Journal of Applied Polymer Science

Properties of Electrically Responsive Hydrogels as a Potential Dynamic Tool for Biomedical Applications

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ABSTRACT: Hydrogels with electric responsive properties are gaining research focus due to increasing demand for miniaturized devices that can be precisely controlled using an external stimulus. Such systems are well suited due to their ability to expand and contract when in contact with different types of fluid. This study reports on the synthesis of a "smart" electroresponsive network, using a neutral, "non-smart," biocompatible hydrogel forming building block, Pluronic F127 (PF127), as a starting molecule. The PEO–PPO–PEO copolymer was modified with telechelic methacrylic end functionalities to form a triblock linear prepolymer with crosslinkable end groups (crosslinker). This bifunctional prepolymer, PF127 bismethacrylate (PF127BMA), was copolymerized covalently with anionic methacrylic acid sodium salt groups into a nonsoluble 3D hydrogel network in the presence of redox initiators. The polyelectrolyte domains in the pluronic hydrogel afforded controllable swelling capabilities with volumetric expansion exceeding 8500% in deionized water or 1400% in Krebs solution. The hydrogels were further assessed for their mechanical and electroactive response as a function of increasing acid salt content. © 2014 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2014**, *131*, 41195.

KEYWORDS: electroactuation; pluronics; smart hydrogels; stimuli responsive hydrogels; tuneable hydrogels

Received 30 November 2013; accepted 19 June 2014

DOI: 10.1002/app.41195

INTRODUCTION

Interest in hydrogels has remained unabated for decades due to their excellent ability to retain water without dissolution. The 3D structure of hydrogels is maintained either by physical forces such as van der Waals forces (hydrophobic), hydrogen bonds, ionic complexation, or chemical (covalent) linkages. These interactions (or in combination) determine many of their properties such as viscoelasticity, mechanical strength, fluid uptake, solute release kinetic, weight, and degradability (via hydrolysis of the polymer network).[1] For systems that require long-term use, covalent crosslinked networks or strongly self-assembled systems are the most appropriate. Achieving such crosslinked network requires hydrophilic monomers or prepolymers that are polymerized either via UV, redox, or thermal methods to generate free-radical entities from the initiating species.[2–4] The free-radical initiation in turn propagates the formation of long chain polymers via carbon–carbon addition mechanism and where a *bis*-vinylic component exists, a crosslink junction can be formed.[4,5] A termination reaction is known to be achieved mostly via a combination mechanism.[6] Alternative chemistries that do away with free radicals, such as "click" reaction and siloxanes' polycondensations (to name a few) are also favored routes in achieving crosslinked polymer networks.

As demand for precisely controlled smart materials is highly sought after, exploitative ways to expand the capabilities of existing hydrogels has further raised interests in this class of materials.[7] Principally, fluid behavior and its consequential volumetric changes is exploited in drug delivery devices, actuators, implants, tissue replacement scaffolds, batteries, and sensing devices.[3,8–12] In this class of materials, diffusion is known to be the determinant mechanism that governs this volumetric change via the exchange of ions and its solvating water molecules in a polymer network.[5] It is noteworthy to mention that for hydrogel systems to achieve a "smart" status, their responsiveness to an external stimuli must be inherently built into the network.[12,13] It is thus, very well documented that external stimuli forces such as pH, ion concentration, metabolite, temperature, magnetic, and electrical fields influence volumetric changes via attraction or repulsion between neighboring polymer chains.[3,4,12,14,15] This in turn leads to a "shape shifting" behavior of the bulk hydrogel as a result of contraction or expansion of the network.

Stimuli based on electrical input have advantages such as precise control with regards to the magnitude and duration of current.[8,16–18] Anxiety over the implementation of electrical current is usually unfounded due to the array of literature that have supported and explored its use in vivo, especially in pacemakers. In addition, its safe use in ionophoresis and electroporation in transdermal drug delivery systems is known.[4] We have also recently reported that electro-activated hydrogels can be possibly used as an active blood vessel occlusion system.[12]

Electrical responsiveness in a hydrogel system is accomplished as a result of ionization of functional moieties such as —OH, —NH_2, —CONH—, —$CONH_2$, —COOH, and —HSO_3, as described in the literature.[19–21]

As such, the degree of ionization as well as the maintenance of the ionized state largely determines the extent and degree of responsiveness under stimuli control. Polymers synthesized from monomers with ionizable functional moieties are known as polyelectrolytes, and they provide sensing functionality in most networks. Polymers synthesized from weakly ionizable monomeric acid (p*K*a values > 4.0) such as methacrylic acid impart weak polyelectrolyte properties. To increase the electroresponsive behavior of the methacrylic acid monomer used in this study, it was ionized into a salt derivative. In this article, the synthesis and characterization of a novel electroresponsive PF127 bismethacrylate-*co*-methacrylic acid sodium salt hydrogel network is reported. PF127, an ABA block (co)polymer, was chosen as the base polymer for synthesizing the novel hydrogel network. This was due to its well-known properties that include biocompatibility, nontoxicity, FDA-approved status, and commercial availability in a wide array of molecular weights.[22] The base polymer is an amphiphilic poly(ethylene oxide)-*b*-poly(propylene oxide)-*b*-(polyethylene oxide) [PEO–PPO–PEO] triblock (co)polymer with known thermoresponsive properties. This is due to its tendency to aggregate into micelles below room temperature and concentration above 20 wt %.[23] However, there exists no report on the precise control, with external stimuli, of the swelling behavior of this (co)polymer, in its hydrogel form. Important to note is that since the thermoresponsive of PF127 has been extensively reported,[24–26] but it will not be investigated here.

Herein, we report on transforming a well-known "non-smart," amphiphilic PF127 bismethacrylate-based hydrogel into a smart network with the aid of an electrically responsive anionic methacrylic acid sodium salt monomer. To facilitate a facile method of crosslinking the hydrogel, a methacrylate-terminated derivative (PF127BMA) was synthesized using methacryloyl chloride under optimized conditions (Figure 1). The benefit of crosslinking is that it affords greater mechanical strength as well as the required stability under physiological conditions.

Hydrogels were synthesized and crosslinked with varying the modified base polymer and monomer feed compositions. Their swelling behaviors in deionized water and salt solution were examined. The viscoelastic properties were determined as a function of ionic monomer content and their initial response to electrical stimulus was investigated.

EXPERIMENTAL

Materials

PF127 powder (M_n = 12,500 g mol^{-1}), high purity (98%) methacroylyl chloride (MAC), triethylamine (Et_3N, TEA), 4-*tert* butylcatechol (TBC), milli-Q water, toluene, pentane, diethyl ether, methacrylic acid, sodium hydroxide pellets, ammonium persulphate (APS), *N*,*N*,*N*,*N*-tetramethylenediamine (TEMED), and trichloroacetyl isocyanate (TAIC) were purchased from Sigma-Aldrich, Belgium. Toluene, Et_3N, and MAC were purified via vacuum distillation prior to usage. PF127 was azeotropically distilled in toluene. Krebs solution was prepared according to Table I.

Method

Methacrylation of Hydroxyl Telechelic PF127. As batch-to-batch variation of the base polymer is known to prevail, confirming that the mole ratio of PEO–PPO–PEO was important to ascertain the polymer number average molecular weight via ^{1}H NMR spectroscopy. Neat PF127 (20 mg) was dissolved in deuterated chloroform and trichloroacetyl isocyanate (two drops) was added. This reaction occurs via the conjugation of telechelic hydroxyl groups to the isocyanate thus forming a urethane linkage.

Methacrylation. Native PF127 polymer possesses no crosslinking abilities with regard to using a facile free-radical polymerization technique. As such, the telechelic hydroxyl groups were converted to vinylic end groups via methacrylation using the following procedure. PF127 (250 g, 0.04 mol OH groups) was added to distilled toluene in a 4 : 1 ratio and connected to a condenser via a Dean-Stark apparatus. Azeotropic distillation was carried out for 4 h at 110°C. Once cooled, while preserving the feed concentration, TEA (0.16 mol) and TBC (0.01 mol) were added and stirred under a nitrogen gas atmosphere. After 20 min, MAC was added via an additional funnel in a dropwise manner. The reaction was allowed to proceed on ice and then room temperature overnight. Modified PF127 was concentrated with a rota-vapor and then diluted with 10 : 1 toluene : PF127BMA. The diluted solution was filtered using a number 4 glass filter compacted with 4 cm celite 545. The filtrate was precipitated in an ice cold mixture of pentane : diethyl ether (1 : 1) and dried in vacuo for 3–4 days whilst protected from light.

Synthesis of Methacrylic Acid Sodium Salt. Sodium hydroxide was dissolved in water (5.8*M*) and added dropwise to methacrylic acid monomer under constant stirring. Partial neutralization of the acid moiety was conducted in an ice bath for 4 h until the temperature of the solution was equivalent to room temperature. The majority of the acid moieties (approx. 85 mol %) was ionized using stoichiometric amounts.

Development of Hydrogels. Electroactive hydrogels were prepared by crosslinking modified PF127BMA with methacrylic acid sodium salt monomer using redox initiators at low temperatures. Five formulations were prepared according to Table II. As an example, P3 was prepared by adding PF127BMA (1.5 g, 0.12 mmol) to the acid salt (2.4 g, 9.4 mmol) and argon flushed deionized water (4.6 mL). This was mixed using a magnetic stirrer at 350 rpm and left at 4°C overnight. The mixture was later placed in an ice bath with APS (1*M*) and TEMED (1*M*) added

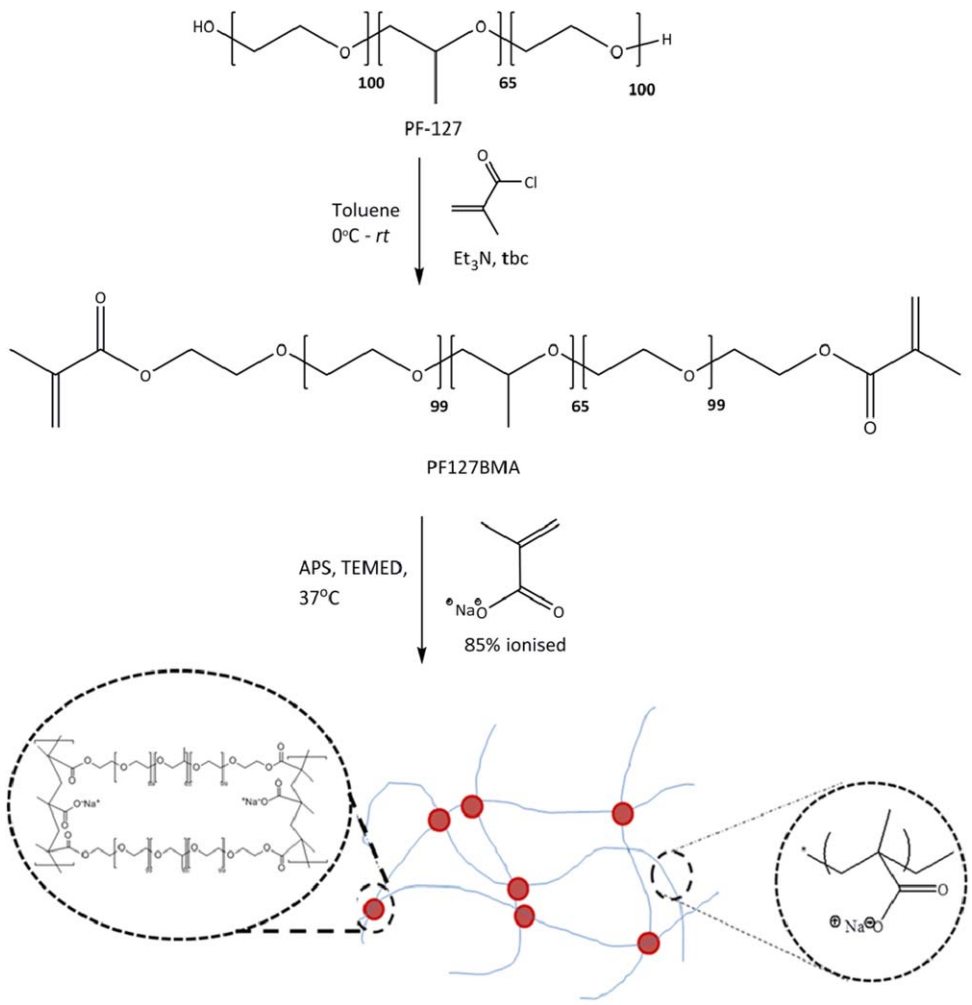

Figure 1. Schematic illustration of methacrylation of PF127, ionization of methacrylic acid sodium salt, and synthesis of the hydrogels. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

to a final concentration of 100 m*M*. The mixture was stirred, purged one more time with argon, capped, and transferred to a refrigerator for 1 h. This was later transferred to a thermostatically controlled water bath (37°C) for 3 h. The gel fraction was determined via extraction of the soluble fraction while the solid fraction was lyophilized overnight. The gel fraction is the insoluble (dry) content of the polymer network after the extraction of its soluble content in a purification step. For P1, the same procedure was followed but no methacrylic acid sodium salt monomer was added.

Table I. Krebs Solution Composition in 1 L of Deionized Water Prepared at Room Temperature

Salt	Concentration (m*M*)
NaCl	118.5
KCl	4.7
Mg_2SO_4	1.2
KH_2PO_4	1.2
$CaCl_2$	2.5
$NaHCO_3$	25
EDTA	374.28

Characterization Methods

^{1}H NMR Spectroscopy. The degree of conversion of the hydroxyl end groups to methacrylates was quantified using ^{1}H NMR spectroscopy. The operating frequency for the ^{1}H was performed at 300 MHz (Bruker Avance NMR spectrometer) with tetramethylsilane (TMS) and chloroform-*d* ($CDCl_3$) as the internal standard and solvent, respectively. The polymer

Table II. Feed Composition of the Hydrogels with Varied Anion Acid Monomer Salt

Sample	PF127-BMA ($\times10^{-4}$ mol)	Methacrylic acid salt ($\times10^{-3}$ mol)	Deionized water (mL)	Gel fraction (%)
P1	2.0	0	6	75
P2	1.6	4.2	5.3	84
P3	1.2	9.4	4.6	85
P4	0.8	14.0	4	65

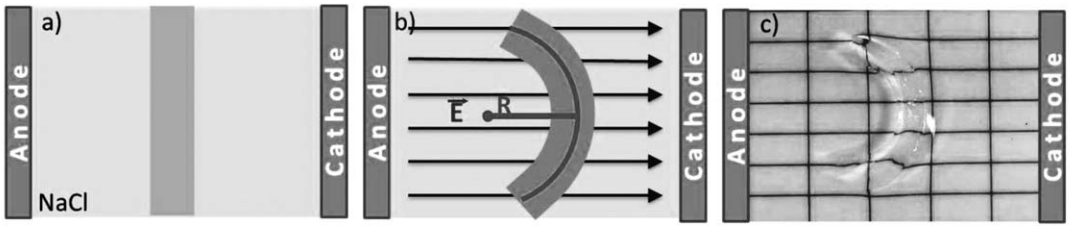

Figure 2. Electroactuation scheme. The rod-like hydrogel is placed between two electrodes immersed in salt solution (a) and an electric field is applied (b). The magnitude of electroactuation is measured as the change in hydrogel's curvature ($1/R$) as illustrated in (b). (c) Real image of an actuating hydrogel.

(20 mg) was added to $CDCl_3$ (800 µl). The same procedure was followed for the determination of the vinylic protons on the acid salt monomer.

Attenuated Total Reflectance Fourier Transform Spectroscopy. Attenuated total reflectance Fourier transform spectroscopy (ATR-FTIR) was used to determine the presence of the acid salt in the monomer and dried hydrogel formulations. These were recorded at room temperature using a Biorad at a range of 4000–600 cm^{-1}. Each spectrum was taken with 32 scans at a resolution of 8 cm^{-1}.

Swelling Study. Swelling studies were conducted using pre-cut hydrogel discs (Ø = 7 mm, h = 4 mm) which were subsequently purified in deionized water for 3 days. The dried hydrogels were immersed in either deionized water or Krebs ionic solution while performing periodic weight measurements. Swelling studies were conducted in solution at 37°C until constant weight and superficial fluid on the surface of the hydrogels was removed before each weighing. The swelling ratio was calculated as follows:

$$SR\% = \frac{Wt_i - Wt_0}{Wt_0} \times 100 \quad (1)$$

where Wt_i and Wt_0 are wet weight at time t and dry weight at time 0, respectively.

Kinetics of the swelling character, k, and mechanism, n, of the hydrogel network was determined using the classical Fickian diffusion theory of early fluid uptake as shown in eq. (2)[27]:

$$\frac{M_t}{M_\infty} = kt^n \quad (2)$$

where M_t is the mass of solvent diffused at time t; M_∞ is the equilibrium uptake, k is the proportionality constant, and n is the diffusional exponent. Three proposed models [n = 0.45 Fickian; n = 1.0 Zero order non-Fickian; $n = 0.45 < n < 1$ anomalous non-Fickian] are accepted to define the solvent or solute transport in polymer networks where $M_t/M_\infty \leq 0.6$.

Furthermore, as equilibrium is reached, the swelling mechanism for a cylindrical hydrogel is described by eq. (3):

$$\frac{M_t}{M_\infty} = 4\left(\frac{Dt}{\pi l^2}\right)^{1/2} - \pi\left(\frac{Dt}{\pi l^2}\right) - \frac{\pi}{3}\left(\frac{Dt}{\pi l^2}\right)^{3/2} + \ldots\ldots\ldots \quad (3)$$

where the diffusion coefficient, D, can then be determined from eq. (4):

$$\frac{M_t}{M_\infty} = 4\left(\frac{Dt}{\pi l^2}\right)^{1/2} \quad (4)$$

where l is the thickness (cm) and D is the diffusion coefficient ($cm^2\ s^{-1}$).

Rheology Measurements. A TA Instruments AR-G2 rheometer in parallel plates configuration was used to characterize the viscoelastic behavior of the swollen gels and all data were collected at 25°C. Hydrogel samples, swollen in demineralized and deionized water, were taken out of the solution and 2.5 cm discs (height = 0.5 cm) were punched out. The discs were then placed between the rotating upper plate and a stationary lower one. The gap between the plates was determined by the sample thickness and was monitored by the rheometer. To prevent sample's slippage during data acquisition, a constant compressive force (1 N) was applied to the sample. Measurements were performed three times for gel. Oscillatory shear measurements at a constant strain of 0.5 % (in the middle of the linear regime) were imposed to the sample and frequency sweeps over 0.1–100 rad s^{-1} range were performed.

Electroactive Stimulation. The electroactuation experiments were performed in a flat bed electrophoresis unit Multi (Carl Roth GMBH). This unit consists of two platinum wire electrodes, mounted in a moveable frame and a glass plate upon which samples were placed. The distance between the two electrodes was fixed at 10 cm, and the hydrogel was cut into a square beam shape (4 cm × 0.5 cm × 0.5 cm) dimensions. The hydrogels were immersed in NaCl (0.1M) solution as shown schematically in Figure 2 while an electric potential difference of 15 V was applied between the electrodes. The experiments were conducted at a steady voltage mode, therefore whatever current was necessary to maintain the voltage was provided by the power. During electroactuation, the shape of the hydrogel was monitored every 30 seconds with a Nikon coolpix 4500 camera placed above the unit. Images were then processed with Image J software and the gel curvature versus time was obtained.

RESULTS AND DISCUSSION

Chemical Modification of PF127 (co)Polymer and Methacrylic Acid

Methacrylation of PF127 Block (co)Polymer. The purity and number average molecular weight of PF127 polymer was confirmed via ^1H NMR analysis. Transformation of the terminal hydroxyl functional group to a trichloroacetyl urethane

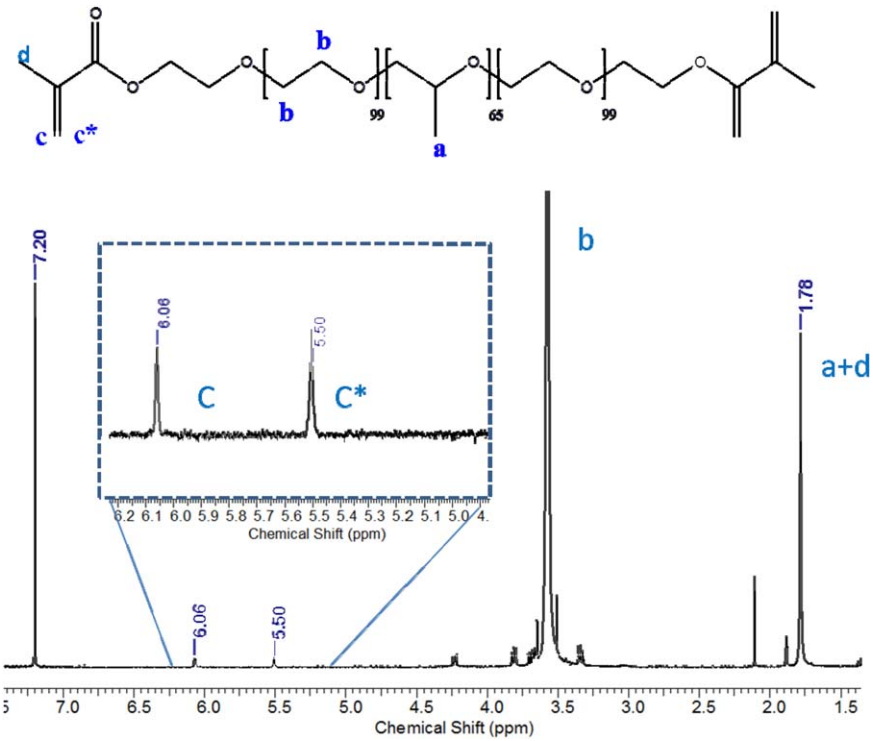

Figure 3. ^{1}H NMR spectra of modified PF127 in deuterated chloroform using a 300 MHz Bruker instrument. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

derivative was observed by a shift in the methylene proton in the α position of the hydroxyl end group from 3.6 ppm to about 4.5 ppm (data not shown). This is in agreement with reports that have investigated the use of this reagent (i.e., TAIC) as a means to quantify the number of primary alcohols in long chain polymers.[28,29] Furthermore, the hydroxyl end functionalities presented a route to introduce redox system liable methacrylic end groups. Methacryloyl chloride was chosen to modify PF127 block (co)polymer into the required PF127BMA prepolymer (needed for polymerization and crosslinking) due to the high reactivity of its acid chloride toward the nucleophilic primary hydroxyl. The optimized method used afforded a high degree of modification of ≥95% as indicated by the vinylic protons observed at 5.5 ppm and 6.0 ppm (Figure 3). In addition, the presence of the carbonyl group in the ester was observed at 1716 cm^{-1} (Figure 4) which confirmed the presence of the modified end groups.

Methacrylic Acid Conversion to its Salt Derivative. As aforementioned, introducing an electroactive responsive character to PF127 required the presence of a salt monomer in the resulting hydrogel network. As such, the modification of methacrylic acid monomer into an anionic salt derivative was performed. ^{1}H NMR confirmed the preservation of the vinylic protons at 5.3 ppm, 5.6 ppm and methyl protons at 1.7 ppm (data not shown). No methyl group protons in polymeric form were observed upfield (<1.7 ppm), thus, indicating that the optimized method for ionization preserved the vinylic group from polymerizing. Furthermore, infrared spectroscopy confirmed the presence of the carboxylate anion at 1548 cm^{-1} (Figure 5). The hydroxyl group in the free carboxylic acid form was observed at 3500 cm^{-1}, confirming the partial (de)protonation of the monomer as intended. It is noteworthy to highlight that the aim of the partial (de)protonation was to provide a route for further post-hydrogel modification with the free carboxylic acid group (using carbodiimide chemistry) if necessary. However, this step is beyond the scope of the present investigation.

Hydrogel Development

Anionic hydrogels were synthesized by reacting the prepolymer, PF127BMA, and the methacrylic acid sodium salt in water initiated by APS under an argon atmosphere. Upon mixing, TEMED catalyzes the decomposition and stability of APS, thus generating free sulphate (SO_4^{2-}) radicals. These radicals propagated the conjugation of methacrylate end groups via an addition mechanism. Resultant hydrogels yielded soft transparent bulk materials which were purified for 3 days to remove

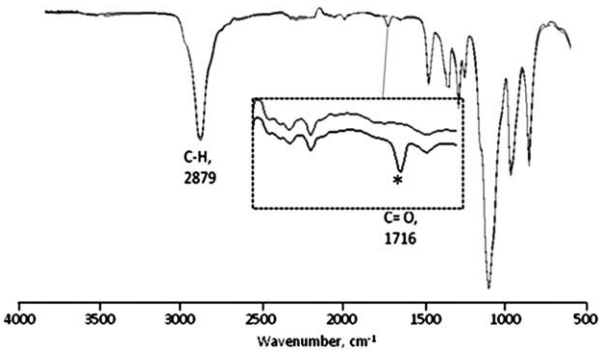

Figure 4. ATR-FTIR spectra of neat and methacrylated (*) PF127 block (co)polymer.

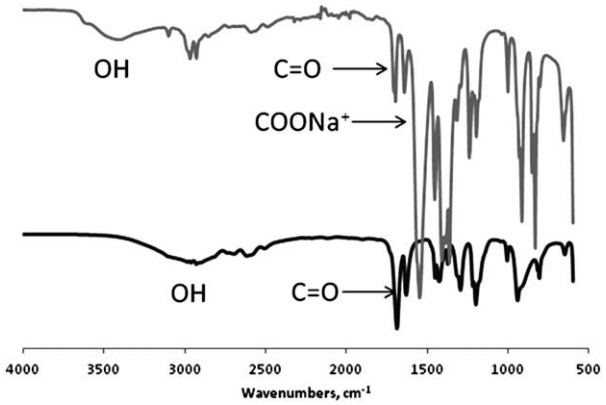

Figure 5. ATR-FTIR spectra of unmodified and modified methacrylic acid monomer.

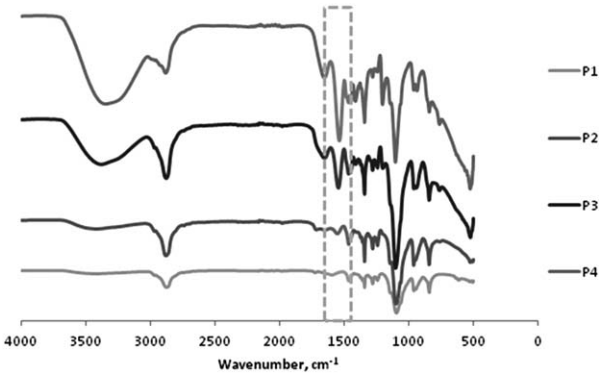

Figure 6. IR spectra of purified dried hydrogels (highlighted band indicates carboxylate anion).

residual unreacted monomers. Gel fraction, as a measure of the solid content after purification, was found to be in the range 65–85% (Table II).

In Figure 6, infrared spectroscopy revealed the differences between the hydrogel formulations. Characteristic peaks associated with methylene (—CH_2—, symmetric stretch), carbonyl (—C═O, stretch), carboxylate anion (—COO^-Na^+, asymmetric stretch) (highlighted), and ether (—C—O—C—, stretch) were observed at 2960, 1750, 1548, and 1100 cm^{-1}, respectively. An inherent presence of carboxylate anion in the hydrogel network was confirmed. It was evident that increasing the amount of the anion monomer led to higher intensity of this peak. Interestingly, the hydroxyl peak, 3000–3500 cm^{-1}, increased in tandem with an increase in the carboxylate anion content for two reasons. First, an increase in methacrylic acid salt monomer resulted in increased free carboxylic acid form due to the partial deprotonation. Secondly, the increase in anion salt imparted a hygroscopic effect on the dried hydrogels. It can be further observed that the P1 reference formulation spectrum did not reveal the peak at 1548 cm^{-1} (Figure 6) as it did not possess the acid salt in its network.

Swelling Study

Uptake and retention of fluid in a hydrogel network defines its underlining property. Upon fluid imbibition, the distance between crosslinked junctions (mesh size) is increased due to hydration of the hydrophilic moieties. This in turn leads to volumetric and mass increase as more fluid is retained. However, a balance between crosslink density and polymer osmotic pressure (due to anions) regulates the degree of swelling. As a consequence, tuning (via controlled swelling) of viscoelastic properties and solute release kinetics can be used to better help in understanding the swelling mechanism to suit varied applications.[1,5,16,30]

In this article, the swelling behavior of the hydrogel formulation was obtained in either deionized water or Krebs solution. Figure 7(a) shows that increasing the anionic monomer content resulted in a controlled increased uptake of water. The swelling percentage of the charged hydrogels was found to be 2.5 (P2), 6.5 (P3), and 20 (P4) times greater than the noncharged formulation (P1) (after hydrogel purification). P1, hydrogel contributes structural and hydrophilic functions to the hydrogel network. Upon changing the solution [from non ionic to ionic, Figure 7(b)] a similar trend was observed. As expected, uptake

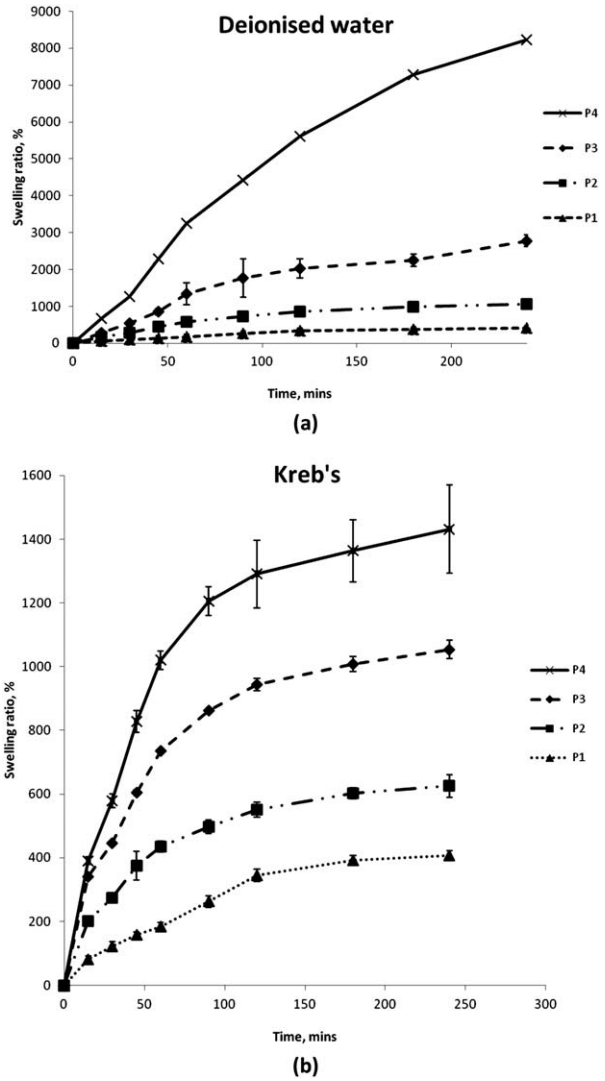

Figure 7. Swelling behavior profile of hydrogels in (a) deionized water and (b) Krebs solution at 37°C, $n = 4$ for each data point.

Table III. Summary of Hydrogel Properties in Water and Krebs Solution

Solution	Sample	N	$K \times 10^{-2}$	$D \times 10^{-6}$ ($cm^2\ s^{-1}$)
Water	P1	0.86	1.27	0.33
	P2	0.79	1.4	1.77
	P3	0.98	0.74	3.28
	P4	1.06	0.47	3.07
Krebs	P1	0.69	2.8	0.37
	P2	0.53	7.7	1.43
	P3	0.52	7.8	1.68
	P4	0.61	5.3	1.79

of fluid was observed to be much lower in Krebs solution than in deionized water. For example, the swelling percentage of P3 (1100%) and P4 (8500%) in water was observed to decline by a factor of 3 and 6, respectively in Krebs solution.

In the series of formulations developed, the determinant factor that affected the swelling behavior in solution was due to the presence of a hydrophilic network. Ionization of methacrylic acid created domains of fixed charges with mobile sodium counter ions thus enhancing the swelling capacity. This resulted in a positive ion pressure inside the gel affording a significant osmotic pressure and an ion gradient across the hydrogel membrane. As the methacrylic acid sodium salt content increased, so did the osmotic pressure difference consequently driving the flow of fluid into the hydrogel to equilibrate the ion concentration (Donnan equilibrium). Additionally, electrostatic repulsion of similar charged groups between close proximity chains will also lead to the expansion of the network. Although, the monomer was partially ionized (stoichiometric ratio), the lower degree of free carboxylic acid groups were only likely partially dissociated in water, hence, their ionic presence contribution would be expected to be significantly lower.

In the case of Krebs (ionic) solution, the degree of swelling followed the same trend as observed for water; however, it was noticeably less. This is because the amount of solvent needed to equilibrate the osmotic pressure difference (diffusable and fixed ions) was diminished due to the high ionic concentration of the Krebs solution when compared to deionized water. Overall, P1 was shown to imbibe the least amount of solvent due to the absence of charged domains.

Uptake of fluid by a hydrogel is a continuous process that leads to a transition of the polymer network from the polymer glassy to a rubbery phase driven by mass transport (diffusion) and mechanical deformation. Diffusion involves movement of fluid into spaces between polymer chains while swelling induces long-range segmental motion that leads network expansion. It is known that the classic theory of diffusion may not predict the swelling behavior due to the slow macromolecular chain orientation and association of pendant functional groups close to or below the polymer glass transition temperature.[5] As such parameters like the swelling constant, exponent, and diffusion coefficient that are indicative of the swelling phenomenon are determined. In this study, a comparison of the effect of the different swelling media is shown in Table III. Analysis of the diffusion mechanism, [exponent ***n***], was determined from the slope of ln (M_t/M_∞) vs. ln t [Figure 8(b)]. In water, n fell in the range 0.45 and 1 thus indicating a non-Fickian type diffusion system. This type of mechanism is determined by a comparable influence of polymer relaxation (chain mobility) and penetrant solvent movement. This indicated that the network changed from a glassy to a soft rubbery state during swelling. In Krebs solution, a similar trend was observed.

Another parameter, ***k*** (kinetic rate constant), determines the network structure pertaining to crosslink density and the greater the crosslink density the lower the ***k*** value. In deionized water,

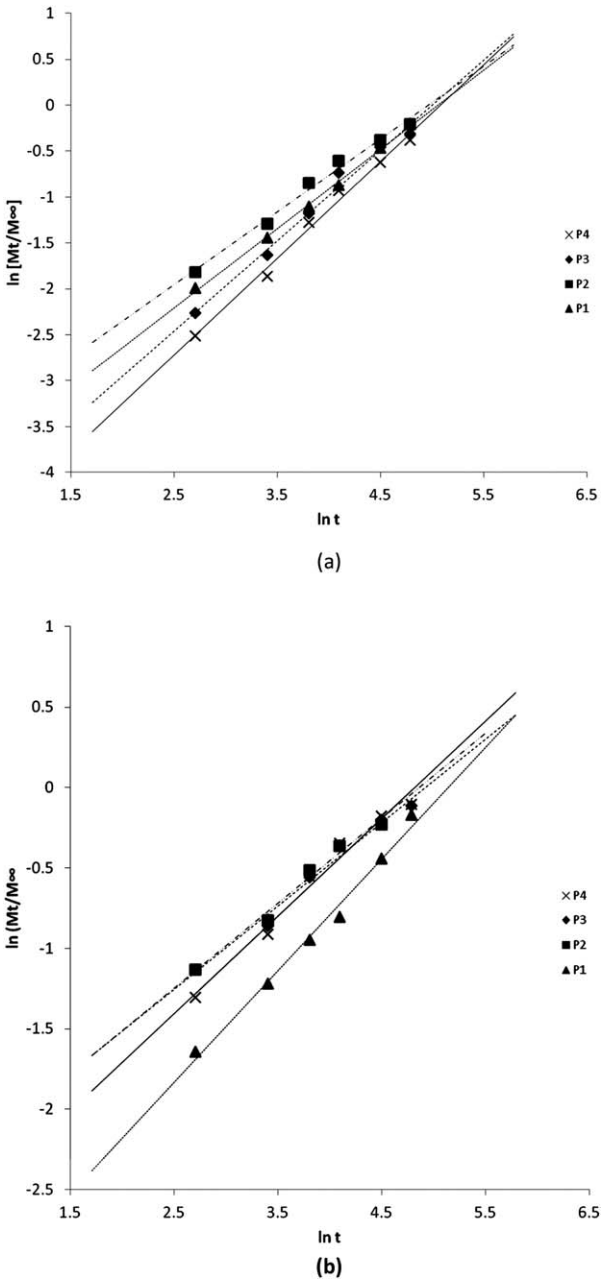

Figure 8. Linear swelling kinetic plots of hydrogels in (a) deionized water and (b) Krebs solution.

Table IV. Frequency Sweep of Hydrogels Swollen in Deionized Water and Held in Place with a Nominal Force of 1 N

Sample	P1	P2	P3	P4
G' (kPa)	14.6	6.10	4.02	1.54
G'' (kPa)	0.87	0.24	0.18	0.06

G' and G'' data were collected at 0.5% strain and at 25°C.

k decreased with decreasing covalent crosslinking density (crosslinker). This is in agreement with the work on ionic poly(*N*,*N*-dimethylacrylamide-*co*-acrylamide) hydrogels.[31]

In Krebs solution, the k value was found to increase with decreasing covalent crosslink density. This phenomenon can be explained by considering the electrostatic bridging of close proximity oppositely charged domains in the network (enhanced in the xerogel state during drying).[32] It would appear that the solvating effect of Krebs ionic solution in disrupting the bridges was lower than deionized water. This indicated that long range segmental motion (swelling) of the chains was restricted. Another possibility is the screening effect of the salt content in Krebs solution.[33] The combined effects of covalent crosslink density, ionic bridges, and increased hydrophilic character led to reduced diffusion coefficient of P1–P4 hydrogels in Krebs when this parameter is compared to deionized water. This is in agreement with the report that demonstrated, via a small-angle neutron scattering technique, the presence of heterogenic domains in polyacrylic acid crosslinked with tetra functional bis(acrylamide) hydrogels.[33]

Rheological Analysis

As a measure of the mechanical strength, rheological data on the swollen hydrogels were collected. The storage modulus (G') was found to be in the range of kPa. The shape of the obtained curves indicated no gel sample slippage when exposed to perturbation oscillatory frequencies. In addition, G' was an order of magnitude higher than the loss modulus (G'') at all the shear strain rates tested. As anticipated, the highest G' was observed for the P1 hydrogel, the least swollen hydrogel without the methacrylic acid salt. G' values decreased with increasing methacrylic acid salt content due to increased volumetric expansion. The data confirmed that the volumetric expansion of the hydrogels can be fine tuned to regulate their elastic moduli as shown (Table IV).

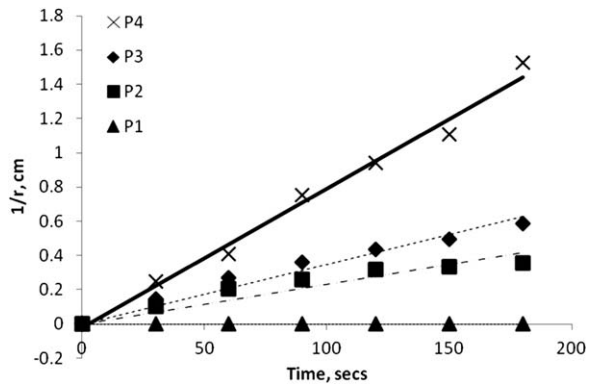

Figure 9. The influence of the methacrylic acid content on electroresponsiveness in a 0.1*M* NaCl solution. The linear fitting is added to guide the eye.

Electroactive Stimulation

Bending electroactuation of the polylectrolyte hydrogels, induced by an external electric field, is governed to a large extent by the migration of ions across the hydrogel boundary (Figure 2). The original difference in ion concentration between the hydrogel and the surrounding solution plays an important role.[34] To assess the degree by which the methacrylic acid sodium salt determines the amplitude and time of bending actuation, the curvature was measured as a function of time. Data for four different hydrogels are shown in Figure 9, and it was evident that the electroresponsiveness increases with the acid sodium content. For instance, the actuation of P4 within the first was approximately a factor of 5 higher than P2 in comparable conditions. As expected, P1 (a neutral hydrogel) did not show any sign of actuation. Although, the relationship between the local change, storage modulus, and ion diffusion during actuation is not known, the trend revealed a correlation between electroresponsiveness (fixed charge polymer content) and network elasticity.

CONCLUSIONS

In this article, the copolymerization of an acid sodium salt monomer with a crosslinkable neutral Pluronic block copolymer was investigated. The synthesis yielded hydrogel structures that were capable of absorbing fluid to several times their original mass without dissolution. Experimental data showed that increasing the acid sodium salt content allowed regulation of the amount of fluid uptake. In addition, the sorption kinetics showed that the highest rate of fluid uptake was observed in water (nonionic solution) when compared to Kreb's solution (an ionic medium mimicking physiological conditions). Sorption mechanism showed the influence of the acid sodium salt content on the hydrogel swelling behavior in both media. Since the aim of this article was to introduce electrical stimuli responsiveness in a hydrogel matrix that did not possess this ability, electroactuation studies in NaCl solution were performed. The results showed that the bending angle of the developed hydrogels increased with increasing acid sodium salt content and higher hydrogel elasticity. This hydrogel system has been shown to possess a promising potential as an electroactive implant material in biomedical applications such as actuators, drug delivery implants, biochemical sensing devices, and diagnostic microfluidic devices.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the European Union under the framework 7 ICT program (Heart-e-Gel project, Grant number 258909) as well as UGent for supporting the Multidisciplinary Research Partnership Nano- and Biophotonics (2010–2014), the UGent-GOA project (BOF10/GOA/005, Biomedical Engineering for Improved Diagnosis and Patient-Tailored Treatment of Aortic Aneurysms and Dissection) (2010–2015), and the

UGent-BOF project (Production of porous polymer structures via Bioplotting for cardiovascular applications) (2009–2013).

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