Chapter 11
Smart Polymer Gels

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1 Introduction

Polymer gels (PGs) are defined as viscoelastic cross-linked hydrophilic three-dimensional polymeric networks with dissociated ionic functional groups. PGs can absorb large amount of water or other biological fluids in short time and release them under certain conditions (Thakur and Thakur 2014a, b, 2015). Smart polymer gels (SPGs) are one class of polymer gels with a special characteristic which is the response to the environment change such as temperature, electric, light, sound field, magnetic fields, and pH. The response to the environment change gives this class of materials wide range of application in many fields such as medical and water treatment. SPGs are polymerized via normal polymerization methods such as solution, suspension, and emulsion polymerization. Cross-linking process of SPGs occurs via chemical (using cross-linking agent) or physical method (entanglements or crystallites).

2 Classification of Smart Polymer Gels

SPGs are classified depending on their response to surrounding environment as illustrated in Fig. 1.

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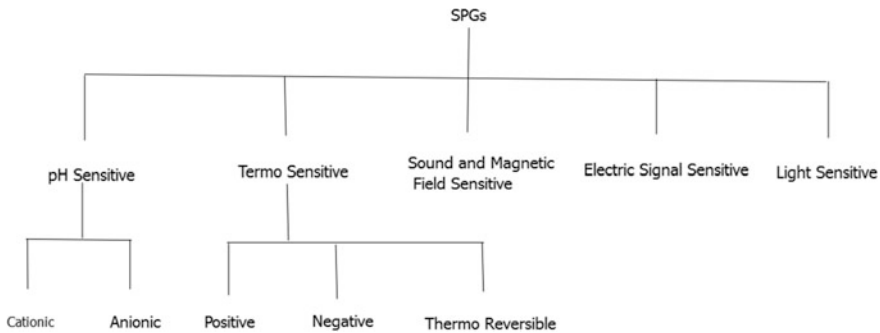61004 Basrah, Iraq

Fig. 1 Classification of SPGs according to their response to the external medium

2.1 Thermosensitive Gels

This class of SPGs is defined by its ability to swell and shrink when the temperature of surrounding fluid is change (Hongyan He 2006). This kind of PGs can be divided into three classes: negative temperature sensitive, positive temperature sensitive, and thermoreversible.

2.1.1 Negative Temperature Sensitive

This class of SPGs has critical parameter called low critical solution temperature (LCST), which means that SPGs will shrink when the temperature increases above LCST and showing swelling behavior at temperature less LCST. LCST of this class of SPGs can be controlled using different ways such as changing the molar ratio of ionic copolymer or by changing the solvent composition. In general, LCST of polymer of more hydrophobic constituent shifts to low degree which means changing the percentage ratio of hydrophobic to hydrophilic contents of SPGs leads to change LCST (Schild 1992; Hongyan He 2006). Figure 2 shows the structures of some of these polymers.

From the structure of negative thermosensitive SPGs, it can be seen that the polymers have two parts; the first is hydrophilic part –CONH–, and the second is hydrophobic part –R– (Zhang et al. 2003). At temperatures lower than LCST water or fluid interact with the hydrophilic part by forming hydrogen bonds which leads to dissolution and swelling behavior. At temperature higher than LCST hydrophobic interaction among hydrophobic part will be stronger and hydrogen bonds will become weaker; therefore, network shrinking occurs due to inter-polymer chain association (Qiu and Park 2001), and the absorbed fluid will go out of the structure (de-swelling process).
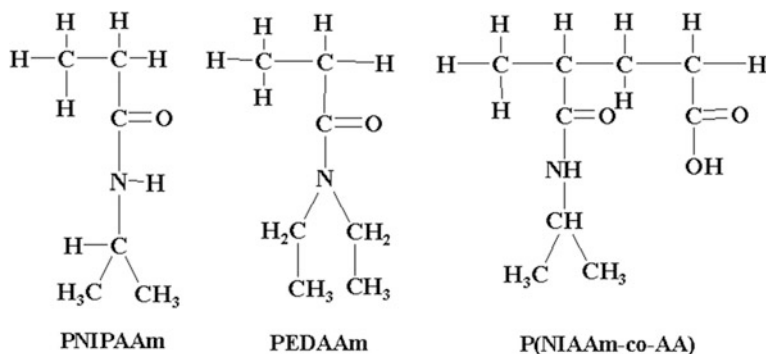
Fig. 2 Negatively pH-sensitive polymer gels

2.1.2 Positive Temperature Sensitive

Positive temperature SPGs are known with their upper critical solution temperature (UCST) (Peppas et al. 2000). When the temperature is below UCST network structure contract and release absorbed fluids (dehydration). Network relaxation occurs at temperature higher than UCST (swelling). This type of PGs is retrogressive with negatively temperature sensitive gels. This class of SPGs is shrinking at low temperature due to the formation of complex structure via hydrogen bonds. Network structure dissociates at high temperature due to breaking of hydrogen bonds and SPGs swelling to maximum possible extent rapidly above the UCST. There are a wide range of polymers and copolymers that are positive temperature such as poly(AAm-co-BMA), and poly(AA-co-AAm-co-BMA) (Hongyan He 2006).

2.1.3 Thermoreversible

This class SPGs has similar structure and contents of negative and positive temperature SPGs with deference in kind of bonds. Polymer chains in this class are not covalently cross-linked, and SPG undergoes sol–gel phase transitions instead of swelling–shrinking transition (Hongyan He 2006). Sol–gel phase transformation depends on glucose concentration in the surrounding medium. Sol–gel reversible SPGs require glucose response cross-linking. The most commonly used thermoreversible gels are pluronic and tetronic compounds as illustrated in Fig. 3 (Qiu and Park 2001).
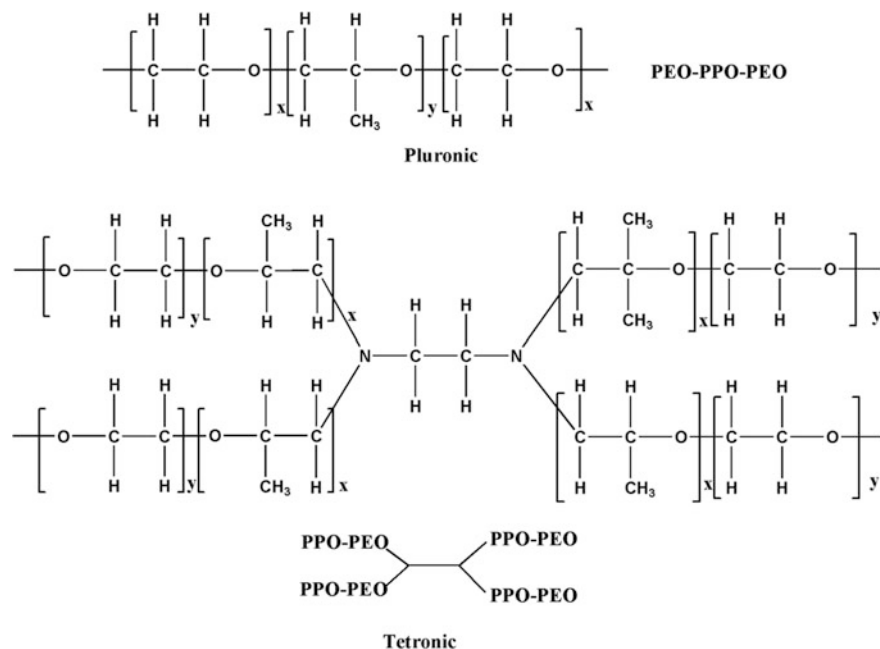
Fig. 3 Polymer structures of pluronic and tetronic

2.2 pH-Sensitive Polymer Gels

pH-sensitive gels are materials that respond to pH values of surrounding medium. Swelling behavior occurs due to changes in hydrophobic–hydrophilic nature of chains or due to hydrogen bonds and the complexation of inter- and intramolecular or electrostatic repulsion. Depending on nature of polymer pendant group, pH-sensitive PGs are classified into anionic and cationic polymer gels (Hongyan He 2006).

2.2.1 Anionic Polymer Gels

This class of SPGs often has carboxylic or sulfonic acid groups (Qiu and Park 2001). The more important parameter of anionic gels is the relation between pKa of the polymer and pH of surrounding environment, which means that, when pKa is higher than pH of surrounding medium, the ionized structure will increase the electrostatic repulsion of the network and enhance the swelling properties (Hongyan He 2006). Examples of anionic pH-sensitive PGs are shown in Fig. 4.
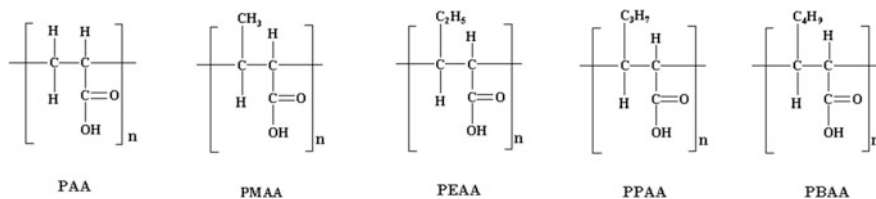
**Fig. 4** Anionic pH-sensitive polymer gels

2.2.2   Cationic Polymer Gels

Cationic SPGs usually have pendant group such as amine (Qiu and Park 2001). The more important parameter in these materials is the relation between polymer pKb and pH of surrounding medium. When pH of environment is lower than polymer pKb amine group is changing from NH_2 to NH_3^+ which subsequently increase the hydrophilicity, electrostatic repulsion, and absorption capacity (Peppas et al. 2000). Polyacrylamide (PAAm) is the most used polymer as cationic polymer gels.

2.3   Electric Signal Sensitive

Raw matrix of this class is polyelectrolyte which is similar to pH-sensitive SPGs. Electric-sensitive SPG undergoes swelling and de-swelling as a response of applied electric signal. Electric-sensitive PGs have three kinds of transition phases: swelling, shrinking or de-swelling, and bending. These phases depend on a number of conditions such as the system that has been used to apply electric field (contact system or spread system) (Kim et al. 2003; Hongyan He 2006). In the last decades, new class of smart gels has been emerged called core–shell gels. Core–shell gels are structured composite particles consisting of at least two different components: one in principle forms the core and the other the shell of the particles (Ha et al. 2002). This class of materials has attracted much attention because of the combination of superior properties not possessed by the individual components. The systems might combine the characteristics and properties of both shell and core (Hendrickson et al. 2010). Core–shell gels might be pH and thermosensitive at same time. This characteristic granted this class of gels numbers of applications as impact modifiers, surface coatings, printing, catalysis, pollution control, sensing, and drug delivery in biomedical application (Jones and Lyon 2003; Li and Stöver 2000; Sasa and Yamaoka 1994; Khan et al. 2008). Core–shell gels are usually prepared in spherical form, implying a particle structure with the initially polymerized polymer located at the center of the particle, and the later-formed polymers becoming incorporated into the outer shell layer as illustrated in Fig. 5 (Dimonie et al. 1997). The core part may be a solid or a liquid or a gas; however, the shell materials usually a solid but its

Fig. 5 Core–shell polymers (CSPs) consisting of central part may be a solid, liquid, or a gas and shell part usually a solid
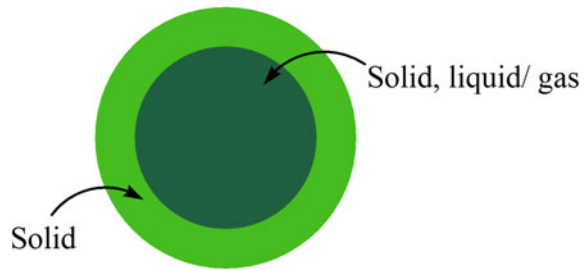
nature depends on the type of applications (Jones and Lyon 2003). Core–shell polymer gels can be in nanosize and microsize according to preparation methods and targeted applications (Blackburn and Lyon 2008; Berndt et al. 2006).

3 Composites of Smart Polymer Gels

Composite of different materials can be possible solution to get special desired properties for particular applications or to gain the desired properties from each material in the compound. SPG composite has been carried out using different kind of polymers, fibers, and fillers of different sizes from micro- to nanosize. Many minerals have been used to act as filler for production of SPG composite such as kaolin, diatomite, potassium humate, glass, smectite, kaolinite, sodium silicate, bentonite, and montmorillonite (Kabiri et al. 2011). Natural fibers also have been used in some areas such as study by Rui Liang et al. used wheat straw (WS) to improve PGs properties and investigate the effect of WS on absorption capacity of PAA superabsorbent hydrogel in distilled water and 0.9% sodium chloride (NaCl). The result showed that the maximum absorbency attained at 20% of WS and absorbency started decreasing after further increase in WS % as shown in Fig. 6 (Liang et al. 2009). Composite of SPGs was prepared to improve mechanical properties, swelling behavior, and reduce cost. In fact, composites of polymer gels were successfully prepared and utilized in many filed when mechanical properties is needed. More information on polymer gel composites can be found in very good review by Kabiri et al. (2011).

4 Properties of Smart Polymer Gels

4.1 Absorption Properties

Swelling behavior and absorption capacity (AC) are the most important properties that give SPGs wide applications. In general, swelling and absorption properties are

Fig. 6 Influence of wheat
straw content on the
absorbency of WS/APP
superabsorbent composites
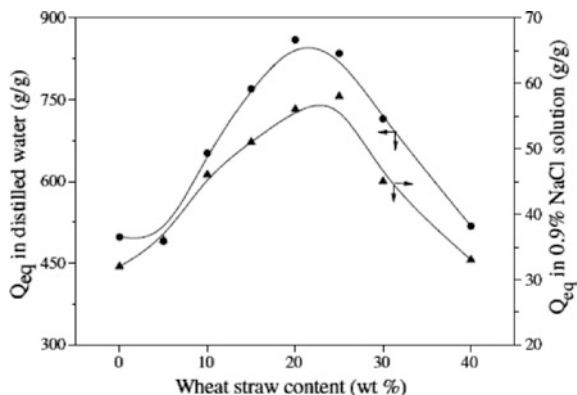
attributed to the presence of hydrophilic groups such as –OH–, CONH–, –CONH$_2$–, and –SO$_3$H in the chemical structure of the network (Hamidi et al. 2008). The ratio of sample weight at swelling and de-swelling actions is called swelling ratio (SR) (Tang et al. 2008; Kim et al. 2003; Zuo Chun et al. 2007). There are many factors affecting SR and AC of SPG such as chemical compositions (Karadag et al. 2005; Guilherme et al. 2005), network structure (Patachia et al. 2007), cross-linking ratio, specific stimuli or the surrounding medium (Peppas et al. 2000; Hongyan He 2006), polymers molecular weight (Raj et al. 2009), and chemical structure of polymer repeating unit (Chun et al. 2009). The swelling process of SPGs can be explained as follows: The solvent tries to penetrate the polymer networks to produce 3D-molecular network at the same time expanding the molecular chains between the cross-linked points, thus decreasing the configuration enthalpy value. The molecular network has an elastic contractive force which tries to make the networks contract. When these opposite forces reach equilibrium, the expansion and contraction also reach a balance. In this process, the osmotic pressure is the driving force for expansion of swelling and network elastic force is the driving force of the contraction of gel. AC is estimated using volumetric, gravimetric, spectroscopic, and microwave method. The volumetric method measures the sample volume changes or absorbed fluid before and after absorption. The gravimetric method depends on measuring sample weight changes. Spectrometric method uses UV-spectrum of sample change, and the microwave method measures microwave absorption by energy changes. Absorbed water in network structure of PAA can exist in three states: bound, half-bound, and free water. Free water shows freezing point when the environment temperature is around 0 °C. However, this freezing point cannot be seen with bound water. The half-bound water shows property between them. Bounded water is usually 0.39–1.18 g/g. Absorption capacity of SPG mainly depends on osmotic pressure, network affinity, and network cross-linking density.

4.1.1 Cross-Linker and Cross-Linking Density

Cross-linker plays major role to adjust SPGs properties in terms of absorption and mechanical properties. Cross-linking density of SPGs is controlled by the fraction of cross-linking agent present in the polymerization and double bond conversion. Therefore, smaller amount of cross-linking agent leads to different cross-linking degree and change in AC of PGs. At low percentage of cross-linking agent, the three-dimensional PGs do not form effectively and the water molecules cannot be held resulting in SR and AC decrease. At high concentration of cross-linker a large number of growing polymer chains are involved to produce an additional network structure. High tied network does not allow water to enter the network and decrease AC (Turkington and Paradise 2005; Peppas et al. 2000). Effect of cross-liker content on SR of copolymer of carboxymethyl chitosan-g-polyacrylic acid is shown in Fig. 7 (Shah et al. 2010).

Some researchers reported that the number of functional groups of cross-linker has affected AC of polymer gels. Different AC of PGs of polyacrylamide (PAAm) and polyacrylamide sodium acrylate (PAAm/SA) was obtained using different type of cross-linker as shown in Fig. 8. AC via using 1,4-butanediol dimetacrylate (BDMA), ethylene glycol dimethacrylate (EGDMA), N,N′-methylenebisacrylamide (MPA), and trimethylolpropane triacrylate (TMPTA) were in the following order:

$$MPA > BDMA > EGDMA > TMPTA$$

Different AC is observed as a result of functional groups of each type of cross-linker. MPA, BDMA, and EGDMA are tetrafunctional cross-linkers and TMPTA is hexafunctional cross-linker. NH group of MPA increases SR and AC via causing new hydrophilic interaction. Using TMPTA cross-linker led to many cross-linking sites; therefore, the cross-linking density is higher than using other cross-linker at same concentration which leads to decreased AC (Ren and Sun 2010). The chemical structure of cross-linker can affect absorption properties. Cross-linking agent with hydrophilic property such as MPA enhances the AC as a result of presences of amide groups (Vital et al. 2008). In addition, water solubility,

Fig. 7 Effect of MBAN/mAA on the swelling ratio of superabsorbent polymer
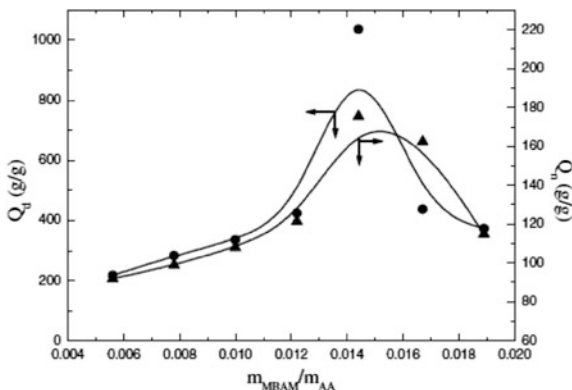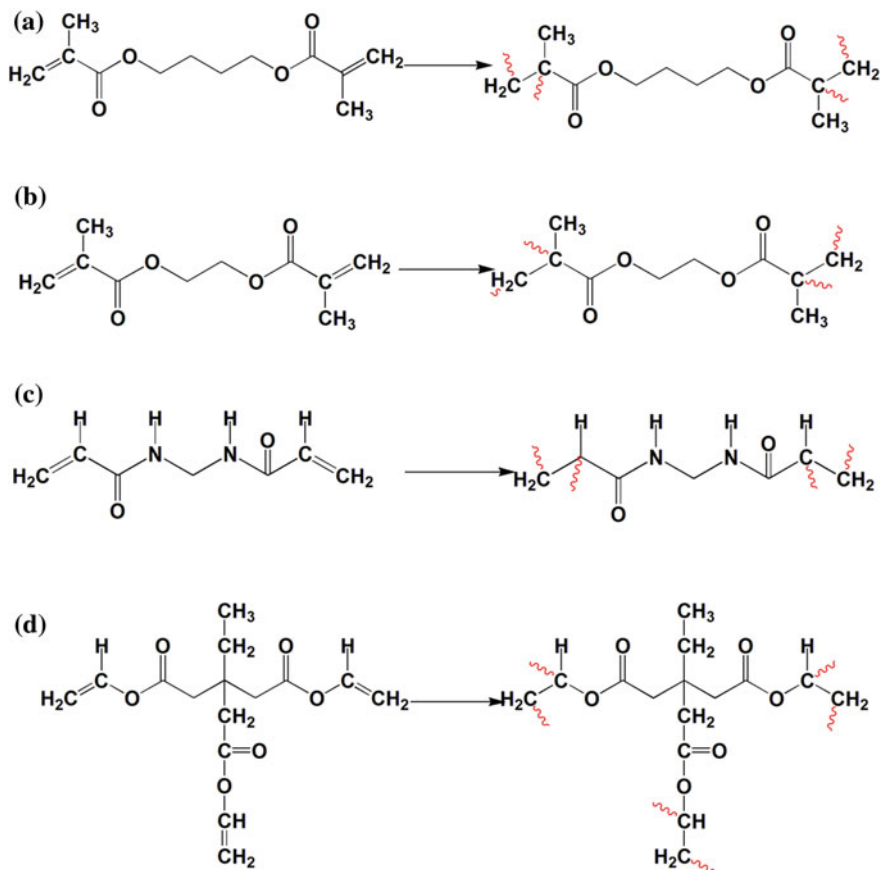
Fig. 8 Linking sites of **a** 1,4-butanediol dimetacrylate (BDMA), **b** ethylene glycol dimethaacrylate (EGDMA), **c** N,N´-methylenebisacrylamide (MPA), **d** trimethylolpropane triacrylate (TMPTA)

short chains, and high activity of MPA give this kind of cross-linker wide use in free radical polymerization (Turkington and Paradise 2005).

4.1.2 Initiator Content

Absorption capacity of SPGs is affected by the initiator content as a result of change in polymer molecular weight. At low molecular weight, the relative amount of polymer chain ends increases (polymer chain ends do not contribute to AC); therefore, AC will decrease at high content of initiator (D'Ulivo 2004). Moreover, when the content of initiator is low, the polymerization reaction takes place slowly and leads high molecular weight and network structure with big pore size.

Fig. 9 Effect of mAPS/mAA on the swelling ratio of superabsorbent polymers
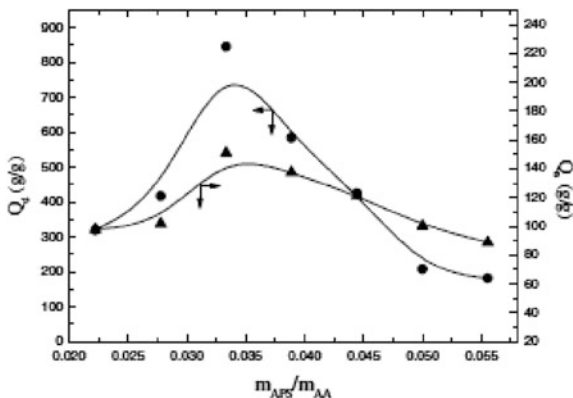
Network with large voids has less ability to hold water and less WAC. At high initiator content, the polymerization rate is high and the product has smaller space size and that prevents fluid molecules from entering the network (Lin et al. 2007). Figure 9 shows the effect of ammonium persulfate (Desrosiers et al. 2000) on water absorbency of copolymer of PAA-co-PAAm filled with inorganic clay (Li and Wang 2005). From above-mentioned, there is an optimum voids size to get maximum WAC and that can be controlled via initiator content.

4.1.3 Degree of Neutralization (DON)

DON is normally used between 0 and 80% for most polymerization process (Talpur et al. 2009; Pourjavadi et al. 2004). Neutralization of acrylic acid (AA) using sodium hydroxide (NaOH), the negatively charged carboxyl groups attached to polymer chains, produces an electrostatic repulsion (ESR) which leads to network expansion which means high AC is associated with high ESR. After certain degree of neutralization, AC decreases with a corresponding increase in chain stiffness and counterion condensation on the polyion "(screening effect)" (Dall and Sharples 1991). At low DON, the ESR is low which ultimately decreasing the absorption capacity of the hydrogel networks. When DON start to increase the content of $-CO_2-Na$ groups increases leading to enhancement in osmotic pressure between the inside and outside network and enhancing AC of SPGs. However, AC stop's at certain value of DON and starts to decline. The main cause of decline in AC is the presence of Na^+ ions which leads to shielding of carboxylate anions on PAA chains and inhibits anion–anion repulsion forces (El Bakouri et al. 2008). Table 1 shows DON effect on water absorbency of PAA hydrogel at various cross-linking agent concentrations (Yadvinder et al. 2005).

Table 1 The effect of neutralization degree of acrylic acid at various cross-linking agent concentrations on water absorbency of the synthesized beads

	Water absorption capacity g g^{-1}		
Neutralization degree of acrylic acid %	N,N-MBA		
	0.025 mol%	0.05 mol%	0.075 mol%
100	775 ± 99	568 ± 27	476 ± 15
76	581 ± 18	557 ± 51	471 ± 42
59	570 ± 68	523 ± 39	428 ± 28
46	507 ± 59	476 ± 17	447 ± 14

4.1.4   Solvent Volume and Concentration

Network structure of SPGs is affected by solvent concentration as a result of enhanced primary cyclization rate of multi-vinyl monomer during the polymerization process. Increasing the reaction solvent volume leads to decrease in contents reaction of cross-linking agent, initiator, and monomer and finally decreases in polymerization rate and cross-linking density. Low solvent volume means reaction contents' viscosity is high and difficult movement for free radicals and monomer in the reaction (El Bakouri et al. 2008; Munshi et al. 1978). Solvent concentration affects network properties by affecting radical propagation dynamics. At low solvent concentration, the double bond concentration surrounding by free radical is relatively high. This leads to fast propagation step and less opportunity for free radicals to recycle by reacting with its own pendant double bond. Solvent type and quality have been reported to affect SPGs properties. Poor solvent use results in loose network structure, and firm networks are a result of using good solvent (Elliott and Bowman 2002). Previous study indicated that high solubility monomer and homopolymer in solvent lead to difficulty in grafting polymerization. In the same study, effect of solvent contents was determined by fixing other reaction contents. The result showed that the maximum percentage of grafting was obtained at 50-ml-total reaction mixture. As a conclusion of this section, solvent concentration can be used to control free radical polymerization in both microscopic and molecular levels.

4.1.5   Fiber Type and Content

AC of SPGs is highly affected by chemical composition and concentration of used fibers. Hydrophilic groups on fiber surface contribute to enhance network absorption capacity. If the fibers act as additional cross-linking agent inside SPGs network, high concentration of fibers leads to rigid network structure and less. Previous work on sodium alginate (Na–Ag) grafted with carboxymethylcellulose (CMC) showed that SR of polymer gels increase gradually with increase in Na–Ag content, and the maximum AC is achieved at 0.5 weight ratio of Na–Ag/CMC.

After this ratio, AC decreases as a result of increase in viscosity of reaction mixture which hindered reactants movement (Yang et al. 2003; Shah et al. 2010). Kappa-carrageenan (kC) used as a fiber showed that WAC of the network was increased with increase in kC content. Same result has been obtained using CMC grafted with polyacrylonitrile (PAN), and starch-poly(sodium acrylate-co-acrylamide) (Pourjavadi et al. 2007a; Bonakdar et al. 2010; Seoudi 2008). Another study indicated that absorption properties of SPG were enhanced by filling the structure with inorganic clay (attapulgite) (Li and Wang 2005).

4.1.6   Chemical Structure and Monomer Molar Ratio

Blending of two monomers to produce desirable properties of SPGs has been studied intensively in the area of gels (Adem et al. 2009; Abd El-Rehim et al. 2006; Kadlubowski et al. 2007; Zhang et al. 2009; Mahdavinia et al. 2008). The effect of molar ratio of poly(acrylamide-acrylic acid) is shown in Fig. 10.

Increasing the polyacrylamide to more than 0.51 molar ratios leads to decrease AC, and counter result was observed at ratio less than this value. This study reported that the incorporation in suitable ratio of hydrophilic groups (–CONH, COONa, and COOH) inside the network reduces the repelling action and increases water absorbency (Li and Wang 2005). The chemical structure of polymer repeating unit affects SR and AC by changing the ratio of hydrophilic to hydrophobic groups (Chun et al. 2009). Network of high contents of hydrophilic groups swells to higher degree than those of high hydrophobic groups. Hydrophobic groups may collapse in the presence of water. The collapse chains minimize their exposure to water molecule as such lower absorption capacity and swelling rate.

Fig. 10 Effect of molar ratio of AM to AA content on water absorbency of superabsorbent polymer
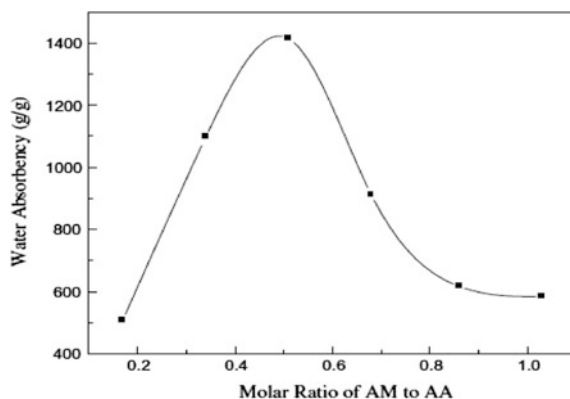
4.1.7 pH of Absorbed Fluid

Swelling behavior and absorption capacity of SPGs are affected by surrounding medium (Peppas et al. 2000; Hongyan He 2006). Affect of swollen pH on absorption and swelling capacity of polyelectrolytes has been considered in many studies (Varshosaz and Falamarzian 2001; Liu et al. 2006; Sahoo et al. 2007; Yoo et al. 2000; Kim and Park 2010; Karppi et al. 2007, 2008; Zhang et al. 2004; Wang et al. 2008; Singh et al. 2007; Sheikh et al. 2010; Yang et al. 2009, Abd El-Rehim et al. 2006). Effect of pH medium on swelling ratio of PAA hydrogel in Fig. 11 indicates that the high swelling ratio was at pH 4.9 solution. The cause of this value is associated with pKa of polyacrylic acid (PAA) and swollen medium. PAA has pKa of 4.9; therefore, when pH of swollen sample is less than pKa of PAA that leads to high strength of H^+ which affect carboxylic group ionization. At pH higher than pKa of PAA, more carboxylic ions are formed which enhances electrostatic repulsion and create more network free space and lead to increase in swelling ratio (Sheikh et al. 2010).

4.2 Releasing Behavior

Definition of SPG indicated that the network has the ability to release absorbed fluid as a response to environmental change (temperature, pH, ions, electric signal, sound, and magnetic field). Releasing behavior of SPGs draws great attention of many researches (Lee and Chen 2006; Kim and Peppas 2003; Tomic et al. 2007; Liu et al. 2006; Chen et al. 2009; Lee et al. 2008; Fundueanu et al. 2001; Siemoneit et al. 2006; Uchida et al. 2003; Issa et al. 1990; Huynh et al. 2009; Alemzadeh and Vossoughi 2002; Chun et al. 2005; Tada et al. 2005). Releasing character of SPGs via its sensitivity to environmental change grants this class of materials' advantages
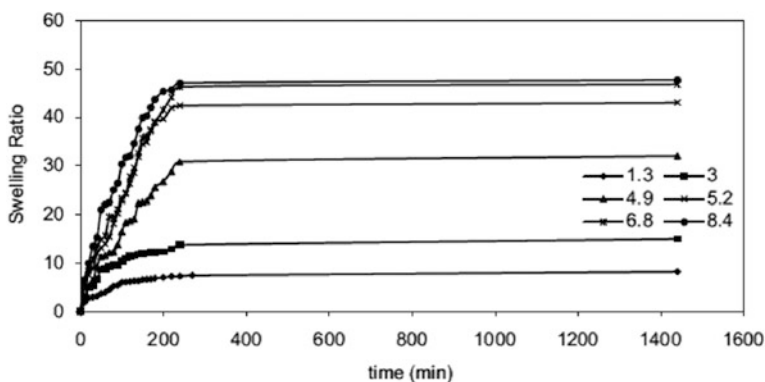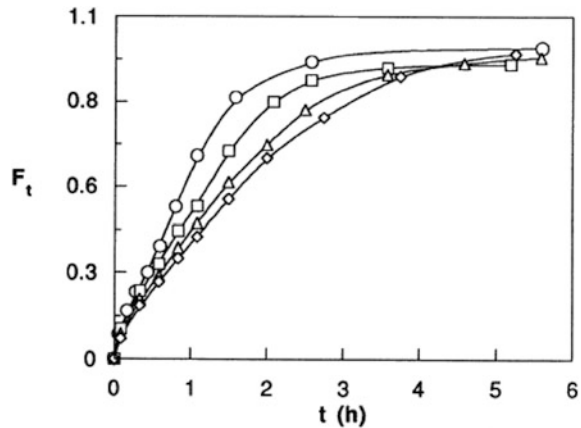

Fig. 11 Swelling ratio of PAA in media of different pH values as function of time

Fig. 12 Fractional release
profiles of theophylline at
310 ± 0.2 K from
glassy poly(acrylic
acid-co-acrylamide)
(50/50%)/MBAAm gels in
water: (○) (0.67%)
MBAAm, (□) (1.00%)
MBAAm, (△) (1.25%)
MBAAm, (◇) (1.50%)
MBAAm

to be used in drug control release in medical and water treatment applications. Theophylline release from P(AA-co-AAm) hydrogel in distilled water indicated that low release rate related with samples of high degree of cross-linking as illustrated in Fig. 12 (Katime et al. 1999).

4.3 Mechanical Properties SPGs

Applications of SPGs are limited in some areas because of their poor mechanical properties (Tanaka et al. 2005). Mechanical properties of SPG are very important in applications such as drug delivery system and agriculture when the hydrogel has to withstand certain pressure in deep placement process (Omidian et al. 2005). There are some methods such as increasing the cross-linking density, copolymerizing of two kinds of polymer, and grafting with rigid substrates used to enhance mechanical properties of polymer gels in general (Cauich-Rodriguez et al. 1996; Katime et al. 2001). Mechanical properties of SPG can be controlled by changing system cross-linking degree. High cross-linking degree leads to more brittle and stronger network structure. Therefore, to achieve a relatively strong and elastic property network, suitable cross-linking degree has to be optimized. Also, mechanical properties are affected by the main monomers used to synthesize SPGs which means copolymerization of two types of repeating unit (hydrophilic–hydrophobic) (Katime et al. 2001; Patachia et al. 2007). The structural strength of polymer gels can be enhance by introducing a comonomer to the main networks which contribute to new hydrogen bonding and stable network structure (Solpan et al. 2003; Peppas et al. 2000). Mechanical properties are improved using nanomaterials, such as inorganic nanoclay and carbon nanotubes to produce nanocomposites network structure (Xiang et al. 2006; Pourjavadi et al. 2007a).

5   Application of Smart Polymer Gels

Unique properties of PGs such as absorption, swelling and de-swelling behavior, hydrophobicity, biocompatibility, and sensitivity to environmental change are the main reason for its wide applications. Homopolymer and copolymer of PGs have been used in various applications in our daily life such as agricultural, biomedical, water treatment, and other industrial applications (Katime et al. 1999, 2004; Liang et al. 2009; Solpan et al. 2008; Shukla et al. 2009; Zhao et al. 2004; M'Bareck et al. 2006; Devine et al. 2006; Nho et al. 2004; Hoffman 2002).

5.1   Biomedical Application

SPGs materials have wide application in biomedical and pharmaceutical because of their desirable properties such as minimal interfacial tension with surrounding biological fluids, gas permeation, diffusion of low molecular weight, less mechanical, and friction irritation to tissue (Cauich-Rodriguez et al. 1996). One of the difficulties biomedical experts are facing nowadays is how to deliver such a drug completely to particular place in the human body. Experts used a system called drug delivery system to manage release and deliver drug to specific positions (Wang et al. 2010; Blanco et al. 1996; Lukowski et al. 1992; Miao et al. 2010; Kakoulides et al. 1998; Kamath and Park 2010; Gong et al. 2009; Kaetsu 1996; Miyata et al. 2002; Geever et al. 2008; Nam et al. 2004; El-Hag et al. 2009; Bhattarai et al. 2010; Adnadjevic and Jovanovic 2009; Li et al. 2009; Cheddadi et al. 2011; Tu et al. 2010). SPGs of thermosensitive and pH sensitive are wildly used in medical application as drug delivery system because of their sensitivity to pH and temperature of human body. Many monomer and polymer were used in this kind of application but the most used are PAA and PAAm and their copolymers. PAA grafted with *n*-alkyl methacrylate was prepared to study swelling and release kinetics of theophylline and aminophylline. This study indicated that the release of theophylline is fairly independent of alkyl chain length while the release of aminophylline is highly dependent on alkyl chain length (Katime et al. 2001). Copolymer of P(AA-co-AAm) hydrogel was used for theophylline release in distilled water (Katime et al. 1999). SPG based of PAA filled with cotton fiber was synthesized for gentamicin release. The outcome of this study showed the release of drug from the grafted network is a chain relaxation controlled manner (Bajpai and Das 2011). SPG of PAA grafted with gelatin (Ge) and cotton fiber was prepared for gentamicin sulfate release (Changez et al. 2003; Bajpai and Das 2011; Changez et al. 2004). The result of these studies regarded to use hydrogel based on PAA to deliver gentamicin sulfate in controlled manner. Loaded gentamicin sulfate showed fair antibacterial action against *Escherichia coli*. Grafted PAA with polyethylene oxide using radiation polymerization was prepared as insulin carrier. This study

indicated that insulin loaded on hydrogel has higher effect on lowering of blood glucose over injection insulin solution (Nho et al. 2004).

SPGs of pH-sensitive material are able to convert chemical energy to mechanical energy as such can serve as actuators or artificial muscles in medical applications. SPGs have also been used in many other biomedical application including diagnostic, therapeutic, and implantable devices such as catheters, biosensors (Pourjavadi et al. 2007b; Adhikari and Majumdar 2004), artificial skin (Devine et al. 2006), and tissue engineering (Kim et al. 2008; Landers et al. 2002).

5.2 Water Treatment Application

Water pollution is considered as one of the most important issues facing humanity these days. Usually, water is polluted by different undesirable ions and dyes. The sources of these contaminants are either industrial or agricultural. Most factories effluents are discarded into water (rivers, lakes, and seas). These ions and dyes change the biological system of rivers and lakes and affect life of several kinds of species. Wastewater has been treated using several methods such as biological treatment, chemical precipitation, supercritical water oxidation, steam-stripping, microwave radiation, ion exchange, and absorption methods. Absorption method gets high attention because of its low energy consumption and easy operation (Zheng and Wang 2009). Therefore, using the ability of such material to absorb and separate particular ions or dyes from solution can be helpful (Guilherme et al. 2007; Paulino et al. 2007). SPGs have been used in this felid for past forty years. Some researchers studied AC of copolymer of PAA-PAAm-polysaccharide to methylene blue (MB) from water. The result showed good AC of this copolymer and excellent methylene blue removal (48 mg of dye per 1 g of SAP) (Paulino et al. 2006). In another study, SPGs of PAA grafted with chitosan was prepared for ammonium removal applications. This study indicated that PGs have high absorption capacity of 30 mg/g ammonium nitrogen in a wide pH range of 4–9 (Zheng et al. 2009). In another work, grafted PAA/chitosan/vermiculite gels were synthesized for adsorption of methylene blue from water. The results showed that grafted hydrogel has high adsorption for MB dye and suggested that it has the potential as adsorbent for cationic dye removal from wastewater (Liu et al.). Many other SPGs based on PAA copolymer were synthesized and absorption of cationic dyes such as methylene blue, safranine-O (SO), magenta (M), Janus Green B (JGB), and ions such as lead (Pb^{+2}), cadmium (Cd^{+2}), copper (Cu^{+2}), (Ni^{+2}), iron (Fe^{+3}), (Mn^{+2}) were studied (Solpan et al. 2008; Xiong et al. 2009; Zheng et al. 2010; Duran et al. 1999; Li et al. 2011; Kangwansupamonkon et al. 2010; Dai et al. 2011; Zheng et al. 2011; El-Hag et al. 2003; Wei et al. 2009; Shirsath et al. 2011).

6   Conclusion

SPGs are polymer gels that response to the surrounding environmental change in their swollen and dry state. Conventional polymerization techniques were used to syntheses and prepare SPGs such as solution, suspension, emulsion, and radiation polymerization. Solution polymerization is the most widely used technique because of its advantage of pure product (free of surfactants and other contaminants). SPGs are classified depended on their sensitivity to thermo, pH, electric, magnetic, and sound-sensitive gels. Swelling, release, and mechanical properties are the most important criteria to select the correct SPGs for particular application. SPGs properties are affected by initiator content, cross-linker kind and content, chemical composition of polymer network, fiber content pH, and ion concentration of surrounding medium. SPGs properties granted these materials very wide applications in biomedical and water treatment.

References

Abd El-Rehim, HA, Hegazy ESA, Abd El-Mohdy HL (2006) Effect of various environmental conditions on the swelling property of PAAm/PAAcK superabsorbent hydrogel prepared by ionizing radiation. J Appl Polym Sci 101:3955–3962

Adem E, Burillo G, Bucio E, Magaña C, Avalos-Borja M (2009) Characterization of interpenetrating networks of acrylic acid (AAc) and N-isopropylacrylamide (NIPAAm) synthesized by ionizing radiation. Radiat Phys Chem 78:549–552

Adhikari B, Majumdar S (2004) Polymers in sensor applications. Prog Polym Sci 29:699–766

Adnadjevic B, Jovanovic J (2009) A comparative kinetics study of isothermal DRUG release from poly(acrylic acid) and poly(acrylic-co-methacrylic acid) hydrogels. Colloids Surf B 69:31–42

Alemzadeh I, Vossoughi M (2002) Controlled release of paraquat from poly vinyl alcohol hydrogel. Chem Eng Process 41:707–710

Ali AE, Shawky HA, El Rehim HA, Hegazy EA (2003) Synthesis and characterization of PVP/AAc copolymer hydrogel and its applications in the removal of heavy metals from aqueous solution. Eur Polym J 39:2337–2344

Bajpai SK, Das P (2011) Gentamicin-loaded poly(acrylic acid)-grafted cotton fibers, part 1: synthesis, characterization, and preliminary drug release study. J Appl Polym Sci 122:366–374

Berndt I, Pedersen JS, Richtering W (2006) Temperature-sensitive core-shell microgel particles with dense shell. Angew Chem 118:1769–1773

Bhattarai N, Gunn J, Zhang M (2010) Chitosan-based hydrogels for controlled, localized drug delivery. Adv Drug Delivery Rev 62:83–99

Blackburn W, Lyon LA (2008) Size-controlled synthesis of monodisperse core/shell nanogels. Colloid Polym Sci 286:563–569

Blanco MD, García O, Trigo RM, Teijón J, Katime I (1996) 5-Fluorouracil release from copolymeric hydrogels of itaconic acid monoester: I. Acrylamide-co-monomethyl itaconate. Biomaterials 17:1061–1067

Bonakdar S, Emami SH, Shokrgozar MA, Farhadi A, Ahmadi SA, Amanzadeh A (2010) Preparation and characterization of polyvinyl alcohol hydrogels crosslinked by biodegradable polyurethane for tissue engineering of cartilage. Mater Sci Eng C 30:636–643

Cauich-Rodriguez JV, Deb S, Smith R (1996) Effect of cross-linking agents on the dynamic mechanical properties of hydrogel blends of poly(acrylic acid)-poly(vinyl alcohol-vinyl acetate). Biomaterials 17:2259–2264

Changez M, Burugapalli K, Koul V, Choudhary V (2003) The effect of composition of poly (acrylic acid)-gelatin hydrogel on gentamicin sulphate release: in vitro. Biomaterials 24:527–536

Changez M, Koul V, Krishna B, Dinda AK, Choudhary V (2004) Studies on biodegradation and release of gentamicin sulphate from interpenetrating network hydrogels based on poly(acrylic acid) and gelatin: in vitro and in vivo. Biomaterials 25:139–146

Cheddadi M, López-Cabarcos E, Slowing K, Barcia E, Fernández-Carballido A (2011). Cytotoxicity and biocompatibility evaluation of a poly(magnesium acrylate) hydrogel synthesized for drug delivery. Int J Pharm 413:126-133

Chen J, Liu M, Liu H, Ma L (2009) Synthesis, swelling and drug release behavior of poly(N, N-diethylacrylamide-co-N-hydroxymethyl acrylamide) hydrogel. Mater Sci Eng, C 29:2116–2123

Chun KW, Lee JB, Kim SH, Park TG (2005) Controlled release of plasmid DNA from photo-cross-linked pluronic hydrogels. Biomaterials 26:3319–3326

Chun C, Lee SM, Kim SY, Yang HK, Song S-C (2009) Thermosensitive poly(organophosphazene)-paclitaxel conjugate gels for antitumor applications. Biomaterials 30:2349–2360

Dai J, Yan H, Yang H, Cheng R. (2011) Simple method for preparation of chitosan/poly(acrylic acid) blending hydrogel beads and adsorption of copper(II) from aqueous solutions. Chem Eng J 165:240–249

Dall W, Sharples DJ (1991) References. Advances in marine biology. Academic Press

Desrosiers G, Savenkoff C, Olivier M, Stora G, Juniper K, Caron A, Gagne JP, Legendre L, Mulsow S, Grant J, Roy S, Grehan A, Scaps P, Silverberg N, Klein B, Tremblay JE, Therriault JC (2000) Trophic structure of macrobenthos in the Gulf of St. Lawrence and on the Scotian Shelf. Deep-Sea Res Part Ii-Topical Stud Oceanogr 47:663–697

Devine DM, Devery SM, Lyons JG, Geever LM, Kennedy JE, Higginbotham CL (2006) Multifunctional polyvinylpyrrolidinone-polyacrylic acid copolymer hydrogels for biomedical applications. Int J Pharm 326:50–59

Dimonie VL, Daniels ES, Shaffer OL, El-Aasser MS (1997) Control of particle morphology. In: Lovell P, El-Aasser MS (eds) Emulsion polymerization and emulsion polymers. Wiley, West Sussex, England

D'Ulivo A (2004) Chemical vapor generation by tetrahydroborate(III) and other borane complexes in aqueous media: a critical discussion of fundamental processes and mechanisms involved in reagent decomposition and hydride formation. Spectrochim Acta, Part B 59:793–825

Duran S, Solpan D, Güven O (1999) Synthesis and characterization of acrylamide-acrylic acid hydrogels and adsorption of some textile dyes. Nucl Instrum Methods Phys Res, Sect B 151:196–199

El Bakouri H, Aassiri A, Morillo J, Usero J, Khaddor M, Ouassini A (2008) Pesticides and lipids occurrence in Tangier agricultural soil (northern Morocco). Appl Geochem 23:3487–3497

El-hag Ali A, Alarifi A (2009) Characterization and in vitro evaluation of starch based hydrogels as carriers for colon specific drug delivery systems. Carbohydr Polym

Elliott JE, Bowman CN (2002) Effects of solvent quality during polymerization on network structure of cross-linked methacrylate copolymers. J Phys Chem B 106:2843–2847

Fundueanu G, Mocanu G, Constantin M, Carpov A, Bulacovschi V, Esposito E, Nastruzzi C (2001) Acrylic microspheres for oral controlled release of the biguanide buformin. Int J Pharm 218:13–25

Geever LM, Cooney CC, Lyons JG, Kennedy JE, Nugent MJD, Devery S, Higginbotham CL (2008) Characterisation and controlled drug release from novel drug-loaded hydrogels. Eur J Pharm Biopharm 69:1147–1159

Gong C, Shi S, Wu L, Gou M, Yin Q, Guo Q, Dong P, Zhang F, Luo F, Zhao X, Wei Y, Qian Z (2009) Biodegradable in situ gel-forming controlled drug delivery system based on thermosensitive PCL-PEG-PCL hydrogel. Part 2: Sol-gel-sol transition and drug delivery behavior. Acta Biomaterialia, In Press, Corrected Proof

Guilherme MR, Reis AV, Takahashi SH, Rubira AF, Feitosa JPA, Muniz EC (2005) Synthesis of a novel superabsorbent hydrogel by copolymerization of acrylamide and cashew gum modified with glycidyl methacrylate. Carbohyd Polym 61:464–471

Guilherme MR, Reis AV, Paulino AT, Fajardo AR, Muniz EC, Tambourgi EB (2007) Superabsorbent hydrogel based on modified polysaccharide for removal of Pb2 + and Cu2 + from water with excellent performance. J Appl Polym Sci 105:2903–2909

Ha J-W, Park IJ, Lee S-B, Kim D-K (2002) Preparation and characterization of core–shell particles containing perfluoroalkyl acrylate in the Shell. Macromolecules 35:6811–6818

Hamidi M, Azadi A, Rafiei P (2008) Hydrogel nanoparticles in drug delivery. Adv Drug Deliv Rev 60:1638–1649

Hendrickson GR, Smith MH, South AB, Lyon LA (2010) Design of multiresponsive hydrogel particles and assemblies. Adv Func Mater 20:1697–1712

Hoffman AS (2002) Hydrogels for biomedical applications. Adv Drug Deliv Rev 54:3–12

Hongyan He MS (2006) Multifunctional medical device based on PH-sensitive hydrogels for controlled drug delivery. PhD, Ohio State University

Huynh DP, Im GJ, Chae SY, Lee KC, Lee DS (2009) Controlled release of insulin from pH/temperature-sensitive injectable pentablock copolymer hydrogel. J Controlled Release 137:20–24

Issa R, Akelah A, Rehab A, Solaro R, Chiellini E (1990) Controlled release of herbicides bound to poly[oligo(oxyethylene) methacrylate] hydrogels. J Controlled Release 13:1–10

Jones CD, Lyon LA (2003) Shell-restricted swelling and core compression in poly (N-isopropylacrylamide) core–shell microgels. Macromolecules 36:1988–1993

Kabiri K, Omidian H, Zohuriaan-Mehr MJ, Doroudiani S (2011) Superabsorbent hydrogel composites and nanocomposites: a review. Polym Compos 32:277–289

Kadlubowski S, Henke A, Ulanski P, Rosiak JM, Bromberg L, Hatton TA (2007) Hydrogels of polyvinylpyrrolidone (PVP) and poly(acrylic acid) (PAA) synthesized by photoinduced crosslinking of homopolymers. Polymer 48:4974–4981

Kaetsu I (1996) Biomedical materials, devices and drug delivery systems by radiation techniques. Radiat Phys Chem 47:419–424

Kakoulides EP, Smart JD, Tsibouklis J (1998) Azocross-linked poly(acrylic acid) for colonic delivery and adhesion specificity: synthesis and characterisation. J Controlled Release 52: 291–300

Kangwansupamonkon W, Jitbunpot W, Kiatkamjornwong S (2010) Photocatalytic efficiency of TiO2/poly[acrylamide-co-(acrylic acid)] composite for textile dye degradation. Polym Degradation Stability 95:1894–1902

Karadag E, Üzüm ÖB, Saraydin D, Güven O (2005) Dynamic swelling behavior of [gamma]-radiation induced polyelectrolyte poly(AAm-co-CA) hydrogels in urea solutions. Int J Pharm 301:102–111

Karppi J, Akerman S, Akerman K, Sundell A, Nyyssönen K, Penttilä I (2007) Isolation of drugs from biological fluids by using pH sensitive poly(acrylic acid) grafted poly(vinylidene fluoride) polymer membrane in vitro. Eur J Pharm Biopharm 67:562–568

Karppi J, Akerman S, Akerman K, Sundell A, Nyyssönen K, Penttilä I (2008) Erratum to "Isolation of drugs from biological fluids by using pH sensitive poly(acrylic acid) grafted poly (vinylidene fluoride) polymer membrane in vitro". Eur J Pharm Biopharm 68:847–850 (Eur J Pharm Biopharm 67:562–568 (2007))

Katime I, Novoa R, Díaz de Apodaca E, Mendizábal E, Puig J (1999) Theophylline release from poly(acrylic acid-co-acrylamide) hydrogels. Polym Testing 18:559–566

Katime I, Novoa R, Zuluaga F (2001) Swelling kinetics and release studies of theophylline and aminophylline from acrylic acid/n-alkyl methacrylate hydrogels. Eur Polym J 37:1465–1471

Katime I, Novoa R, De Apodaca ED, Rodriì Guez E (2004) Release of theophylline and aminophylline from acrylic acid/n-alkyl methacrylate hydrogels. J Polym Sci, Part A: Polym Chem 42:2756–2765

Khan AK, Ray BC, Dolui SK (2008) Preparation of core-shell emulsion polymer and optimization of shell composition with respect to opacity of paint film. Prog Org Coat 62:65–70

Kim K-S, Park S-J (2010) Effect of porous silica on sustained release behaviors of pH sensitive Pluronic F127/poly(acrylic acid) hydrogels containing tulobuterol. Colloids Surf B 80:240–246

Kim B, Peppas NA (2003) In vitro release behavior and stability of insulin in complexation hydrogels as oral drug delivery carriers. Int J Pharm 266:29–37

Kim SJ, Yoon SG, Lee YM, Kim SI (2003) Electrical sensitive behavior of poly(vinyl alcohol)/ poly (diallyldimethylammonium chloride) IPN hydrogel. Sens Actuators B: Chem 88:286–291

Kim J, Lee KW, Hefferan TE, Currier BL, Yaszemski MJ, Lu L (2008) Synthesis and evaluation of novel biodegradable hydrogels based on poly(ethylene glycol) and sebacic acid as tissue engineering scaffolds. Biomacromol 9:149–157

Landers R, Hübner U, Schmelzeisen R, Mülhaupt R (2002) Rapid prototyping of scaffolds derived from thermoreversible hydrogels and tailored for applications in tissue engineering. Biomaterials 23:4437–4447

Lee W-F, Chen Y-C (2006) Effects of intercalated hydrotalcite on drug release behavior for poly (acrylic acid-co-N-isopropyl acrylamide)/intercalated hydrotalcite hydrogels. Eur Polym J 42:1634–1642

Lee C-F, Lin C-C, Chien C-A, Chiu W-Y (2008) Thermosensitive and control release behavior of poly(N-isopropylacrylamide-co-acrylic acid)/nano-Fe3O4 magnetic composite latex particle that is synthesized by a novel method. Eur Polymer J 44:2768–2776

Li W-H, Stöver HDH (2000) Monodisperse cross-linked core–shell polymer microspheres by precipitation polymerization. Macromolecules 33:4354–4360

Li A, Wang A (2005) Synthesis and properties of clay-based superabsorbent composite. Eur Polym J 41:1630–1637

Li D, Omalley BW, Paulson D (2009) Composition for controlled release delivery for treating otorhinolaryngology—and head and neck-associated pathologies e.g. allergy and laryngology comprises Chitosan-glycerophosphate hydrogel, and agent for treatment of the pathologies

Li S, Zhang H, Feng J, Xu R, Liu X (2011) Facile preparation of poly(acrylic acid-acrylamide) hydrogels by frontal polymerization and their use in removal of cationic dyes from aqueous solution. Desalination, In Press, Corrected Proof

Liang R, Yuan H, Xi G, Zhou Q (2009) Synthesis of wheat straw-g-poly(acrylic acid) superabsorbent composites and release of urea from it. Carbohyd Polym 77:181–187

Lin J, Tang Q, Wu J (2007) The synthesis and electrical conductivity of a polyacrylamide/Cu conducting hydrogel. React Funct Polym 67:489–494

Liu MZ, Liang R, Zhan F, Liu Z, Niu AZ (2006) Synthesis of a slow-release and superabsorbent nitrogen fertilizer and its properties. Polym Adv Technol 17:430–438

Lukowski G, Müller RH, Müller BW, Dittgen M (1992) Acrylic acid copolymer nanoparticles for drug delivery: I. Characterization of the surface properties relevant for in vivo organ distribution. Int J Pharm 84:23–31

Mahdavinia GR, Pourjavadi A, Zohuriaan-Mehr MJ (2008) Synthesis and properties of highly swelling PAAm/chitosan semi-IPN hydrogels. Macromolecular Symposia 274:171–176

M'Bareck CO, Nguyen QT, Alexandre S, Zimmerlin I (2006) Fabrication of ion-exchange ultrafiltration membranes for water treatment: I. Semi-interpenetrating polymer networks of polysulfone and poly(acrylic acid). J Membr Sci 278:10–18

Miao Q, Xu D, Wang Z, Xu L, Wang T, Wu Y, Lovejoy DB, Kalinowski DS, Richardson DR, Nie G, Zhao Y (2010) Amphiphilic hyper-branched co-polymer nanoparticles for the controlled delivery of anti-tumor agents. Biomaterials 31:7364–7375

Miyata T, Uragami T, Nakamae K (2002) Biomolecule-sensitive hydrogels. Adv Drug Deliv Rev 54:79–98

Munshi SK, Singh R, Vij VK, Jawanda JS (1978) Mineral composition of leaves in relation to degree of granulation in sweet orange. Sci Hortic 9:357–367

Nam K, Watanabe J, Ishihara K (2004) The characteristics of spontaneously forming physically cross-linked hydrogels composed of two water-soluble phospholipid polymers for oral drug delivery carrier I: hydrogel dissolution and insulin release under neutral pH condition. Eur J Pharm Sci 23:261–270

Nho YC, Mook Lim Y, Moo Lee Y (2004) Preparation, properties and biological application of pH-sensitive poly(ethylene oxide) (PEO) hydrogels grafted with acrylic acid(AAc) using gamma-ray irradiation. Radiat Phys Chem 71:239–242

Omidian H, Rocca JG, Park K (2005) Advances in superporous hydrogels. J Controlled Release 102:3–12

Patachia S, Valente AJM, Baciu C (2007) Effect of non-associated electrolyte solutions on the behaviour of poly(vinyl alcohol)-based hydrogels. Eur Polym J 43:460–467

Paulino AT, Guilherme MR, Reis AV, Campese GM, Muniz EC, Nozaki J (2006) Removal of methylene blue dye from an aqueous media using superabsorbent hydrogel supported on modified polysaccharide. J Colloid Interface Sci 301:55–62

Paulino AT, Guilherme MR, Reis AV, Tambourgi EB, Nozaki J, Muniz EC (2007) Capacity of adsorption of $Pb2+$ and $Ni2+$ from aqueous solutions by chitosan produced from silkworm chrysalides in different degrees of deacetylation. J Hazard Mater 147:139–147

Peppas NA, Bures P, Leobandung W, Ichikawa H (2000) Hydrogels in pharmaceutical formulations. Eur J Pharm Biopharm 50:27–46

Pourjavadi A, Harzandi AM, Hosseinzadeh H (2004) Modified carrageenan 3. Synthesis of a novel polysaccharide-based superabsorbent hydrogel via graft copolymerization of acrylic acid onto kappa-carrageenan in air. Eur Polym J 40:1363–1370

Pourjavadi A, Hosseinzadeh H, Mahdavinia GR, Zohuriaan-Mehr MJ (2007a) Carrageenan-g-poly (sodium acrylate)/kaolin superabsorbent hydrogel composites: synthesis, characterisation and swelling behaviour. Polym Polym Compos 15:43–51

Pourjavadi A, Hosseinzadeh H, Sadeghi M (2007b) Synthesis, characterization and swelling behavior of gelatin-g-poly(sodium acrylate)/kaolin superabsorbent hydrogel composites. J Compos Mater 41:2057–2069

Qiu Y, Park K (2001) Environment-sensitive hydrogels for drug delivery. Adv Drug Deliv Rev 53:321–339

Raj Singh TR, Mccarron PA, Woolfson AD, Donnelly RF (2009) Investigation of swelling and network parameters of poly(ethylene glycol)-crosslinked poly(methyl vinyl ether-co-maleic acid) hydrogels. Eur Polym J 45:1239–1249

Ren JL, Sun RC (2010) Hemicelluloses. Cereal straw as a resource for sustainable biomaterials and biofuels. Elsevier, Amsterdam

Sahoo A, Ramasubramani KRT, Jassal M, Agrawal AK (2007) Effect of copolymer architecture on the response of pH sensitive fibers based on acrylonitrile and acrylic acid. Eur Polym J 43:1065–1076

Sasa N, Yamaoka T (1994) Surface-activated photopolymer microgels. Adv Mater 6:417–421

Schild HG (1992) Poly(N-isopropylacrylamide): experiment, theory and application. Progress Polym Sci 17:163–249

Seoudi R (2008) Effect of polyvinyl alcohol molecular weight and UV-photoactivation on the size of gold nanoparticle. Physica B 403:4236–4240

Shah CP, Singh KK, Kumar M, Bajaj PN (2010) Vinyl monomers-induced synthesis of polyvinyl alcohol-stabilized selenium nanoparticles. Mater Res Bull 45:56–62

Sheikh N, Jalili L, Anvari F (2010) A study on the swelling behavior of poly(acrylic acid) hydrogels obtained by electron beam crosslinking. Radiat Phys Chem 79:735–739

Shirsath SR, Hage AP, Zhou M, Sonawane SH, Ashokkumar M (2011) Ultrasound assisted preparation of nanoclay Bentonite-FeCo nanocomposite hybrid hydrogel: a potential responsive sorbent for removal of organic pollutant from water. Desalination

Shukla NB, Daraboina N, Madras G (2009) Oxidative and photooxidative degradation of poly (acrylic acid). Polym Degrad Stab 94:1238–1244

Siemoneit U, Schmitt C, Alvarez-Lorenzo C, Luzardo A, Otero-Espinar F, Concheiro A, Blanco-Méndez J (2006) Acrylic/cyclodextrin hydrogels with enhanced drug loading and sustained release capability. Int J Pharm 312:66–74

Singh B, Chauhan GS, Kumar S, Chauhan N (2007) Synthesis, characterization and swelling responses of pH sensitive psyllium and polyacrylamide based hydrogels for the use in drug delivery (I). Carbohyd Polym 67:190–200

Solpan D, Duran S, Saraydin D, Güven O (2003) Adsorption of methyl violet in aqueous solutions by poly(acrylamide-co-acrylic acid) hydrogels. Radiat Phys Chem 66:117–127

Solpan D, Duran S, Torun M (2008) Removal of cationic dyes by poly(acrylamide-co-acrylic acid) hydrogels in aqueous solutions. Radiat Phys Chem 77:447–452

Tada D, Tanabe T, Tachibana A, Yamauchi K (2005) Drug release from hydrogel containing albumin as crosslinker. J Biosci Bioeng 100:551–555

Talpur FN, Bhanger MI, Memon NN (2009) Milk fatty acid composition of indigenous goat and ewe breeds from Sindh, Pakistan. J Food Compos Anal 22:59–64

Tanaka Y, Gong JP, Osada Y (2005) Novel hydrogels with excellent mechanical performance. Prog Polym Sci 30:1–9

Tang Q, Wu J, Sun H, Fan S, Hu D, Lin J (2008) Superabsorbent conducting hydrogel from poly (acrylamide-aniline) with thermo-sensitivity and release properties. Carbohyd Polym 73:473–481

Thakur VK, Thakur MK (2014a) Recent trends in hydrogels based on psyllium polysaccharide: a review. J Clean Prod 82:1–15

Thakur VK, Thakur MK (2014b) Recent advances in graft copolymerization and applications of Chitosan: a review. ACS Sustain Chem Eng 2(12):2637–2652

Thakur VK, Thakur MK (2015) Recent advances in green hydrogels from lignin: a review. Int J Biol Macromol 72:834–847

Tomic SL, Micic MM, Filipovic JM, Suljovrujic EH (2007) Swelling and drug release behavior of poly(2-hydroxyethyl methacrylate/itaconic acid) copolymeric hydrogels obtained by gamma irradiation. Radiat Phys Chem 76:801–810

Tu H, Qu Y, Hu X, Yin Y, Zheng H, Xu P, Xiong F (2010) Study of the sigmoidal swelling kinetics of carboxymethylchitosan-g-poly(acrylic acid) hydrogels intended for colon-specific drug delivery. Carbohydr Polym 82:440–445

Turkington AV, Paradise TR (2005) Sandstone weathering: a century of research and innovation. Geomorphology 67:229–253

Uchida R, Sato T, Tanigawa H, Uno K (2003) Azulene incorporation and release by hydrogel containing methacrylamide propyltrimenthylammonium chloride, and its application to soft contact lens. J Controlled Release 92:259–264

Varshosaz J, Falamarzian M (2001) Drug diffusion mechanism through pH-sensitive hydrophobic/ polyelectrolyte hydrogel membranes. Eur J Pharm Biopharm 51:235–240

Vital SA, Fowler RW, Virgen A, Gossett DR, Banks SW, Rodriguez J (2008) Opposing roles for superoxide and nitric oxide in the NaCl stress-induced upregulation of antioxidant enzyme activity in cotton callus tissue. Environ Exp Bot 62:60–68

Wang B, Xu X-D, Wang Z-C, Cheng S-X, Zhang X-Z, Zhuo R-X (2008) Synthesis and properties of pH and temperature sensitive P(NIPAAm-co-DMAEMA) hydrogels. Colloids Surf B 64:34–41

Wang Q, Xie X, Zhang X, Zhang J, Wang A (2010). Preparation and swelling properties of pH-sensitive composite hydrogel beads based on chitosan-g-poly (acrylic acid)/vermiculite and sodium alginate for diclofenac controlled release. Int J Biol Macromol 46:356–362

Wei Q, Li J, Qian B, Fang B, Zhao C (2009) Preparation, characterization and application of functional polyethersulfone membranes blended with poly (acrylic acid) gels. J Membr Sci 337:266–273

Xiang Y, Peng Z, Chen D (2006) A new polymer/clay nano-composite hydrogel with improved response rate and tensile mechanical properties. Eur Polym J 42:2125–2132

Xiong Z, Chen H, Xu LA, Zhang LF, Xiong CD, Huang X (2007) Preparation and properties of thermo-sensitive hydrogels of konjac glucomannan grafted *N*-isopropylacrylamide for controlled drug delivery. Iran Polym J 6:425–431

Xiong C, Yao C, Wang L, Ke J (2009) Adsorption behavior of Cd(II) from aqueous solutions onto gel-type weak acid resin. Hydrometallurgy 98:318–324

Yadvinder S, Bijay S, Timsina J, Donald LS (2005) Crop residue management for nutrient cycling and improving soil productivity in rice-based cropping systems in the tropics. Advances in agronomy. Academic Press

Yang C-C, Lin S-J, Hsu S-T (2003) Synthesis and characterization of alkaline polyvinyl alcohol and poly(epichlorohydrin) blend polymer electrolytes and performance in electrochemical cells. J Power Sources 122:210–218

Yang S, Li J, Shao D, Hu J, Wang X (2009) Adsorption of Ni(II) on oxidized multi-walled carbon nanotubes: effect of contact time, pH, foreign ions and PAA. J Hazard Mater 166:109–116

Yoo MK, Sung YK, Lee YM, Cho CS (2000) Effect of polyelectrolyte on the lower critical solution temperature of poly(N-isopropyl acrylamide) in the poly(NIPAAm-co-acrylic acid) hydrogel. Polymer 41:5713–5719

Zhang JT, Cheng SX, Huang SW, Zhuo RX (2003) Temperature-sensitive poly (N-isopropylacrylamide) hydrogels with macroporous structure and fast response rate. Macromol Rapid Commun 24:447–451

Zhang X, Wu D, Chu CCC-C (2004) Synthesis and characterization of partially biodegradable, temperature and pH sensitive Dex-MA/PNIPAAm hydrogels. Biomaterials 25:4719–4730

Zhang YT, Fan LH, Zhi TT, Zhang L, Huang H, Chen HL (2009) Synthesis and characterization of poly(acrylic acid-co-acrylamide)/hydrotalcite nanocomposite hydrogels for carbonic anhydrase immobilization. J Polym Sci Part A Polym Chem 47:3232–3240

Zhao H, Li J, Jiang L (2004) Inhibition of HIV-1 TAR RNA-Tat peptide complexation using poly (acrylic acid). Biochem Biophys Res Commun 320:95–99

Zheng Y, Wang A (2009) Evaluation of ammonium removal using a chitosan-g-poly (acrylic acid)/rectorite hydrogel composite. J Hazard Mater

Zheng Y, Hua S, Wang A (2010) Adsorption behavior of Cu2 + from aqueous solutions onto starch-g-poly(acrylic acid)/sodium humate hydrogels. Desalination 263:170–175

Zheng Y, Huang D, Wang A (2011) Chitosan-g-poly(acrylic acid) hydrogel with crosslinked polymeric networks for Ni2 + recovery. Analytica Chimica Acta 687:193–200