

# A Versatile Approach to Develop Porous Hydrogels with a Regular Pore Distribution and Investigation of their Physicomechanical Properties

Volodymyr Samaryk,<sup>1</sup> Andriy Voronov,<sup>2</sup> Ihor Tarnavchyk,<sup>1</sup> Ananiy Kohut,<sup>2</sup>  
Natalya Nosova,<sup>1</sup> Serhiy Varvarenko,<sup>1</sup> Stanislav Voronov<sup>1</sup>

<sup>1</sup>Department of Organic Chemistry, Lviv Polytechnic National University, Lviv 79013, Ukraine

<sup>2</sup>Department of Coatings and Polymeric Materials, North Dakota State University, Fargo, North Dakota 58108-6050

Received 9 January 2009; accepted 19 March 2009

DOI 10.1002/app.30426

Published online 2 July 2009 in Wiley InterScience (www.interscience.wiley.com).

**ABSTRACT:** Porous polyacrylamide (PAAm) hydrogels with enhanced mechanical properties and regular pore distribution have been synthesized by a unique and facile methodology, which involves formation of the hydrogel pores by leaching out chemically modified silica particles. To improve the pore distribution and mechanical properties of the hydrogel network, porogen particles have been modified with PAAm chains chemically attached to the silica surface. Grafting polymerization initiated by peroxide groups immobilized on the particle surface has been used for this modification. The grafted PAAm layer on the silica surface improves the dispersibility of the porogen material in the hydrogel composition, and simultaneously forms pore "walls" reinforcing the hydrogel network, after leaching out the silica particles. The proposed synthetic way for the development of porous

hydrogels includes three steps: (i) tethering of PAAm chains to silica particles due to the grafting polymerization initiated by an adsorbed polyperoxide macroinitiator (PPM), (ii) simultaneous crosslinking of grafted PAAm chains and PAAm forming hydrogel network, and (iii) pore formation by leaching out silica particles in the presence of hydrofluoric acid. The PPM has been synthesized by a free radical copolymerization of the peroxide monomer (PM) *N*-(*tert*-butylperoxymethyl)acrylamide with acrylamide. Both PM and PPM have been developed in our lab, and applied for the synthesis of porous polymeric hydrogels. © 2009 Wiley Periodicals, Inc. *J Appl Polym Sci* 114: 2204–2212, 2009

**Key words:** porous hydrogel; polyperoxide macroinitiator; peroxide monomer; grafting from

## INTRODUCTION

Porous polymeric hydrogels have received much attention, because of their potential applications in medicine, biology, tissue engineering, etc.<sup>1–3</sup> Porous hydrogels have numerous pores inside them, and the typical pore sizes are from 10–100 nm (microporous hydrogels) to 0.1–10  $\mu\text{m}$  (macroporous hydrogels).<sup>4</sup> These unique structures give them distinctive properties from the traditional nonporous hydrogels. Porous hydrogels swell fast to the equilibrium swollen state.<sup>1</sup> The fast swelling property is based on water absorption through the porous structure by diffusion and capillary forces.<sup>1</sup>

The porous hydrogels are prepared using several techniques, such as, freeze-drying,<sup>5</sup> microemulsion formation,<sup>6</sup> phase separation,<sup>7</sup> and gas blowing.<sup>8</sup> On the other hand, porous hydrogels are often prepared utilizing a porogenation technique, in which a pore former is subsequently removed from a crosslinked polymer matrix.<sup>9–12</sup> Although these techniques have laid the foundation for generating porous structures for a variety of applications, improvement of pore distribution regularity and mechanical properties of the porous polymeric hydrogels still remains challenging with several factors to be considered.

Radical polymerization initiated from the solid surface of an ultrafine powder ('grafting from' approach) is known to be a suitable technique for the attachment of polymeric macrochains to the particulate surface, which provides colloidal stabilization of the particles in different surroundings.<sup>13</sup> It has been reported that peroxide groups immobilized on the surface of different mineral powders are widely used to initiate free radical polymerization from the solid surface.<sup>13–16</sup> A variety of polymeric<sup>17–19</sup> and low molecular weight peroxides<sup>16,19,20</sup> have been utilized for the initiation of grafting polymerization from the solid particulate surface, which results in the encapsulation of the

Additional Supporting Information may be found in the online version of this article.

Correspondence to: A. Voronov (andrejvoronov@hotmail.com).

Contract grant sponsor: DB Hydrogel, Ukrainian Ministry of Education and Science.

Contract grant sponsor: German Federal Ministry of Education and Research (BMBF); contract grant number: UKR 05/006.

*Journal of Applied Polymer Science*, Vol. 114, 2204–2212 (2009)  
© 2009 Wiley Periodicals, Inc.

powder particles because of the formation of a thin polymer layer on the dispersed surface.<sup>21</sup>

The proposed approach is based on the formation of polyacrylamide (PAAm) hydrogels, with enhanced mechanical properties and regular pore distribution using silica particles with grafted polyacrylamide as a porogen and the subsequent leaching out of the particles.

In this work, porous hydrogels with regular pore distribution and enhanced mechanical properties have been developed from the chemically modified silica particles used as porogen materials. To this effect, a new polyperoxide has been synthesized by free radical copolymerization of a peroxide monomer (PM), *N*-(*tert*-butylperoxymethyl)acrylamide with acrylamide. Recently, we reported<sup>22,23</sup> the successful peroxidation of polypropylene surface, using a polyperoxide based on octyl methacrylate and PM of the same chemical composition. In this study, a new peroxide copolymer has been developed and used for the peroxidation of silica surface, following initiation of grafting polymerization of acrylamide. The grafting results in a thin polyacrylamide layer chemically attached on the silica surface. The grafted compatibilizing layer improves the dispersibility of silica particles in the polyacrylamide hydrogel composition due to the decreasing interfacial tension on the mineral filler–matrix boundary. Thus, it provides an improved distribution of the particles within a hydrogel composition. In addition, after the removal of silica particles from the hydrogel, grafted polyacrylamide chains form a “wall” for each of the pore in the hydrogel network. The presence of the pore “walls” significantly enhances the mechanical strength of the porous hydrogel composition.

We believe that our approach to the development of porous hydrogels formed from biocompatible hydrophilic polymers may find potential applications in areas of biomedical materials, drug delivery, tissue engineering, separation and purification of proteins, etc.

## EXPERIMENTAL

### Materials

Acrylamide and *N*-(hydroxymethyl)acrylamide were purchased from TCI America (Portland, OR) and were used as received. Potassium peroxodisulfate, sodium thiosulfate, hydrofluoric acid, diethyl ether, acetone, formaldehyde solution, and azobisisobutyronitrile (AIBN) (all from Aldrich, St. Louis, MO) were utilized without further purification. *tert*-Butyl hydroperoxide (Alfa Aesar, Wardhill, MA) was dried over magnesium sulfate. Silica (quartz powder with a mean particle size of  $X_{50,3} = 2.65 \mu\text{m}$ , Sigma Aldrich, St. Louis, MO) was used as received.

### Syntheses

#### *N*-(*tert*-butylperoxymethyl)acrylamide (PM)

A solution of *tert*-butyl hydroperoxide (10.8 g, 0.12 mol) in diethyl ether (30 mL) was added dropwise to a suspension of *N*-(hydroxymethyl)acrylamide (10.1 g, 0.1 mol) in diethyl ether (25 mL) at 5–7°C. The mixture was stirred and a solution of H<sub>2</sub>SO<sub>4</sub> (2.94 g, 0.03 mol) in diethyl ether (20 mL) was added for 1 h at 14–16°C. After stirring for additional 3 h at 22–25°C, the organic phase was separated, washed in series with water, 5% aq Na<sub>2</sub>CO<sub>3</sub>, and water until pH 7. The organic phase was dried over MgSO<sub>4</sub> for 12 h, and evaporated under reduced pressure, to give *N*-(*tert*-butylperoxymethyl)acrylamide as a colorless transparent liquid (15.5 g, yield 82%),  $d_4^{20} = 0.991$ ,  $n_D^{20} = 1.451$ ,  $MR_D = 46.35$  (calcd. 45.91),  $M = 168$  (by cryoscopy in benzene, calcd. 173.21),  $[O]_{act} 9.31\%$  (by chromatography of decomposition products, calcd. 9.24%).

#### Polyacrylamide

A solution of acrylamide (100 g) and 2-propanol (10 or 30 g) in water (890 or 870 mL, respectively) was degassed with argon. Then potassium peroxodisulfate (0.108 g) and sodium thiosulfate (0.058 g) are added. The mixture was stirred at 40°C under argon for 3–4 h. Polyacrylamide was isolated by precipitation in acetone and purified by multiple reprecipitation in acetone from aqueous solution. The purified polymer was dried under reduced pressure at room temperature, until a constant weight was obtained. Polyacrylamide with a molecular weight of  $780 \times 10^3$  g/mol was synthesized when 10 g of 2-propanol was added into the reaction mixture. The molecular weight of polyacrylamide was  $130 \times 10^3$  g/mol when the polymerization was conducted with 30 g of isopropyl alcohol.

#### Poly-*N*-(hydroxymethyl)acrylamide

To a solution of polyacrylamide [molecular weight of  $780 \times 10^3$  g/mol (25 g) in water (475 mL)], NaOH (pH 9) and 20% aq formaldehyde (52 mL) were consequently added at 50°C. The reaction mixture was stirred for 2 h at 50°C. The polymer was not isolated and was used as an aqueous solution without further purification.

#### Poly[acrylamide-*co*-*N*-(*tert*-butylperoxymethyl)acrylamide] (polyperoxide macroinitiator)

*N*-(*tert*-Butylperoxymethyl)acrylamide, acrylamide, AIBN, and acetone were weighed into a glass ampoule. The total concentration of the monomers were 1.60M, including 0.24M of the PM and 1.36M of

acrylamide. The concentration of AIBN was 0.014M. The ampoule was degassed with argon, sealed up, and placed into a water bath. The polymerization was carried out at 60°C for 40 min. The copolymer precipitated during the synthesis was filtered off and purified by multiple reprecipitation in acetone from an aqueous solution. The purified copolymer was dried under reduced pressure at room temperature until a constant weight.

#### Peroxidation of silica particles

Silica powder (40 g) and a 1.5% aqueous solution of the polyperoxide macroinitiator (PPM) (140 mL) were agitated at room temperature for 24 h. Silica was isolated by centrifugation, washed three times with distilled water, and dried under reduced pressure until a constant weight.

#### Grafting of polyacrylamide

A 0.33M aqueous solution of acrylamide (160 mL) and the peroxidized silica particles (40 g) were charged into a glass pressure vessel. The vessel was degassed with argon, closed up, and placed into an oil bath. The polymerization was carried out at 95°C for 2 h. After grafting, silica was placed into a Soxhlet apparatus and extracted with distilled water for 16 h to remove nongrafted polyacrylamide from the grafted PAAm layer. Then, the silica was dried under reduced pressure until a constant weight was reached.

#### Crosslinking of hydrogels

To an aqueous solution containing 4% polyacrylamide (molecular weight  $130 \times 10^3$  g/mol) and 4% poly-*N*-(hydroxymethyl)acrylamide (PHAAM;  $1100 \times 10^3$  g/mol), silica (either PAAm-modified or bare particles) and 5N H<sub>2</sub>SO<sub>4</sub> (pH 3–4) was added. The mixture was thoroughly agitated for 30 min and kept at 55°C for 4 h.

#### Leaching out silica particles from hydrogel

Hydrogel filled with the silica particles was immersed in 3% aq HF at room temperature for 48 h. Molar ratio of SiO<sub>2</sub> : HF was 1 : 1.25. The hydrogel was washed five times for 6 h with distilled water till pH 6 to remove the excess hydrofluoric acid.

#### Measurements

##### Molecular weight determination

The molecular weight of PPM was estimated by static light scattering in water at 25°C, at a fixed angle of 173° using a Malvern Nano ZS instrument equipped with a He-Ne laser.

The average molecular weight of polyacrylamide was determined from the intrinsic viscosity using the Mark-Houwink equation.<sup>24</sup>

The molecular weight of poly-*N*-(hydroxymethyl)acrylamide was calculated from those of polyacrylamide and formaldehyde, according to the reaction stoichiometry.

The intrinsic viscosity of polyacrylamide in water was measured with an Ubbelohde viscometer.

The Fourier transform infrared (FT-IR) spectra were recorded using a Varian Excalibur FTS 3100 spectrometer, with a resolution of 4 cm<sup>-1</sup>.

<sup>1</sup>H-NMR spectra were recorded at 500 MHz on a Varian VXR-500 NMR spectrometer.

The composition of the polyperoxide was determined both by the chromatographic analysis of decomposition products, using a gas-liquid chromatograph Selmichrom-1 (Selmi, Ukraine), and according to the technique described elsewhere.<sup>25</sup>

#### Thermogravimetric analysis

The amounts of the adsorbed PPM and the grafted PAAm were calculated from the thermogravimetric analysis (TGA) data, by their weight loss in the temperature range from 50 to 700°C. Thermogravimetric analysis was done on a TA Q50 instrument, with a heating rate of 10°C/min in a nitrogen flow.

#### Scanning electron microscopy

Hydrogels (filled with silica particles and porous samples) were investigated on a Leo 1530 Field Emission Scanning Electron Microscope, using back scatter electron (BSE) and secondary electron detectors at 1.0–1.5 kV accelerating voltage.

Before measurements, the hydrogel samples were dried under vacuum and were broken in liquid nitrogen. Then, the broken samples were unfrozen, dried until the constant weight, and measured.

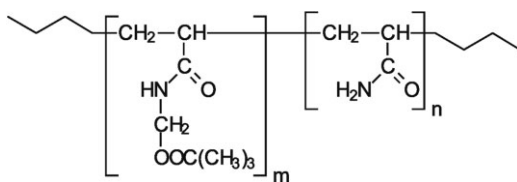
#### Mechanical tests

The complex modulus of elasticity of the hydrogels were measured with the strain-controlled rheometer ARES from Rheometric Scientific/TA Instruments, at a relative deformation of a sample of 1%, and a loading speed of 1.0 rad/s.

## RESULTS AND DISCUSSION

### Synthesis and characterization of polyperoxide macroinitiator for the grafting polymerization on silica particles surface

The PPM for the modification of silica particles with grafted polyacrylamide chains has been synthesized by free radical copolymerization of the PM *N*-(*tert*-



**Scheme 1** Chemical structure of poly[acrylamide-*co*-*N*-(*tert*-butylperoxymethyl)acrylamide] (PPM).

butylperoxymethyl)acrylamide, with acrylamide (Scheme 1).

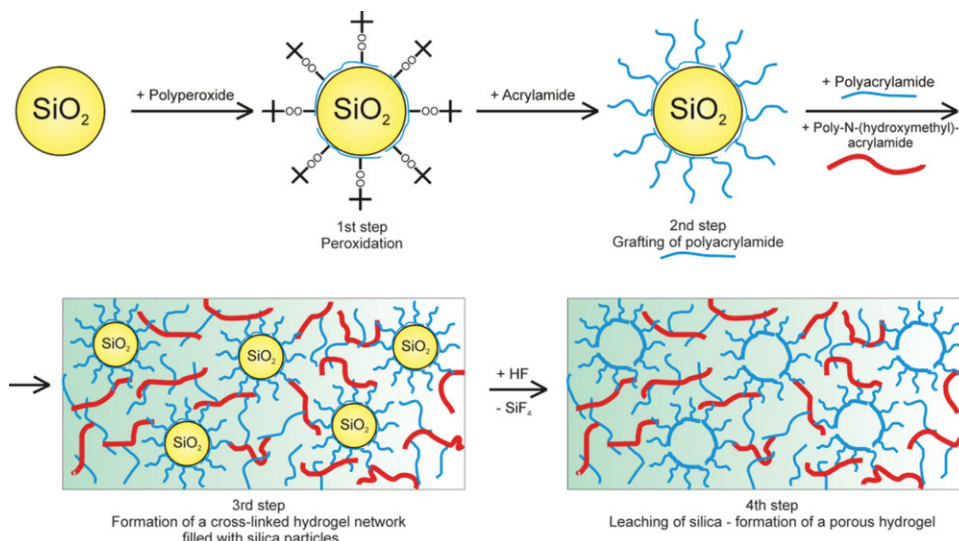
As it is shown in Scheme 1, the PPM contains primary-tertiary alkyl peroxide groups, in the side fragments of the main polymeric backbone. They are stable at room temperature, and allow a long-term storage of reactants without the decay of O—O bonds.<sup>26</sup> A common way for the development of polymeric hydrogels is the free radical polymerization of vinyl monomers in an aqueous medium.<sup>27</sup> It is known that primary-tertiary peroxide groups decompose at 80–100°C<sup>26</sup> and, therefore, are able to initiate a free radical polymerization in an aqueous solution. Therefore, *N*-(*tert*-butylperoxymethyl)acrylamide has been chosen for the development of peroxide macroinitiator. We assumed that being synthesized from *N*-(*tert*-butylperoxymethyl)acrylamide, the polyperoxide poly[acrylamide-*co*-*N*-(*tert*-butylperoxymethyl)acrylamide] can be applied as a macroinitiator of radical processes at the mineral dispersed surface.

The chemical structure of the synthesized *N*-(*tert*-butylperoxymethyl)acrylamide monomer has been confirmed by FT-IR and NMR spectroscopy (Figs. 1 and 2 in Supporting Information). The monomer composition has been proven by an intensive

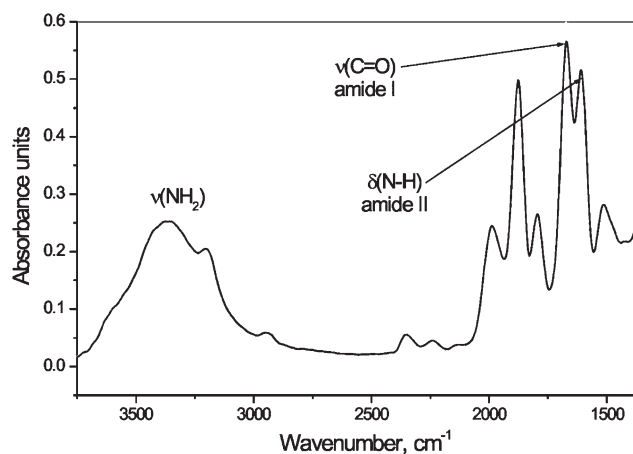
absorption band in the range of 3400–3200 cm<sup>-1</sup>, resulting from the N—H stretch oscillation. The presence of a secondary amide group is displayed as absorption bands at 1670 cm<sup>-1</sup>, resulting from the C=O stretch oscillation (amide I band) and 1540 cm<sup>-1</sup> corresponding to the N—H deformation (amide II band). The spectrum shows an intensive absorption band at 1630 cm<sup>-1</sup> (stretch oscillations of the C=C bond conjugated with C=O) and 880 cm<sup>-1</sup> (oscillations of the O—O moiety), confirming the presence of a peroxide group. The chemical structure of the synthesized monomer has been characterized by <sup>1</sup>H-NMR spectrum analysis. In the spectrum of *N*-(*tert*-butylperoxymethyl)acrylamide, peaks that appeared at 7.53 (2H, CH<sub>2</sub>=) and 6.73 (1H, CH=), agree with those of *N*-(hydroxymethyl)acrylamide. At 1.11 ppm, a peak that can be attributed to the methyl protons of the *tert*-butyl group is observed (9H, t-Bu). The spectrum shows a peak at 5.93, corresponding to the methylene group bound with the peroxide group (2H, CH<sub>2</sub>OO). The structure of the synthesized monomer has been proven by a good coincidence of the found and the calculated molecular refraction as well (46.35 and 45.91, respectively).

The PPM has been synthesized by the free radical copolymerization of PM *N*-(*tert*-butylperoxymethyl)acrylamide with acrylamide. Under the chosen polymerization conditions, the O—O groups in the PM are stable, and the resulting copolymer contains peroxide moieties in side substituents of the polymer backbone.

The presence of the *N*-(*tert*-butylperoxymethyl)acrylamide monomer units in poly[acrylamide-*co*-*N*-(*tert*-butylperoxymethyl)acrylamide] has been proven by FT-IR spectroscopy. The FT-IR spectrum (Fig. 3 in Supporting Information) shows an adsorption



**Figure 1** Formation of porous hydrogels. [Color figure can be viewed in the online issue, which is available at [www.interscience.wiley.com](http://www.interscience.wiley.com).]

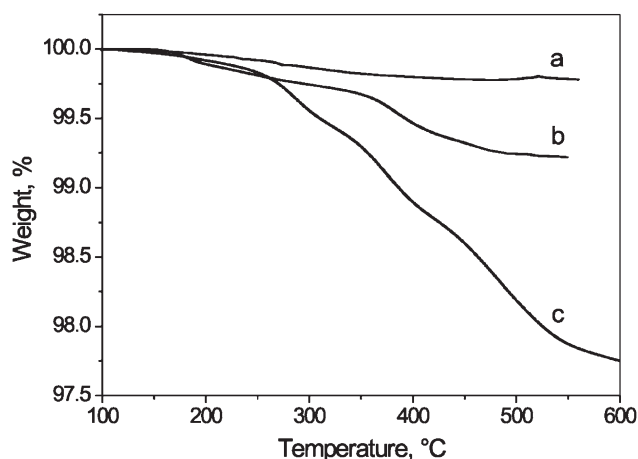


**Figure 2** FT-IR spectrum of silica particles modified with polyacrylamide.

band at  $865\text{ cm}^{-1}$  (oscillations of the O—O moiety), confirming the presence of a *tert*-butylperoxide group in the structure of the resulting copolymer. All other adsorption bands, e.g., at  $3400\text{--}3200\text{ cm}^{-1}$  (N—H stretch oscillation),  $1650\text{ cm}^{-1}$  (C=O stretch oscillation—amide I band), and  $1540\text{ cm}^{-1}$  (N—H deformation—amide II band) are attributed to the repeating units of both *N*-(*tert*-butylperoxymethyl)acrylamide and acrylamide.

The weight average molecular weight of poly [acrylamide-*co*-*N*-(*tert*-butylperoxymethyl)acrylamide] is  $92.1 \times 10^3\text{ g/mol}$ , as determined by the static light scattering. The content of the structural units of the PM is about 9.6% (molar).

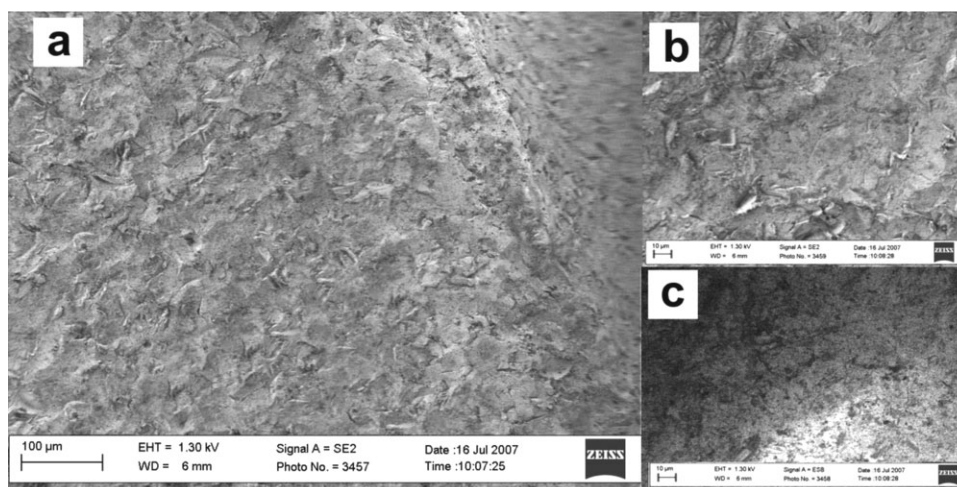
Figure 4 in Supporting Information presents the results of the thermogravimetric analysis of the synthesized PPM. The polyperoxide sample shows two distinct weight loss regions lying between 100 and  $450^\circ\text{C}$ . The weight loss at the first turning point ( $T \approx 185^\circ\text{C}$ ) is an evidence for the thermal degradation of



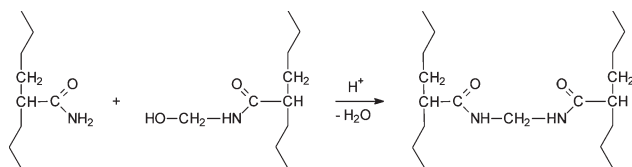
**Figure 3** Thermogravimetry diagrams for silica: (a) bare, (b) modified with the PPM, and (c) with grafted PAAm chains.

the peroxide groups. A rapid mass loss in the range  $350\text{--}450^\circ\text{C}$  (the second step at the curve) corresponds to the decomposition of a whole sample.

To this end, we expected that the synthesized peroxide copolymer can be easily deposited on the surface of silica particles and can initiate radical polymerization, by following heating and decomposition of peroxide groups. The affinity of the peroxide copolymer to the silica surface is provided by the acrylamide fragments serving physical adsorption of PPM, on the surface of dispersed silica particles. On the other hand, the peroxide groups of the PPM are able to initiate free-radical processes, on the surface, at elevated temperatures. As we have shown,<sup>22</sup> the poly-[*N*-(*tert*-butylperoxymethyl)acrylamide-*co*-octyl methacrylate], developed from the PM of the same chemical composition, successfully initiated free radical polymerization on the polyolefins surface.



**Figure 4** SEM micrographs of hydrogels filled with modified silica (a, b). The micrograph (c) is imaged at different (grayscale) contrast using BSE detector.



**Scheme 2** Formation of a three-dimensional crosslinked hydrogel network.<sup>22</sup>

### Development of porous hydrogels: approach description

The porous PAAm hydrogels have been prepared by a procedure schematically represented in Figure 1. In the first step (peroxidation), a thin layer of a peroxide macroinitiator has been adsorbed on the silica particles. Then, acrylamide has been polymerized on the peroxidized particulate surface, resulting in a grafted compatibilizing layer, on the silica particles (grafting of polyacrylamide). The peroxide groups immobilized in the first step on the dispersed silica initiate free radical polymerization of acrylamide, on the silica surface, under the given polymerization conditions.

The hydrogel network filled with the modified silica particles has been formed in the next step (crosslinking), and finally, silica particles have been leached out with hydrofluoric acid to give a porous hydrogel (leaching out silica).

The formation of the hydrogels (crosslinking) has been carried out by the interaction of the polyacrylamide chains grafted to silica surface with an aqueous solution of a mixture of poly-*N*-(hydroxymethyl)acrylamide (used as a structurizing agent) and polyacrylamide. A three-dimensional crosslinked hydrogel network has been developed due to the interaction of NH<sub>2</sub> groups of polyacrylamide with the hydroxyl groups of poly-*N*-(hydroxymethyl)acryl-

amide (Scheme 2). We expect that poly-*N*-(hydroxymethyl)acrylamide does not interact only with ‘free’ polyacrylamide macromolecules in the aqueous solution. Simultaneously, the structurizing agent reacts with the grafted silica surface polyacrylamide chains, and forms covalent bonds between the grafted PAAm and the ‘free’ PAAm from the aqueous solution. Subsequent removal of the dispersed silica, by treating the hydrogel with hydrofluoric acid, results in the formation of a porous hydrogel. In fact, the interaction between silica and HF is a common reaction, resulting in the formation of volatile SiF<sub>4</sub>. We assume, that the pore “walls” are formed by the polyacrylamide, which has been previously attached to the silica particles, and the pore “walls” improve the mechanical properties of the porous hydrogel.

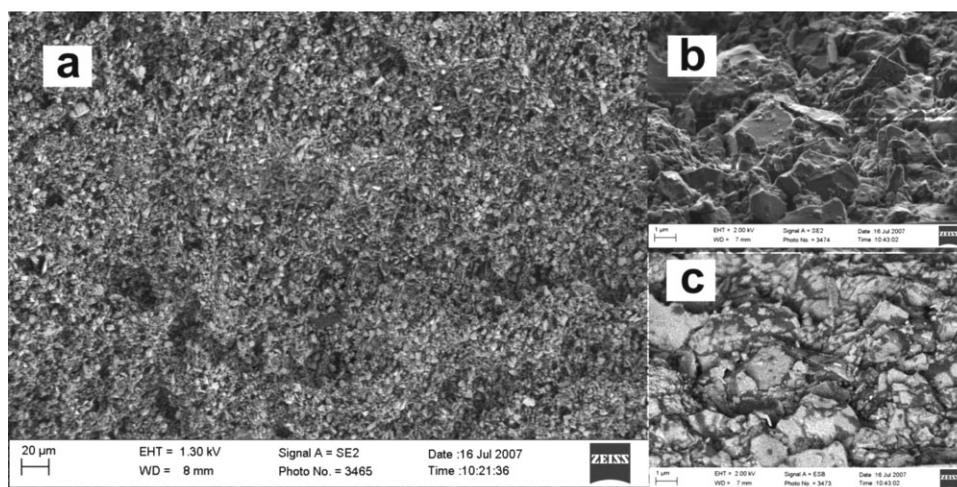
### Peroxidation of the surface of silica particles (PPM adsorption)

Physical adsorption of the PPM on a solid surface occurs when the solution of a PPM is brought into contact with solids, in particular, by mixing the PPM solution in water or in an organic solvent with dispersed fillers or pigments.<sup>28</sup>

In this study, the PPM has been adsorbed on the silica particulate surface from an aqueous solution. It can be assumed that, the adsorption of PPM macromolecules onto silica particles is due to the van der Waals forces, as well as the formation of hydrogen bonds between the amide groups present in the PPM macromolecules and the hydroxyl groups that are usually present on the silica surface.

Thermogravimetric analysis has been used to estimate the amount of the polyperoxide adsorbed on the dispersed silica surface.

Figure 5 in the Supporting Information shows a TGA diagram of the silica modified with PPM. The



**Figure 5** SEM micrographs of hydrogels filled with nonmodified silica (a, b). The micrograph (c) is imaged at different (grayscale) contrast using BSE detector.

sample shows an appreciable weight loss, mainly in the region between 150 and 500°C. According to TGA analysis, the content of the PPM adsorbed from water on the silica surface is 0.78 wt % silica, and this value can be assumed to be the equilibrium adsorption of the PPM on the dispersed SiO<sub>2</sub>, from the 1.5% aqueous solution of the PPM. The sample shows two distinct weight loss regions like the bulk polyperoxide. The first turning point ( $T \approx 185^\circ\text{C}$ ) correlates well with that of the bulk PPM (Fig. 4 in Supporting Information) confirming the presence of the peroxide groups immobilized on the silica surface.

#### PAAm grafting on the peroxidized silica particles

To carry out the grafting of PAAm, the peroxidized silica particles have been immersed in an aqueous solution of acrylamide. The peroxide groups immobilized on the silica surface decompose at 95°C and initiate the polymerization of acrylamide. As a result, a polyacrylamide layer grafted on the surface of dispersed silica has been formed.

Both FT-IR spectroscopy and thermogravimetric analysis confirmed the grafting of polyacrylamide on the silica surface. There is an appreciable difference between the spectra of bare silica and the silica with grafted polyacrylamide. Figure 2 shows an FT-IR spectrum of the PAAm-grafted silica. As compared to the spectrum of bare silica, new characteristic absorption bands appear in the PAAm-modified silica spectrum: (i) a band at 1670 cm<sup>-1</sup> attributed to the valence oscillation of the C=O bond in the amide groups (amide I); a band at 1610 cm<sup>-1</sup> resulting from deformation of the N-H bond (amide II); and (iii) a broad broken band in the range of 3550–3050 cm<sup>-1</sup> attributed to the N-H stretch oscillations. These data clearly show the presence of a grafted polyacrylamide layer on the surface of the silica particles.

The amount of PAAm grafted on the SiO<sub>2</sub> particle surface has been estimated from the thermogravimetric

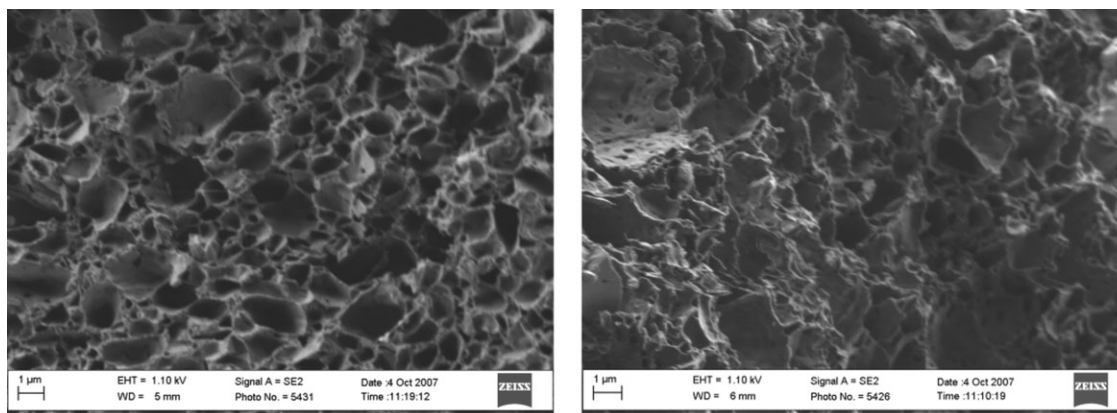
analysis data. Figure 3 shows the TGA diagrams of the nonmodified SiO<sub>2</sub> (a), silica modified with the PPM (b), and silica modified with tethered polyacrylamide macrochains (c). The PAAm-modified sample shows an appreciable weight loss mainly in the region between 250 and 550°C. According to the TGA analysis, the total weight loss for silica modified with PAAm is about 2.35% relative to the initial SiO<sub>2</sub> powder. The percentage of the grafted polyacrylamide has been calculated as 1.57%, after subtracting the contribution of PPM decomposition from the total weight loss.

#### Hydrogel crosslinking and pore formation: effect of silica particles modification

For the development of hydrogels filled with silica particles, the latter have been dispersed in an aqueous solution of a mixture of PAAm and PHMAAm (structuring agent), before the crosslinking reaction. When the hydrogel composition has been crosslinked, the resulting hydrogels have been immersed into an aqueous solution of hydrofluoric acid to remove the silica particles and to develop the pores.

We have studied an effect of the grafted silica polyacrylamide chains on the morphology and the physico-mechanical properties of porous hydrogels formed with the PAAm-modified silica particles and compared it with that formed using nonmodified SiO<sub>2</sub>.

Figures 4 and 5 present scanning electron micrographs (SEM) of samples broken in liquid nitrogen and dried hydrogel samples filled with the grafted PAAm-modified and nonmodified silica particles. It is clearly seen that more regular distribution of the modified silica particles has been observed in the hydrogel composition when compared with nonmodified particles. Furthermore, cohesion failure of the bulk matrix without any stripping of the surface of the filler particles has been detected, when the samples were imaged using BSE detector (as different contrast) [Fig. 4(c)].



**Figure 6** SEM micrographs of porous hydrogels formed after leaching out silica particles: (a) modified with polyacrylamide and (b) nonmodified.

TABLE I  
Characteristics of Porous Hydrogels

Amount of SiO <sub>2</sub> (%)	SiO <sub>2</sub>	Swelling rate [ $g_{\text{water}}/(g_{\text{polym}} \times s)$ ]	Maximum swelling degree (%)	Complex modulus of elasticity G* (Pa)
25	nonmodified	0.015	7520	1800
	PAAm-modified	0.013	7020	3400
50	nonmodified	0.043	11730	1500
	PAAm-modified	0.045	10540	2100
65	nonmodified	0.052	13150	600
	PAAm-modified	0.048	11400	1600

On the contrary, a micrograph in Figure 5(b) shows appreciable agglomeration of the particles, and adhesion failure on the filler–matrix interface has been observed, when the samples were measured using BSE detector [Fig. 5(c)]. These data demonstrate that the grafted PAAm macromolecules are involved in the formation of a crosslinked polymeric hydrogel composition, because of their covalent bonding to a hydrogel network.

Remarkably, the modification of the silica surface has not changed the ability of the silica particles to leach out from a filled hydrogel. Both modified and nonmodified silica have been successfully leached out from hydrogels using an HF aqueous solution. SEM micrographs of the broken surfaces of porous hydrogels, after the removal of silica, (Fig. 6) have shown that silica has been completely dissolved by the treatment of filled hydrogels with hydrofluoric acid.

More regular distribution of the modified SiO<sub>2</sub> particles has resulted in the formation of hydrogels with a regular pore distribution. An important feature of the porous hydrogel formed with the PAAm-modified silica particles is the small amount of pore containing “wall” defects when compared with the hydrogel formed with the nonmodified SiO<sub>2</sub> (Fig. 6).

The data in Table I show that the formation of porous hydrogels with reinforced pore “walls” results in a 1.5–3 times increase in the mechanical strength. The maximum swelling degree and swelling rate retain almost the same as that of the hydrogels formed with the nonmodified silica.

The swelling rate of the nonporous hydrogel formed under the same conditions has been found to be as  $7.0 \times 10^{-5} g_{\text{water}}/(g_{\text{polym}} \times s)$ , and its maximum swelling degree as 1160%. Hence, the formation of pores in the polymeric hydrogels significantly improves their swelling behavior.

## CONCLUSIONS

In summary, we have demonstrated a new and a facile strategy to the development of porous polyacrylamide hydrogels with enhanced mechanical properties and regular pore distribution. This methodology involves the formation of porous hydrogel

network by leaching out chemically modified silica particles. To improve the dispersibility of silica in the hydrogel composition, the silica particles have been modified with the chemically attached polyacrylamide chains. Simultaneously, the grafted polyacrylamide chains form pore walls after leaching out the silica particles, thereby reinforcing the hydrogel composition and improving the mechanical strength of the hydrogel.

The grafting polymerization on the silica surface has been initiated by PPM synthesized by a free radical copolymerization of the PM, *N*-(*tert*-butylperoxy-methyl)acrylamide with acrylamide. Both PM and PPM have been developed in our lab, and applied for the synthesis of porous polymeric hydrogels.

We believe that our approach to the development of porous hydrogels formed from biocompatible hydrophilic polymers may find potential applications in areas of biomedical materials and items, tissue engineering, separation and purification of proteins, drug delivery, etc.

The authors thank Dr. Peter Schulz (Chair for Chemical Reaction Engineering, University of Erlangen-Nuremberg) for performing the NMR analyses and Mrs. Michelle Malter (Institute of Polymer Materials, University of Erlangen-Nuremberg) for her help in using the mechanical measurements.

## References

- Omidian, H.; Rocca, J. G.; Park, K. J. *Controlled Release* 2005, 102, 3.
- Khor, E.; Lim, L. Y. *Biomaterials* 2003, 24, 2339.
- Lee, K. Y.; Mooney, D. J. *Chem Rev* 2001, 101, 1869.
- Chen, J.; Park, H.; Park, K. J. *Biomed Mater Res* 1999, 44, 53.
- Patel, V. R.; Amiji, M. M. *Pharm Res* 1996, 13, 588.
- Bennett, D. J.; Burford, R. P.; Davis, T. P.; Tilley, H. J. *Polym Int* 1995, 36, 219.
- Chirila, T. V.; Constable, I. J.; Crawford, G. J.; Vijayasekaran, S.; Thompson, D. E.; Chen, Y. C.; Fletcher, W. A. *Biomaterials* 1993, 14, 26.
- Kabiri, K.; Omidian, H.; Zohuriaan-Mehr, M. J. *Polym Int* 2003, 52, 1158.
- Oxley, H. R.; Corkhill, P. H.; Fitton, J. H.; Tighe, B. J. *Biomaterials* 1993, 14, 1064.
- Kon, M.; De Visser, A. C. *Plast Reconstr Surg* 1981, 67, 288.



11. Badiger, M. V.; McNeill, M. E.; Graham, N. B. *Biomaterials* 1993, 14, 1059.
12. Mikos, A. G.; Thorsen, A. J.; Czerwonka, L. A.; Bao, Y.; Langer, R.; Winslow, D. N.; Vacanti, J. P. *Polymer* 1994, 5, 1068.
13. Sidorenko, A.; Minko, S.; Gafijchuk, G.; Voronov, S. *Macromolecules* 1999, 32, 4539.
14. Minko, S.; Gafijchuk, G.; Sidorenko, A.; Voronov, S. *Macromolecules* 1999, 32, 4525.
15. Minko, S.; Sidorenko, A.; Stamm, M.; Gafijchuk, G.; Senkovsky, V.; Voronov, S. *Macromolecules* 1999, 32, 4532.
16. Tsubokawa, N.; Ishida, H. *J Polym Sci Part A: Polym Chem* 2003, 30, 2241.
17. Seredyuk, V. A.; Tokarev, V. S.; Voronov, S. A. *Dopov Natsional'noi Akad Nauk Ukr* 2000, 7, 156.
18. Tokarev, V.; Seredyuk, V.; Voronov, S. *Adsorpt Sci Technol* 2000, 18, 135.
19. Hayashi, S.; Handa, S.; Tsubokawa, N. *J Polym Sci Part A: Polym Chem* 1996, 34, 1589.
20. Hayashi, S.; Takeuchi, Y.; Eguchi, M.; Iida, T.; Tsubokawa, N. *J Appl Polym Sci* 1999, 71, 1491.
21. Luzinov, I.; Voronov, A.; Minko, S.; Kraus, R.; Wilke, W.; Zhuk, A. *J Appl Polym Sci* 1996, 61, 1101.
22. Samaryk, V.; Voronov, A.; Tarnavchyk, I.; Kohut, A.; Nosova, N.; Varvarenko, S.; Vasylyev, S.; Peukert, W.; Voronov, S. *Abstracts of Papers, 235th ACS National Meeting, PMSE-355*; New Orleans, LA, 2008.
23. Tarnavchik, I. T.; Samarik, V. Y.; Voronov, A. S.; Varvarenko, S. M.; Nosova, N. G.; Kogut, A. M.; Voronov, S. A. *Dopov Natsional'noi Akad Nauk Ukr* 2008, 7, 146.
24. Hiemenz, P. C.; Lodge, P. T. *Polymer Chemistry*, 2nd ed.; CRC Press: Boca Raton, 2007; p 336.
25. Voronov, S.; Tokarev, V.; Oduola, K.; Lastukhin, Y. *J Appl Polym Sci* 2000, 76, 1217.
26. Rakhimov, A. I. In *Chemistry and Technology of Organic Peroxide Compounds*; Khimiya: Moscow, 1979; p 392 (in Russian).
27. Kishida, A.; Ikada, Y. In *polymeric Biomaterials*, 2nd ed.; Dumitriu, S., Ed.; Marcel Dekker: New York, 2002; p 133.
28. Voronov, S.; Tokarev, V.; Datsyuk, V.; Seredyuk, V.; Bednarska, O.; Oduola, K.; Adler, H.; Puschke, C.; Pich, A.; Wagenknecht, U. *J Appl Polym Sci* 2000, 76, 1228.