrogels, that is still an ongoing research area.<sup>8</sup> In other words, thermodynamic models have been used extensively to explain the swelling mechanisms of hydrogels. Many of the input parameters in the thermodynamic models are difficult to determine and adjust to fit to a particular situation. Recently, second-order kinetic models have been developed to describe hydrogel swelling kinetics.<sup>9</sup> The validity of this model can be tested by obtaining the best fit curve and comparing it with the experimentally observed curve. Many theoretical, empirical, and semi-empirical models can be used for modeling, with the objectives of relating experimental results to physical laws and studying the water absorption behavior of hydrogel samples during soaking.

In the literature, while the studies on absorbant polymers have focused on the different molecular weighted PEGs, polyethylene glycol dimethacrylates (PEGDMAs) have not been widely studied. The aim of this study was to investigate the swelling properties of acrylamide based hydrogels with the addition of a natural polymer, such as sodium alginate, and some multifunctional crosslinkers, such as oxalic acid and polyethylene glycol dimethacrylate (PEGDMA<sub>500</sub>). In this respect,

a series of cross-linked acrylamide-co-alginat hydrogels were synthesized at different concentration of sodium alginate. Then, the swelling kinetics of synthesized hydrogels have been investigated. In addition to this, three modeling studies are performed to represent the swelling kinetics of the hydrogel samples. The Peleg, first order swelling kinetics and exponential association models available in the literature have been used to model the swelling kinetics of the hydrogel samples.

## RESULTS AND DISCUSSION

### Swelling Curves

The water uptake of initially dry hydrogels was followed for a period of time gravimetrically.

The swelling content ( $S$ ) of the dried hydrogels in distilled water was calculated from Eq. 1,

$$S = \frac{W_t - W_d}{W_d} \quad (1)$$

where,  $S$  is the swelling content ( $g_{\text{water}}/g_{\text{dry gel}}$ ),  $W_t$  is the weight of swollen hydrogel at time  $t$  and  $W_d$  is the weight of original dry hydrogel.

Swelling curves of the crosslinked (AAm-co-alginate) hydrogels were constructed and swelling isotherms are shown in Figures 1 and 2.

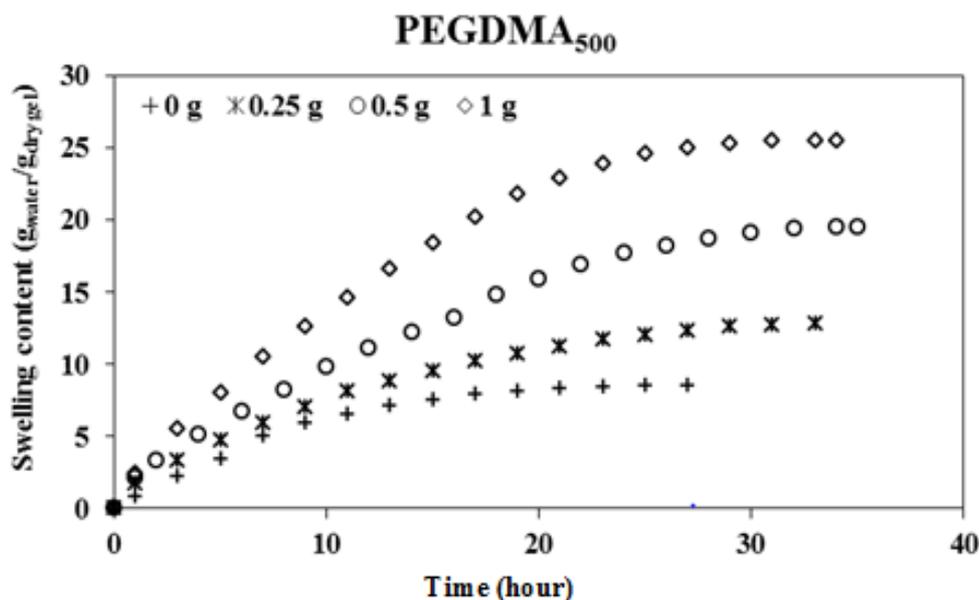


Fig. 1 – Swelling of hydrogels as a function of time at different alginate concentration for crosslinker of polyethylene glycol dimethacrylate (PEGDMA<sub>500</sub>).

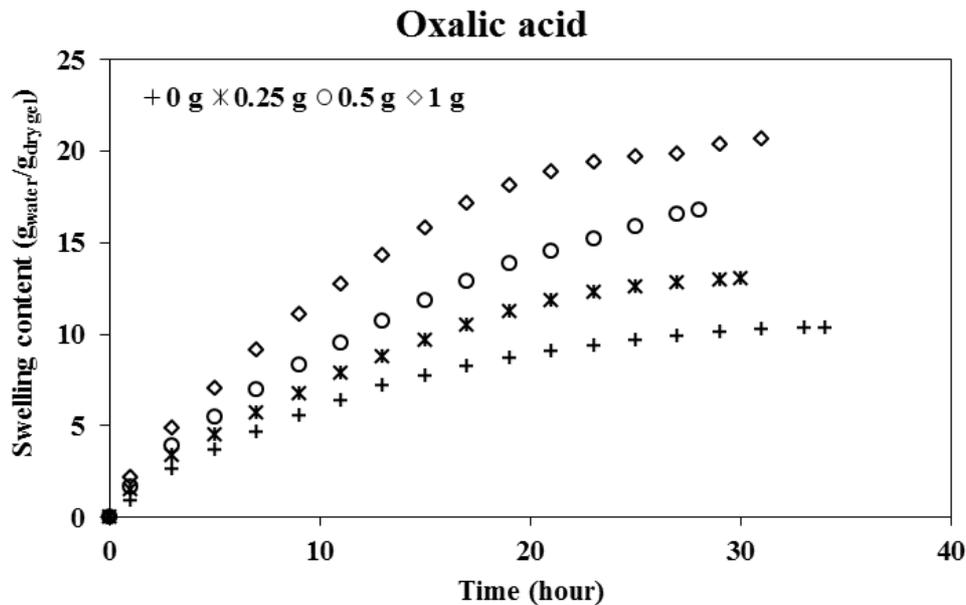


Fig. 2 – Swelling of hydrogels as a function of time at different alginate concentration for crosslinker of oxalic acid.

Figures 1 and 2 show that swelling increases with time up to certain level, then levels off. This value of swelling may be called the equilibrium swelling value. From the results obtained, the hydrogels swelling came to equilibrium at value at different time for different crosslinker and different concentrations of alginate. As seen in Figure 1, the equilibrium swelling values for hydrogels were found as 8.5, 12.72, 19.51 and 25.52  $\text{g}_{\text{water}}/\text{g}_{\text{dry gel}}$  for alginate concentration of 0, 0.25, 0.5 and 1 g, respectively for crosslinker of PEGDMA<sub>500</sub>. In Figure 2, the equilibrium swelling values for hydrogels were found as 10.37, 13.06, 16.76 and 20.67  $\text{g}_{\text{water}}/\text{g}_{\text{dry gel}}$  for alginate concentration of 0, 0.25, 0.5 and 1 g, respectively for crosslinker of oxalic acid. From the results obtained for the hydrogel swelling, equilibrium swelling values increases with high alginate concentrations and different crosslinkers. The variation of water absorption or swelling with increasing content of sodium alginate showed the same tendency and the highest water absorption was achieved at the content of sodium alginate at 1g. This result indicates that sodium alginate content affected the crosslinking density and the water absorption.<sup>10</sup> Another result, the polyacrylamide chains, with increasing molecular weight polyethyleneglycol dimethacrylate, crosslinker density is increased and this leads to an increase in the water absorption capacity. In other words, is that the crosslinker chain length plays an important role for the swelling capacity. An important influence of alginate concentration on swelling curves can be

observed in all figures, mainly at the initial and final stages of the process. This result coincides with the studies of Hua and Wang<sup>11</sup> and Wang and Wang,<sup>10</sup> who found that water absorption increases with increasing sodium alginate amounts.

Uzum *et al.*<sup>12</sup> synthesized acrylamide (AAm)/(SA) of sodium acrylate hydrogels from two different types of cross-linkers, by changing the sodium acrylate monomer concentration. They investigated the swelling ratio change of the synthesized hydrogels by changing the cross linker types and of sodium acrylate monomer concentrations. They reported that hydrogels swelling ratio is increased with the concentrations of sodium acrylate increasing monomer and cross-linkers.

### Calculation of Diffusion Coefficients

Hydrogels, consisting of networks of crosslinked hydrophilic polymers, undergo swelling instead of dissolution in water.<sup>13</sup> Hydrogels made of polyelectrolytes swell more due to the charge repulsion among polymer chains, and such swelling property is useful in environment-sensitive swelling of hydrogels for controlled drug release. Diffusion involves migration of water into pre-existing spaces between hydrogel chains. The Fick laws are the common laws used to explain water diffusion into the dry hydrogel samples. In other words, the Ficks law is used for the calculation of the swelling kinetics and diffusion of hydrogel structure. Based on power law model, liquid transport into polymer networks, *i.e.*

swelling-time curves, may be described by the following Equation:<sup>13</sup>

$$F = \frac{S_t}{S_e} = kt^n \quad (2)$$

where,  $F$  is the fractional uptake at time  $t$ ,  $S_e$  is the equilibrium swelling content of the hydrogel,  $t$  is the time,  $k$  is the constant that changes according to the hydrogel structure and  $n$  is the diffusion exponent.

The diffusion coefficients of the samples (hydrogels) were calculated from the following Equation:<sup>14</sup>

$$D = \pi r^2 \left( \frac{k}{4} \right)^{\frac{1}{n}} \quad (3)$$

where,  $D$  represent coefficient of diffusion as  $m^2/s$ ,  $t$  is in seconds and  $r$  is the radius of the hydrogel samples.

The plots of  $\ln F$  verses  $\ln t$  are obtained through the logarithmic form of the Equation 2. The diffusion coefficients were calculated from the slopes of the obtained straight line equations. The diffusion coefficients were identified for according to the process parameters applied. The values of diffusion coefficient obtained for hydrogel samples are listed in Table 1.

Table 1 show that the values of the diffusion coefficient of (AAM-co-alginate) hydrogels vary from  $3.39 \times 10^{-10} m^2s^{-1}$  -  $4.34 \times 10^{-10} m^2s^{-1}$  for polyethylene glycol dimethacrylate (PEGDMA<sub>500</sub>) and  $3.51 \times 10^{-10} m^2s^{-1}$  -  $3.85 \times 10^{-10} m^2s^{-1}$  for oxalic acid, respectively. Diffusion coefficients, generally, increase with the increasing of sodium alginate in PEGDMA<sub>500</sub> and oxalic acid crosslinkers. The reason of these effects can be the hydrophilic characteristics of sodium alginate. Similar results have been reported by Suryawanshi *et al.*<sup>15</sup> and Hadjiev and Amsden.<sup>16</sup>

### Evaluation of the Models

The swelling content values obtained during the swelling trials of the hydrogel samples was investigated the expressibility by the empirical models available in the literature. Empirical models, namely, the Peleg (4), first-order swelling kinetic (5) and exponential association model (6) were used to describe the swelling process during the swelling of hydrogel samples.<sup>17, 18</sup>

$$S = S_o + \frac{t}{k_1 + k_2 t} \quad (4)$$

where  $S_o$  is the water content at  $t=0$  ( $g_{\text{water}}/g_{\text{dry gel}}$ ),  $S$  is the water content at any time ( $g_{\text{water}}/g_{\text{dry gel}}$ ),  $t$  is the swelling time (s),  $k_1$  is a kinetic constant of the model ( $s \times (g_{\text{water}}/g_{\text{dry gel}})$ ) and  $k_2$  is a characteristic constant of the model ( $g_{\text{water}}/g_{\text{dry gel}}$ ).

If the time of swelling is long enough, the equilibrium swelling or water content ( $S_e$ ) is given by:  $S_e = S_o + 1/k_2$

$$S = S_e + (S_o - S_e) \exp(-k_{R1} t) \quad (5)$$

where,  $k_{R1}$  is the swelling kinetic constant ( $s^{-1}$ ).

$$S = S_e [1 - \exp(-k_{R2} t)] \quad (6)$$

where,  $k_{R2}$  is the kinetic constant.

The statistical analysis of experimental data was determined using *Statistica 6.0 software* (Statsoft Inc., Tulsa, OK), which is based on the Levenberg–Marquardt algorithm. The three criteria of statistical analysis have been used to evaluate the adjustment of the experimental data to the different models: the coefficient of determination ( $R^2$ ), reduced chi-square ( $\chi^2$ ), and root mean square error ( $RMSE$ ).

These parameters can be calculated as

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{N - z} \quad (7)$$

$$RMSE = \left( \frac{1}{N} \sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2 \right)^{1/2} \quad (8)$$

where  $MR_{exp,i}$  and  $MR_{pre,i}$  are the experimental and predicted dimensionless  $MR$ , respectively,  $N$  is the number of data values, and  $z$  is the number of constants of the models. The best model describing the swelling characteristics of hydrogels was chosen as the one with the highest  $R^2$ , the least  $\chi^2$  and  $RMSE$ .<sup>6</sup>

To describe the swelling kinetics of hydrogels on different crosslinked (PEGDMA<sub>500</sub> and oxalic acid), three empirical models, namely, Peleg's, first-order, and exponential association equation, are used, and all data from the models provided a good agreement with the experimental data. The constants,  $R^2$ ,  $\chi^2$ , and  $RMSE$  values of the models are estimated and given in Table 2.

Table 1

Values of diffusion coefficients of hydrogels samples for PEGDMA<sub>500</sub> and oxalic acid crosslinkers

Cross-linked hydrogel	Alg Concentration (g)	$D \times 10^{10} (\text{m}^2 \text{s}^{-1})$
PEGDMA <sub>500</sub>	0	3.39
	0.25	3.53
	0.5	3.90
	1	4.34
Oxalic acid	0	3.51
	0.25	3.72
	0.5	3.83
	1	3.85

Table 2

Model parameters and statistical results obtained from different empirical models for hydrogel samples

**PELEG**

Cross-linked hydrogel	Alg Concentration (g)	$R^2$	$k_1$ ( $\text{s}^*(\text{g}_{\text{dry}}/\text{gel})/\text{g}$ )	$k_2$ ( $\text{g}_{\text{dry}} \text{gel}/\text{g}$ )	$S_e$ ( $\text{g}/\text{g}_{\text{dry}} \text{gel}$ )	$\chi^2$	RMSE
PEGDMA <sub>500</sub>	0	0.9891	0.90068	0.07772	12.895	0.077879	0.268399
	0.25	0.9980	0.78268	0.05285	18.950	0.026175	0.156924
	0.5	0.9954	0.70658	0.02907	34.428	0.158895	0.386843
	1	0.9913	0.46956	0.02333	35.408	0.542124	0.71405
Oxalic acid	0	0.9983	0.99947	0.06479	15.463	0.05730	0.121633
	0.25	0.9963	0.87210	0.04540	22.055	0.056756	0.230214
	0.5	0.9986	0.784056	0.031675	31.599	0.034531	0.179297
	1	0.9947	0.515798	0.030232	33.106	0.205244	0.438652

**FIRST ORDER SWELLING KINETIC MODEL**

Cross-linked hydrogel	Alg Concentration (g)	$R^2$	$k_{R1}$ ( $\text{s}^{-1}$ )	$S_e$ ( $\text{g}/\text{g}_{\text{dry}} \text{gel}$ )	$\chi^2$	RMSE
PEGDMA <sub>500</sub>	0	0.9951	0.105261	9.322	0.034880	0.179695
	0.25	0.9973	0.08003	13.831	0.037196	0.187067
	0.5	0.9960	0.05535	23.449	0.138514	0.361182
	1	0.9946	0.04496	29.758	0.345752	0.570946
Oxalic acid	0	0.9995	0.07771	11.235	0.008866	0.09143
	0.25	0.9965	0.06834	15.237	0.053219	0.223099
	0.5	0.9977	0.05699	20.882	0.056680	0.225745
	1	0.9972	0.05480	23.278	0.109526	0.320438

**EXPONENTIAL ASSOCIATION MODEL**

Cross-linked hydrogel	Alg Concentration (g)	$R^2$	$k_{R2}$ ( $\text{s}^{-1}$ )	$S_e$ ( $\text{g}/\text{g}_{\text{dry}} \text{gel}$ )	$\chi^2$	RMSE
PEGDMA <sub>500</sub>	0	0.9953	0.10597	9.308	0.033319	0.175626
	0.25	0.9971	0.08045	13.813	0.039629	0.193089
	0.5	0.9969	0.05559	23.414	0.141496	0.365049
	1	0.9944	0.04514	29.734	0.345482	0.570722
Oxalic acid	0	0.9989	0.07819	11.217	0.009666	0.095461
	0.25	0.9964	0.06876	15.207	0.055417	0.227658
	0.5	0.9976	0.05736	20.827	0.060040	0.23234
	1	0.9972	0.04505	23.256	0.110032	0.321178

Table 2 shows the mean parameter values obtained from the models for each of the four hydrogels on different crosslinked (PEGDMA<sub>500</sub> and oxalic acid). Values of the  $k_1$  and  $k_2$  parameter calculated from the Peleg model decreases while the alginate concentration increases. On the other hand, the equilibrium swelling content ( $S_e$ ) value also increased. The  $k_1$  value were obtained between 0.446956 - 0.90068 ( $s^*(g_{dry\ gel})/g_{water}$ ) for hydrogel crosslinked with PEGDMA<sub>500</sub> and 0.515798 -- 0.99947 ( $s^*(g_{dry\ gel})/g_{water}$ ) for hydrogel cross-linked with oxalic acid, respectively. In other hand, the  $k_2$  value were calculated in the range 0.02333 - 0.07772 ( $g_{dry\ gel}/g$ ) for hydrogel crosslinked with PEGDMA<sub>500</sub> and 0.030232- 0.06479 ( $g_{dry\ gel}/g$ ) for hydrogel cross-linked with oxalic acid, respectively. Also, Solomon<sup>19</sup> have reported that high water absorption capacity is correlated with the low  $k_1$  and  $k_2$  values. Again it can be seen from Table 2, the scale parameter ( $K_{R1}$  and  $K_{R2}$ ) of first-order and exponential association models are changed inversely proportional to the concentration of alginate. In contrast,  $S_e$  values for all the two models increased as the concentration of alginate increased. As the concentration of alginate increased, the value of  $k_{R1}$  and  $k_{R2}$  decreased, whereas the value of  $S_e$  increased. In other words, the values of  $k_{R1}$  and  $k_{R2}$  are inversely proportional to the  $S_e$ .

The best model describing the swelling characteristics of hydrogel samples was chosen as the one with the highest  $R^2$  values and the lowest  $\chi^2$  and  $RMSE$  values. In all cases, the  $R^2$  values for the models are greater than 0.9891, indicating a good fit. As given in Table 2,  $R^2$  values of the hydrogel gels varies between 0.9891 and 0.995,  $RMSE$  values between 0.09143 and 0.71405, and  $\chi^2$  values between 0.008866 and 0.542124 in the Peleg, first order swelling kinetic and exponential association model. From the investigation of  $R^2$ ,  $\chi^2$ , and  $RMSE$ , it was seen that the  $R^2$  value is almost as "1";  $RMSE$  and  $\chi^2$  are the minimum at the model of first order swelling kinetic model.

## MATERIALS AND METHOD

### Materials

Acrylamide (AAm, from Merck, Schuchardt, Germany) was purified prior to experiments using vacuum distillation to remove hydroquinone. Copper chloride ( $CuCl_2$ ) (Merck) was used to

prevent polymerization during the vacuum distillation. Purified AA was kept in a refrigerator at +4 °C. Sodium alginate from brown algae was purchased as alginic acid sodium salt (Fluka-Sigma-Aldrich). The oxalic acid and polyethyleneglycol dimethacrylate (PEGDMA<sub>500</sub>) with molecular weight ( $M_n \sim 550$ ) were procured from Aldrich, Milwaukee, USA. Ammonium persulfate (ApS), which was used as the initiator, was from Merck, Darmstadt, Germany, and N,N,N',N'-tetramethylethylenediamine (TEMED) that was used as the catalyst was from Merck, Schuchardt, Germany. In the experiments, a digital balance of model BB3000 Metler- Toledo (Switzerland), a vacuum oven of model BINDER (Tuttlingen, Germany) were used.

### Synthesis of Crosslinked Acrylamide-Sodium Alginate based Hydrogels

In this study, crosslinked (AAM-co-alginate) based hydrogels were synthesized by free radical crosslinking copolymerization of acrylamide (AAM) monomer with addition of sodium alginate and some crosslinkers such as oxalic acid and polyethyleneglycol dimethacrylate (PEGDMA<sub>500</sub>). For the synthesis of crosslinked (AAM-co-alginate) hydrogels, acrylamide weighing 1 g was dissolved in 1 mL aqueous solutions of 0, 0.25, 0.50 and 1g sodium alginate. For investigation of the effect of crosslinkers in preparing AAM/Sodium alginate based hydrogels, 0.25 ml of 1% concentration of oxalic acid, or 0.25 ml of 1% concentration of polyethyleneglycol dimethacrylate (PEGDMA<sub>500</sub>) was added to the aqueous solutions. A total of 1mL/0.219 mmol of APS (5 g/100 mL water) and 1 mL/0.086 mmol of TEMED (1/100 mL water) were then added to the solution. The prepared solution was poured into a 3-mm-diameter glass tube and held for the gelling under a nitrogen medium. Fresh hydrogels obtained in long cylindrical shapes were cut into pieces of  $4 \pm 0.5$  mm in length. Synthesized hydrogels were removed from the glass tube and put into distilled water for the washing process. After washing, the hydrogels were dried first at room temperature, then in the vacuum oven at a temperature of 40 °C.

### Swelling procedure

Swelling and diffusion are important parameters in the characterization of the cross-linked hydrogels. Because a fundamental

relationship exists between the swelling of a polymer in a solvent and the nature of the solvent and polymer. In this respect, for crosslinked (AAm-co-alginate) hydrogels, dynamic swelling experiments were performed in distilled water and the increase in mass were followed as a function of time. The starting water contents of the hydrogels were determined as 0.0078 g water/g dry hydrogel. One gram of hydrogels on the dry basis was placed in a net basket and immersed into a 250 mL glass jar with lid containing 150 mL distilled water, which was previously heated to the required soaking temperature (30 °C) by placement in a water bath [Raypa, RFG-10, R.Espinar S.L., TERRASSA (Barcelona), Spain] thermostatically controlled at the required temperature. At every 30 min intervals, hydrogel samples were removed from water, drained and weighed. The weights of samples were measured with an electronic digital balance having a sensitivity of 0.001 g. The experiments were carried out till equilibrium weight of hydrogel was observed. All the measurements were carried out in duplicate and the averages were reported.

### CONCLUSION

In this investigation, cross-linked acrylamide-co-alginate hydrogels were prepared by free radical polymerization in aqueous solution. Two different crosslinkers, such as oxalic acid and polyethylene glycol dimethacrylate (PEGDMA<sub>500</sub>), were used in the polymerizations. Swelling tests of the synthesized hydrogels were carried out at room temperature. The values of swelling kinetics and diffusion coefficients of the hydrogels are calculated with the aid of the data obtained. It was seen that swelling of hydrogels increased with the increasing of content of sodium alginate. Also, very high equilibrium swelling value of acrylamide-co-alginate hydrogels was found for polyethylene glycol dimethacrylate (PEGDMA<sub>500</sub>) crosslinked acrylamide-co-alginate hydrogels while oxalic acid crosslinked hydrogels showed lower values. The

lowest and highest water absorption capacities in polyethylene glycol dimethacrylate (PEGDMA<sub>500</sub>) and oxalic acid crosslinked hydrogels are 8.5–25.52 and 10.37–20.67 g<sub>water</sub>/g<sub>dry gel</sub> respectively. The highest diffusion coefficient (*D*) value was obtained in polyethylene glycol dimethacrylate (PEGDMA<sub>500</sub>) cross-linking hydrogel as 4.34 m<sup>2</sup>s<sup>-1</sup>. The first order swelling kinetic model produced the best statistical results and demonstrated a good agreement with the obtained experimental data.

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