A Novel Hydrogel with High Mechanical Strength: A Macromolecular Microsphere Composite Hydrogel

6 AUTHORS, INCLUDING:

Kexin Jiao
Southern Illinois University Carbondale
4 PUBLICATIONS **228** CITATIONS

SEE PROFILE

Hugh Ralph Brown
University of Wollongong
169 PUBLICATIONS **4,818** CITATIONS

SEE PROFILE

Huiliang Wang
Beijing Normal University
62 PUBLICATIONS **802** CITATIONS

SEE PROFILE

ADVANCED MATERIALS

A Novel Hydrogel with High Mechanical Strength: A Macromolecular Microsphere Composite Hydrogel**

By *Ting Huang*, *Hongguang Xu*, *Kexin Jiao*, *Liping Zhu*, *Hugh R. Brown*, and *Huiliang Wang**

The industrial and biomedical applications of hydrogels made from either natural or synthetic sources are strongly limited by their poor mechanical properties. A normal structure (NS) hydrogel breaks under low stress because there are very few energy dissipation mechanisms to slow crack propagation. In addition, as their crosslinking points are distributed irregularly and the polymer chains between the crosslinking points have different lengths, the stress cannot be evenly distributed between the polymer chains, and crack initiation is facile. Many efforts have been focused on increasing the mechanical strength of hydrogels,[1] but the robustness still remains unsatisfactory. In recent years, three kinds of novel hydrogels with unique structures and high mechanical strength have been developed.[2] Topological (TP) gels have figure-of-eight crosslinkers that can slide along polymer chains.[3] The gel swells to about 500 times its original weight and can be stretched to nearly 20 times its original length. The nanocomposite (NC) hydrogel is made from specific polymers with a water-swellable inorganic clay.[4] Most of the macromolecules are grafted onto nanoparticles, indicating that the nanoparticle clay acts as a highly multifunctional crosslinking agent. We believe that the high mechanical strength of this material has its origin in the very high functionality of the rigid crosslinked points and the lack of short chains between crosslinked components, as every active chain has to stretch between nanoparticles. The extension degree of a chain before breakage is controlled by the relationship between its relaxed end-to-end distance and its contour length, which is low for short chains. When a short chain in an NS hydrogel breaks, its load is thrown onto just one or two other adjacent chains, which dramatically increases their load. Hence, multiple chain fractures

occur, causing voids and microcracks. However, in an NC hydrogel with large, rigid crosslinking points, the load from a single broken chain will be spread over many other chains, and the material is less likely to form the microcracks and voids responsible for initiating bulk failure. Gong et al. have reported a new method of obtaining strong and tough hydrogels by making double-network (DN) materials with a high molar ratio of the second network to the first network. In this case, the first network is highly crosslinked and the second network is loosely crosslinked.[5] These DN hydrogels demonstrate extremely high mechanical strength. By adding a third component to a DN gel, either a weakly crosslinked network or noncrosslinked linear chains, gels with high-strength and low-frictional coefficients were obtained.[6]

Macromolecular microspheres (MMSs) have become an important structure in polymeric materials. The hydrogel microspheres on the micro- or nanoscale are known as microgels or nanogels, respectively. They are usually environmentally sensitive and are mainly used in drug delivery and other biomedical applications.[7] However, it is difficult to form bulk hydrogels (macrogels) with these microgels,[8] and when formed, the macrogels do not exhibit high mechanical strength. Very little work has been done on incorporating other kinds of microspheres into bulk hydrogel structures, and the improvement in mechanical strength is far less than for the three hydrogels mentioned above.[9] Here, we report a new way of synthesizing hydrogels with a novel, well-defined network structure and high mechanical strength. In this method, a peroxidized MMS acts as both an initiator and a crosslinker. The mechanism for the formation of the peroxide and the initiation of polymerization, as well as for the formation of a hydrogel, are proposed in Scheme 1. The new hydrogel is a macromolecular microsphere composite (MMC) hydrogel.

When the MMS emulsion is irradiated with ^{60}Co γ-rays in oxygen, peroxides (POOR and POOH; here P is the macromolecule that comprises the MMS, and R is a short alkyl group) are formed on the surface and possibly, to a certain extent, in the inner part of the MMS. The formation of peroxides on the MMS was proven with iodometry, which is the common method used to verify their formation and determine the amount formed in the polymers. Potassium iodide and isopropyl alcohol were added to the irradiated MMS emulsion, and as the solution was heated and refluxed for 30 min, it gradually became yellow, which indicates the formation of I_2 and further establishes the presence of peroxides on the MMS. The peroxides decomposed under heat to form the free radicals PO•, OR•, and OH•. PO• initiated the grafting of

[*] Prof. H. L. Wang, T. Huang, H. G. Xu, K. X. Jiao, L. P. Zhu
College of Chemistry
Beijing Normal University
Beijing 100875 (P.R. China)
E-mail: wanghl@bnu.edu.cn
Prof. H. R. Brown
Engineering Faculty
University of Wollongong
NSW 2522 (Australia)
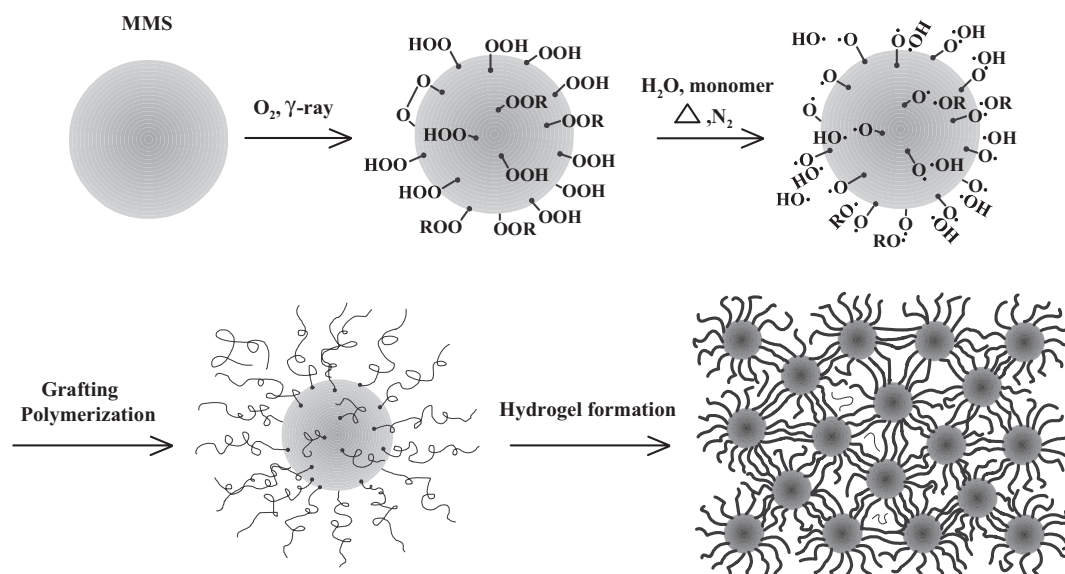
Scheme 1. Proposed mechanism for the formation of an MMC hydrogel and an MMC hydrogel microstructure.

monomers onto the MMS while OR• and OH• initiated the homopolymerization of monomers or terminated the growing polymer chains. The OR• and OH• might be adsorbed onto the surface of the MMS, which has a high specific surface energy, thereby initiating surface grafting. The distance between two vicinal MMSs varied with MMS concentration, but it was usually in the hundreds of nanometers. It is possible for two vicinal MMSs to be joined by a grafted chain, either by the mutual termination of two growing grafted chains that initiate at the two MMSs or by the termination of a grafted chain from one MMS by a radical of a second MMS. The occurrence of this effect has been proven by the fact that the MMC hydrogel cannot be dissolved in a large excess of water or even in a high pH sodium hydroxide solution in the presence of urea to suppress the hydrogen bonding. In addition to the chains forming a covalently coupled link between MMSs, when the length of the grafted polymer chain reaches half of the distance between the MMSs, the grafted polymer chains can become entangled. With the subsequent decomposition of peroxides, more and more poly(acrylic acid) (PAA) chains are formed and become entangled. In general, entanglement coupling is not likely to cause a significant strength or toughness enhancement within a highly swollen gel because the chains are highly mobile and can slip past the entanglements. However, PAA chains are known to form inter- and intramolecular hydrogen bonds that act as stickers and enhance the dissipation involved in pulling out the entanglements.[10] Thus, the solution transforms into a tough solid gel.

The MMS was made from a mixture of styrene, butyl acrylate, and acrylic acid (AA). The synthesized MMS emulsion containing some emulsifiers was directly used as the raw material. Experiments were performed to determine which part plays a vital role in the formation of an MMC hydrogel with high mechanical strength. First, nonirradiated MMS emul-

sions were used in an attempt to synthesize hydrogels under the same synthesis conditions as for irradiated MMS. However, no hydrogels were obtained. This result proves that no initiators remained in the emulsions. Second, a solution containing emulsifiers in the same concentration as in the MMS emulsion was prepared and irradiated, and this solution was used to synthesize hydrogels. In this case, a hydrogel was obtained. This result indicates that the emulsifiers can be peroxidized under γ-ray irradiation in oxygen, and the peroxides act as initiators and crosslinkers. However, the amount of MMS in the emulsion is much higher than the total amount of the emulsifiers. Therefore, it is reasonable to presume that there are more peroxides formed on MMS under irradiation, and thus the polymerization is mainly initiated by the peroxides formed on the MMSs. In addition, although the mechanical strength of this hydrogel is slightly higher than the strength of an NS hydrogel, it is much lower than for an MMC hydrogel, indicating that the emulsifiers are not the key materials in the formation of a hydrogel with high mechanical strength. These results prove that irradiated MMS acts as both an initiator and a crosslinker in the synthesis of an MMC hydrogel.

Our systematic study showed that the concentration of MMS, the irradiation time of MMS, the monomer concentration, and the reaction temperature were critical parameters for the successful synthesis of MMC hydrogels. These factors also affected the final mechanical properties of the MMC hydrogels. The optimum reaction conditions were irradiation of the MMS emulsion for 2 h in oxygen at room temperature, polymerization for 6 h, and a reaction temperature of 40 °C. At elevated temperatures (50, 60, and 65 °C), gel-like materials were also obtained, but they were partly or completely dissolved in water, indicating that there was no strong interaction between the MMSs for a few reasons. First, self-initiated

homopolymerization of AA occurs more easily at a higher reaction temperature. Second, the peroxides decompose much faster at higher temperatures, initiating more grafting reactions, but the growing grafting chains can more easily be terminated by the free radicals (OR$^\bullet$ and OH$^\bullet$). In this case, only short grafted chains are formed. The short terminated chains on two vicinal MMSs cannot entangle each other. A scanning electron microscopy (SEM) study confirmed our assumptions regarding the structure of the gel-like materials, as isolated MMSs could be easily found in these materials, and the size of the MMSs became bigger (ca. 400 nm) because the short grafted chains collapsed on them.

As proposed above, some of the grafted PAA chains on neighboring MMSs can be chemically bonded and some can entangle each other. As there are many grafted chains on each MMS, the number of chains between two MMSs must be quite large. Thus, a bundle (or bundles) of polymer chains between two MMSs can be formed. In addition the polymer chains can interact strongly through hydrogen bonding, thus forming a very strong connection between MMSs. The contribution of hydrogen bonding to the mechanical strength of MMC hydrogels was proven by the fact that the strength decreased significantly after swelling in urea or in a high pH solution. For the reasons discussed above, combined with the lack of short active chains, the large high functionality rigid crosslinks, and the entanglements with hydrogen bonding, the MMC hydrogel would be expected to have very high mechanical strength.

NS hydrogels were also synthesized via free-radical polymerization by using a traditional crosslinker and initiator instead of peroxidized MMSs. The synthesis conditions of MMC and NS hydrogels are shown in Table 1. In this study, AA was the only monomer used.

The mechanical properties of the NS and MMC hydrogels were measured by using compression tests. Not surprisingly, the NS hydrogel (87.5 wt % water content) fractured under low deformation. However, the MMC hydrogel (A6, 89 wt % water content) did not break, even under extremely high strain (most of the hydrogel was squeezed out of the plates), and it quickly recovered its original shape after the release of its load (Fig. 1). Figure 2 shows the corresponding stress–strain curves of the NS and the MMC (A6) hydrogels. The NS hydrogel broke at a stress of 0.08 MPa and a strain of 45.5 %. However, the MMC (A6) hydrogel did not break, even at a stress of 10.2 MPa and a strain of 97.9 %. The stress sustained by the MMC hydrogel was 120 times more than the stress sustained by the NS hydrogel.
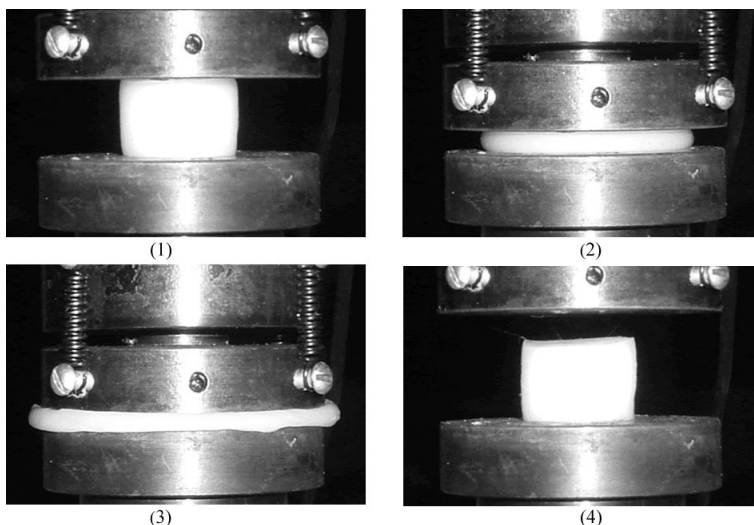

Figure 1. Photographs of an MMC hydrogel during the compression test.

Table 1. The composition of the raw materials, the conditions for NS and MMC hydrogel syntheses, and the compressive properties of the hydrogels.

Hydrogel	Synthesis AA/ P-MMS/ Water [mL]	Reaction time [h]	Water content [wt %]	Strain ε [%]	Stress σ [MPa]	Stress at 96% strain σ [MPa]	Appearance after test
NS	2.0/—/4.0 [a]	6	87.5	45.5	0.08		Fractured
MMC(A1)	1.8/0.5/1.7	6	89	97.9	0.8	0.48	Recovered
MMC(A2)	2.0/0.5/1.5	6	89	98.4	7.3	0.61	Recovered
MMC(A3)	2.2/0.5/1.3	6	89	98.2	1.0	0.50	Recovered
MMC(A4)	2.4/0.5/1.1	6	89	97.3	3.1	1.69	Recovered
			80	96.7	7.0	5.13	Recovered
			70	99.3	78.6	35.56	Deformed
MMC(A5)	2.5/0.5/1.0	6	70	95.5	66.7		Fractured
MMC(A6)	2.6/0.5/0.9	6	89	97.9	10.2	3.74	Recovered
			70	92.3	19.1		Fractured
MMC(B1)	2.0/0.5/1.5	3	89	99.7	2.9	0.42	Deformed
MMC(B2)	2.0/0.5/1.5	6	89	98.4	7.3	0.61	Recovered
MMC(B3)	2.0/0.5/1.5	12	89	98.4	1.4	0.63	Recovered
MMC(B4)	2.0/0.5/1.5	24	89	99.7	7.9	0.96	Recovered

[a] Crosslinker (*N,N'*-methylene-bis(acrylamide), 0.01 g) and initiator (potassium persulfate, 0.01 g) were added.
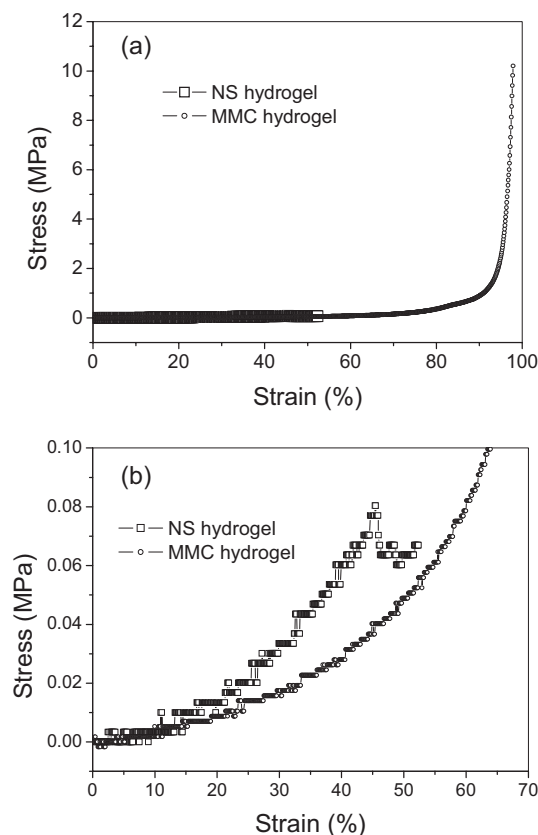
Figure 2. The stress–strain curves for the NS and MMC (A6) hydrogels: a) full range and b) stress at low strain.

As shown in Table 1, all of the MMC hydrogels could sustain a much higher stress and strain than the NS hydrogels. The mechanical strength of the hydrogel has been dramatically improved, as it is several tens to several hundreds times that of an NS hydrogel.

It should be mentioned that, because the hydrogels with high water content (89 wt%) did not break, fracture stress values could not be obtained. Cyclic compression up to 90% strain of a sample of the MMC hydrogel (A2) was carried out, but no significant change in the stress–strain curve could be seen even after cycling, suggesting there is no permanent damage to the hydrogel. The stresses shown in Table 1 were not the highest stresses that the MMC hydrogels could sustain. When the hydrogels were compressed further, higher stresses could be obtained. The MMC hydrogels with high water content almost completely recovered their original shapes after the compression tests. Some of the hydrogels could be slightly broken at high strains, but there was only one crack, and the hydrogels partly recovered their original shapes. The hydrogels with lower water content (70 wt%) fractured under high strains (more than 90%) but broke into only a few pieces rather than the multiple pieces observed for the NS hydrogels. The fracture stress of the hydrogel with 70 wt% water (A4) was 78.6 MPa at 99.3% strain, similar to that of an articular cartilage. However, the mechanical

strength of the MMC hydrogel with water decreased dramatically. After equilibrium swelling in water (about 900 times), the hydrogels became very brittle.

For convenient comparison, the stresses at the same strain (96%) are also listed in Table 1. The stress at this strain for the MMC hydrogel increased with increasing monomer concentration (A series) and reaction time (B series) but decreased with increasing MMS concentration. The stress at 96% strain also increased dramatically with decreasing water content in the MMC hydrogel.

The stress of the MMC hydrogel with high water content was very similar to or even a little lower than the stress of the NS hydrogel when the strain was low (Fig. 2b). However, with increasing strain, when the NS hydrogel broke, the stress sustained by the MMC hydrogel increased. Specifically, when the strain reached 90%, there was a rapid increase in stress (Fig. 2a). The elastic modulus increased dramatically with decreasing water content. The elastic modulus of the MMC hydrogel was lower than that of the DN hydrogel at low strain, even when the water content was smaller.[5] These results are consistent with the proposed microstructure of the MMC hydrogel. Because of the very long flexible chains between crosslinks (MMS particles), the elastic modulus of the MMC hydrogel was low, as would be expected from classic rubber elasticity theory. With an increase in strain, some chains between crosslinks (MMSs) came close to their full extension, causing the stress to quickly increase. The water content in the hydrogel influences the hydrogen bonding and therefore, the effectiveness of the entanglement of the chains; hence, the elastic modulus changes more rapidly with water content than would be predicted by simple Gaussian theory.

The swelling behaviors of the MMC hydrogels were also investigated. The swelling rates of the MMC hydrogel decreased with increasing monomer concentration and reaction time, but increased with decreasing MMS concentration. In comparison to the compression-test results, it can be seen that the change of mechanical strength with synthesis conditions is entirely contrary to that of swelling rate (i.e., the MMC hydrogels with lower swelling rates usually had a higher mechanical strength or vice versa). The MMC hydrogels did not dissolve in large excesses of water but showed equilibrium swelling behavior after a long time (1 week). They could swell to about 900 times their dry weight, much higher than that of an NC hydrogel, indicating that the chains between effective crosslinks (MMC particles) were very long.

In conclusion, we have successfully synthesized a novel MMC hydrogel with a unique microstructure and very high mechanical strength. It is worth mentioning that the meaning of composite in this work is different from the traditional definition. In our case, most polymer chains are chemically grafted onto MMSs, not just physically attached or entangled. Hydrogel is also not the traditional concept but rather refers to an inhomogeneous material that has a dry component (MMS) and a wet component (the hydrophilic gel). The MMC hydrogel also differs from a fiber-reinforced hydrogel whose mechanical properties are basically determined by the

tough dry component. Similar to the NC hydrogels,[4] the crosslinking density and the intercrosslinking distance can be easily controlled by adjusting the peroxide concentration on the MMS and the concentration of MMS. In contrast to the synthesis of NC hydrogels, which requires a specific monomer and inorganic clay, the synthesis of MMC hydrogels described here may become a new, general strategy for hydrogel synthesis. The MMC hydrogels were made from only organic components. The compositions and the properties of the MMC hydrogels can be tailored by changing MMS and monomer(s). Many kinds of MMSs have been synthesized, and most of them can be used in the synthesis of MMC hydrogels. The component(s) and their ratios, as well as the size of the MMS, can be controlled. In addition, it is possible to incorporate other inorganic nanoparticles into the MMSs to obtain MMC hydrogels with special electrical and magnetic properties. It is necessary to point out that the amount of peroxide and/or hydroperoxide groups that can be generated on the microsphere surface is dependent on the chemical nature of the polymer chain constructing the microsphere. Fortunately, most of the polymers can be peroxidized under high-energy irradiation in the presence of oxygen. For the polymers more resistant to irradiation-induced peroxidation, a longer irradiation time is necessary to obtain the required amount of peroxide and/or hydroperoxide groups. The microsphere used in this work was mainly (ca. 70 %) composed of polystyrene, which is a polymeric material with a high radiation resistance, but our results show that the microspheres can be easily peroxidized. By replacing the AA monomer with *N*-isopropyl acrylamide (NIPAAm) or other monomers, MMC hydrogels could be made with thermal or other environmentally sensitive properties. The surface of MMC hydrogels is mainly covered with polymer chains with one side grafted onto MMSs; this surface may have some special properties that are different than NS hydrogels. This approach may also be used to synthesize other complex polymeric materials.

The continuous swelling of the MMC hydrogels may impede their biomedical applications. However, it can be overcome by introducing a second NS network with proper crosslinking density into the MMC hydrogel, similar to the DN hydrogel.[5] Our preliminary studies show that the swelling property of the new DN hydrogels can be easily adjusted. Therefore, it also is possible to create biocompatible hydrogels with extremely high mechanical strength that can be used as substitutes for tissues in the body, such as articular cartilage, semilunar cartilage, tendons, and ligaments.

Experimental

AA (AR grade, Bodi Chemicals, Tianjin, China) was redistilled before use. Macromolecular microsphere emulsions were prepared as follows and directly used after synthesis. Deionized water (15 mL) was added to a three-necked flask and heated to 60 °C. Ammonium persulfate (0.0308 g) dissolved in 5 mL of deionized water was added to the flask, which was then heated to 78 °C. Monomers (15.44 mL styrene, 3.34 mL butyl acrylate, 2.86 mL AA) and a mixture of emulsifiers and/or initiators (0.444 g nonylphenol poly(ethenoxy ether) OP-10, 0.266 g sodium lauryl sulfate, 0.0924 g ammonium persulfate, and 0.03 g sodium carbonate dissolved in 20 mL deionized water) were slowly added to the flask through two addition funnels simultaneously over a period of 3 h. The solution was further heated for 1 h. The MMSs obtained were ca. 100 nm in diameter and monodisperse.

Preparation of MMC hydrogels was achieved by using a two-step method. In the first step, the macromolecular microsphere emulsion was diluted four times (volume) with deionized water and then irradiated with ^{60}Co γ-rays (dose rate: 10 kGy h^{-1}) in oxygen for 2 h to create peroxides on the surface of the macromolecular microspheres. In the second step, water and an AA monomer (as specified in Table 1) were added to a test tube containing a specific amount of the irradiated MMS solution. The mixture was deaerated with bubbling nitrogen, and the test tube was placed in a water bath at the required temperature for the specified time to create the MMC hydrogel.

The compressive stress–strain measurements were performed on hydrogels swollen to a defined water content (not to equilibrium) by using a CSS-2202 electronic universal testing machine (Changchun Institute of Experimental Machines, Changchun, China) at a crosshead speed of 5 mm min^{-1}. The cylindrical gel samples were 24–26 mm in diameter and 12–18 mm in thickness. The stress, σ, was calculated by $\sigma = Load/\pi r^2$, where r is the initial unloaded radius. The strain, ε, under compression was defined as the change in the thickness relative to the thickness of the freestanding specimen.

[1] a) S. R. Stauffer, N. A. Peppas, *Polymer* **1992**, *33*, 3932. b) C. M. Hassan, N. A. Peppas, *Adv. Polym. Sci.* **2000**, *153*, 37. c) E. C. Muniz, G. Geuskens, *Macromolecules* **2001**, *34*, 4480. d) H. J. Kong, E. Wong, D. J. Mooney, *Macromolecules* **2003**, *36*, 4582.

[2] Y. Tanaka, J. P. Gong, Y. Osada, *Prog. Polym. Sci.* **2005**, *30*, 1.

[3] Y. Okumura, K. Ito, *Adv. Mater.* **2001**, *13*, 485.

[4] K. Haraguchi, T. Takehisa, *Adv. Mater.* **2002**, *14*, 1120.

[5] J. P. Gong, Y. Katsuyama, T. Kurokawa, Y. Osada, *Adv. Mater.* **2003**, *15*, 1155.

[6] D. Kaneko, T. Tada, T. Kurokawa, J. P. Gong, Y. Osada, *Adv. Mater.* **2005**, *17*, 535.

[7] a) X.-C. Xiao, L.-Y. Chu, W.-M. Chen, J.-H. Zhu, *Polymer* **2005**, *46*, 3199. b) X. Yin, H. D. H. Stoever, *J. Polym. Sci., Part A: Polym. Chem.* **2005**, *43*, 1641.

[8] S. Kara, O. Pekcan, *Polymer* **2000**, *41*, 3093.

[9] L. J. Puig, J. C. Sanchez–Diaz, M. Villacampa, E. Mendizabal, J. E. Puig, A. Aguiar, I. Katime, *J. Colloid Interface Sci.* **2001**, *235*, 278.

[10] N. Tanaka, H. Kitano, N. Ise, *Macromolecules* **1991**, *24*, 3017.