# Homogeneous Poly(acrylamide) Hydrogels Made by Large Size, Flexible Dimethacrylate Cross-Linkers

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Polymer gels exhibit an important scattering at low scattering vectors, corresponding to concentration fluctuations at length scale between $10°$ and $10^2$ nm.[1,2] Such large-scale concentration fluctuations, which are absent in polymer solutions, indicate existence of mesoscopic static structures in gels due to the spatial inhomogeneity. The inhomogeneity in gels can be visualized as strongly cross-linked microgels embedded in a less densely cross-linked environment. Light scattering investigations show a significant increase in the gel inhomogeneity with increasing cross-link density.[1–5] As a consequence, strong hydrogels made at a high cross-linker content are highly inhomogeneous. Spatial inhomogeneity is undesirable because it dramatically reduces the optical clarity and the mechanical performance of gels, which are properties closely connected with many industrial applications.

Here we demonstrate by dynamic rheological and light scattering measurements that homogeneous poly(acrylamide) (PAAm) hydrogels with a relatively high cross-link density could be obtained by increasing the distance between the vinyl groups of the cross-linker molecule. Because of the easy availability of various chain lengths of glycols, oligomeric ethylene glycol dimethacrylates were used as the cross-linker, whose structure is represented as follows:
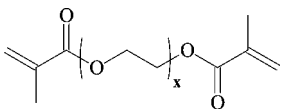
The cross-linkers were denoted by DMA-*x*, where DMA denotes the two methacrylate moieties and *x* is the number of ethylene glycol units in the molecule, which was varied between 1 and 14. Free-radical cross-linking copolymerization of acrylamide monomer and DMA-*x* cross-linker was carried in an aqueous solution at 25 °C in the presence of ammonium persulfate (4.39 mM)−*N*,*N*,*N′*,*N′*-tetramethylethylenediamine (0.025 v/v %) redox initiator system. The initial monomer concentration was kept constant at 10 w/v %, while the cross-linker concentration, denoted by the mol % of DMA-*x* in the monomer−cross-linker mixture, was varied over a wide range up to the onset of turbidity in the gelation system.[6]

Gelation reactions were first monitored by rheometry using oscillatory deformation tests. A frequency of $\omega = 1$ Hz and a deformation amplitude $\gamma = 0.01$ were selected to ensure that the oscillatory deformation is within the linear regime. Typical gelation profiles in the presence of various amounts of DMA-4 are given in Figure 1A, where the elastic modulus $G'$ and the viscous modulus $G''$ are shown as a function of the reaction
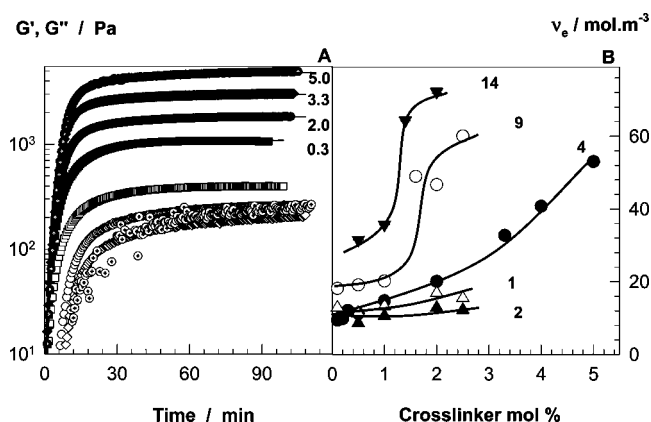


**Figure 1.** (A) $G'$ (filled symbols) and $G''$ (open symbols) of the reaction system in the presence of DMA-4 shown as a function of the reaction time. DMA-4 = 0.3 (■), 2.0 (●), 3.3 (♦), and 5 mol % (○). (B) The effective cross-link density $\nu_e$ of the hydrogels shown as a function of the cross-linker concentration. The solid curves are a guide to the eye. $x$ = 1 (△), 2 (▲), 4 (●), 9 (○), and 14 (▼).

time. Both moduli increase rapidly and then approach plateau values after 1 h. The gelation process is assumed to be complete when $G'$ and $G''$ reach a plateau value with time. To estimate the final modulus of the gels, $G'_\infty$, the experimental time-dependent modulus data of gels were fitted to a modified Hill equation:[7–10]

$$G'(t) = G'_\infty \frac{t^r}{t^r + t_{1/2}{}^r} \tag{1}$$

where $t$ is the reaction time, $t_{1/2}$ is the half-gelation time, and the exponent $r$ is a constant.[8,10] The fitting results using eq 1 are also drawn in Figure 1A by the solid curves, which are not distinguishable from the data points. Similar plots were also obtained for other cross-linkers of chain length $x$ = 1, 2, 9, and 14 (Figure S1). The values of $G'_\infty$ extracted from the fits indicate that the larger the cross-linker size, the larger is the elastic modulus of the resulting hydrogels (Figure S2). Half-gelation times $t_{1/2}$ and the coefficient $r$ of eq 1 were $11 \pm 3$ min and $1.8 \pm 0.3$, respectively, for all the cross-linkers used (Figure S2).

Assuming that the final elastic modulus $G'_\infty$ corresponds to the equilibrium shear modulus $G$, one may calculate the effective cross-link density $\nu_e$ of the hydrogels. $G$ relates to $\nu_e$ for a tetrafunctional phantom network by[11,12] $G = 0.5 \nu_e RT \nu_2^0$, where $\nu_2^0$ is the volume fraction of cross-linked polymer in the gel and $R$ and $T$ have their usual meanings. The calculation results are shown in Figure 1B plotted against the cross-linker content. Figure 2A shows cross-linker content dependence of the efficiency of the cross-linking reactions $\epsilon$, that is, the fraction of cross-linker molecules forming effective cross-links. $\epsilon$ was calculated using the equation $\epsilon = \nu_e/\nu_{chem}$, where $\nu_{chem}$ is the chemical cross-link density, which would result if all cross-linker molecules formed effective cross-links in the hydrogel.[5] Increasing the distance between the vinyl groups of the cross-linker represented by $x$ significantly increases the cross-linker efficiency and, thus, the effective cross-link density of the hydrogels, which was also evidenced by the swelling tests (Figure S3). Three effects may contribute to this behavior: (i) A small size cross-linker is more susceptible to form cycles during gelation, while this is not observed as much when a long size cross-linker is used.[13–16] (ii) Cross-linker bearing longer

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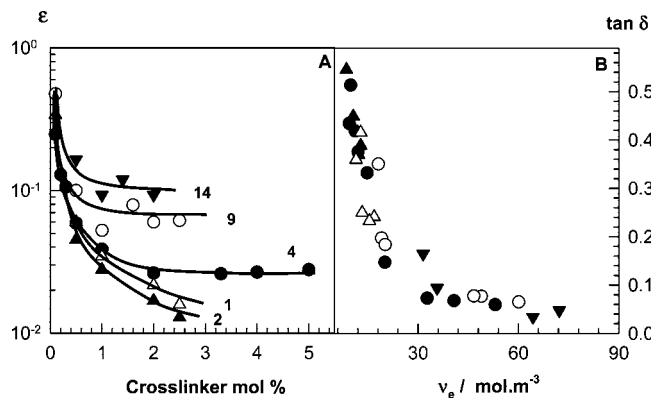[‡] Istanbul Technical University.

**Figure 2.** (A) Cross-linker efficiency $\epsilon$ is shown as a function of the cross-linker content. The cross-linker lengths $x$ are indicated. (B) Tan $\delta$ is shown as a function of $\nu_e$. $x = 1$ ($\triangle$), 2 ($\blacktriangle$), 4 ($\bullet$), 9 ($\circ$), and 14 ($\blacktriangledown$).



**Figure 3.** (A) $R(q)$ vs $q$ plots for hydrogels prepared using DMA-4 cross-linker. DMA-4 = 0 ($\bullet$), 2.0 ($\triangledown$), 2.5 ($\triangle$), 2.9 ($\blacktriangle$), 3.3 ($\blacktriangledown$), 4.0 ($\blacklozenge$), and 5.0 mol % ($\bullet$). (B) $R_{ex,90}$ shown as a function of the cross-linker content. The cross-linker lengths $x$ are indicated.



**Figure 4.** (A) $R_{ex,90}$ and (B) $\langle \eta^2 \rangle$ shown as a function of $\nu_e$ of hydrogels. The cross-linker lengths $x$ are indicated.

ethylene glycol repeating units bonds more water molecules so that the water solubility of the DMA-$x$ cross-linker is an increasing function of the chain length $x$.[17,18] Hence, the cross-linker having longer chain length has a less tendency to form cross-link clusters in gels so that $\epsilon$ increases. (iii) Increasing length and flexibility of the cross-linker also increases the number of quasi-cross-links formed by physical entanglements. This effect is also observable in Figure 1B. The intersection of the curves with the y-axes corresponding to the $\nu_e$ value at zero cross-linker content increases as $x$ is increased, indicating increasing contribution of the chain entanglements to the equilibrium elasticity of hydrogels. We should also note that a large size cross-linker has a larger molar volume compared to the small size cross-linkers which may also affect the results of our observations. From the limiting values of $G'$ and $G''$, the loss factor tan $\delta = G''/G'$ was calculated for each gelation system and is shown in Figure 2B plotted against $\nu_e$. The quantity tan $\delta$, representing the ratio of dissipated energy to stored energy during one deformation cycle, is below unity, that is, the reaction system shows a gel-like response over the whole range of the cross-linker concentrations. However, for the hydrogels with $\nu_e < 30$ mol $\cdot$ m$^{-3}$, tan $\delta$ is above 0.1, indicating that these gels belong to the category of weak gels. Indeed, frequency sweep tests conducted after a reaction time of 2 h showed that $G'$ is frequency dependent at cross-link densities below 30 mol$\cdot$m$^{-3}$. Therefore, the equilibrium modulus $G$ for such gels should deviate from $G'_\infty$measured at 1 Hz and, thus, the upturn in $\epsilon$ at low cross-link densities may partially originate from nonequilibrium effects.

Gelation reactions were also carried out in light scattering vials. After a reaction time of 1 day, the scattered light intensities of gels were recorded at various scattering angles $\theta$ from 14.5 to 152.5°, which correspond to the scattering vector $q$ range from $3.1 \times 10^{-4}$ to $2.4 \times 10^{-3}$ Å$^{-1}$. Figure 3A shows the Rayleigh ratio $R(q)$ versus $q$ plots for hydrogels prepared at various concentration of DMA-4. $R(q)$ for both gels and solution is nearly $q$-independent due to the fact that we are probing length scales that are large compared with those typical for polymer gels and for semidilute solutions. Similar plots such as those given in Figure 3A were also obtained using other cross-linkers, except DMA-2, which gave a maximum in $R(q)$ versus $q$ plots. Excess scattering intensity $R_{ex}(q)$, which is a measure of the degree of gel inhomogeneity, was calculated as $R_{ex}(q) = R_{gel}(q) - R_{sol}(q)$, where $R_{gel}(q)$ and $R_{sol}(q)$ are the Rayleigh ratios for the gel and polymer solution, respectively. To compare the excess scattering of different gels, we will focus on the excess
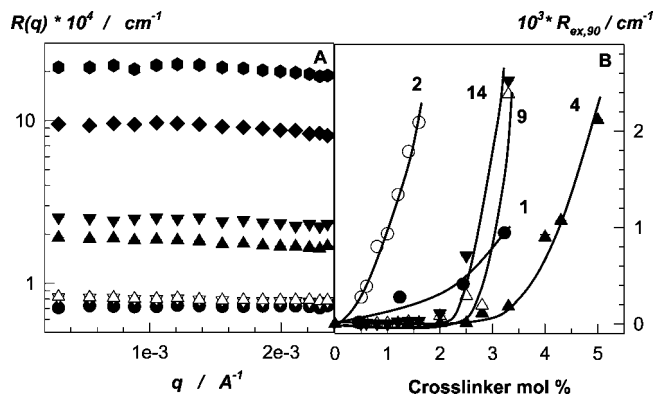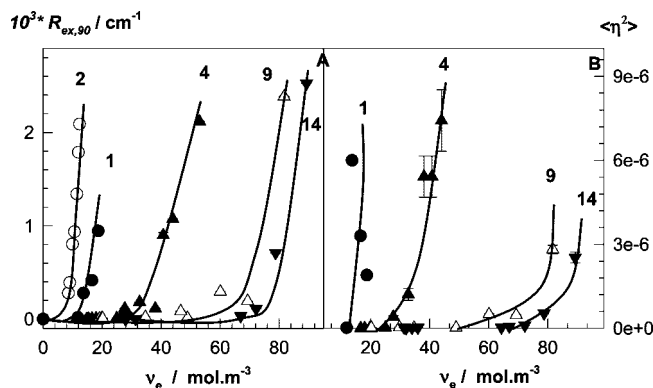
scattering intensity measured at a fixed scattering angle of 90° ($R_{ex,90}$). Figure 3B shows $R_{ex,90}$ plotted as a function of the concentration of cross-linker with $x = 1$ to 14. It is seen that $x = 2$ and 4 represent the two extremes, where the upturn in the excess scattering appears at the lowest and highest cross-linker contents, respectively, while at $x = 9$ and 14, the upturn appears at intermediate levels of cross-linker. For $x = 1$, excess scattering gradually increases with increasing content of the cross-linker. Thus, no distinction can be made from Figure 3B regarding the cross-linker size-dependence of spatial gel inhomogeneity.

However, a different behavior was observed if the effective cross-link density $\nu_e$ was taken as the independent parameter. In Figure 4A, the data given in Figure 3B were replotted as a function of $\nu_e$. The results clearly demonstrate that the upturn in the excess scattering appears later, that is, the gel remains homogeneous over a wider range of the cross-link density, as the size of the cross-linker is increased. Transparent PAAm hydrogels with $\nu_e = 70$ mol/m³ could be obtained using DMA-9 or DMA-14 cross-linkers. To estimate the amplitude and correlation length of the concentration fluctuations in the hydrogels, the experimental $R_{ex}(q)$ versus $q$ data were fitted to the Debye–Bueche equation[4,5,19–22]

$$R_{ex}(q) = \frac{4\pi K \xi^3 \langle \eta^2 \rangle}{(1 + q^2 \xi^2)^2} \qquad (2)$$

where $K$ is the optical constant, $K = 8\pi^2 n^2 \lambda^{-4}$, $n$ is the refractive index of the medium, $\lambda$ is the wavelength of the incident light in vacuum, $\xi$ is the correlation length of the scatterers, and $\langle \eta^2 \rangle$ is the mean square fluctuation of the refractive index. Calculated values of $\langle \eta^2 \rangle$ are shown in Figure 4B plotted as a function of

the cross-link density. In accord with Figure 4A, the magnitude of the concentration fluctuations represented by $\langle \eta^2 \rangle$ is much smaller in gels formed using long cross-linker molecules. The correlation length $\xi$ of the scatterers was found to be $10^1$ nm, which increased slightly with increasing cross-linker length (Figure S5).

In conclusion, the length of DMA cross-linkers plays an important role in the elasticity and spatial inhomogeneity of PAAm hydrogels. A clear correlation was found between the size and the efficiency of the cross-linker and the spatial gel inhomogeneity. A cross-linker having a longer chain length produces more effective cross-links during gelation and, thus, results in highly homogeneous hydrogels.

**Supporting Information Available:** Experimental procedures, methods, instrumentation, and supporting figures. This information is available free of charge via the Internet at http://pubs.acs.org.

## References and Notes

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(22) According to eq 2, the slope and the intercept of $R_{ex}(q)^{-1/2}$ vs $q^2$ plot (Debye−Bueche plot) give $\xi$ and $\langle \eta^2 \rangle$ of a gel sample.[4,5] In Figure S4, the excess scattering data from gel samples prepared in the presence of DMA-14 cross-linker are given in the form of Debye− Bueche plots. It is seen that straight lines are obtained in this analysis. Such straight lines were also obtained for other sets of gels prepared using cross-linkers with $x = 1$, 2, and 9.