VISCOELASTIC PROPERTIES OF HYDROPHILIC POLYMERS IN AQUEOUS DISPERSIONS[#]

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[#]This paper is dedicated to Professor Dr. Roman Modic

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Abstract

Rheological characterization of polymer solutions and polymer dispersions deals with wide range of mechanical responses. Flow behaviour and especially the viscoelastic properties of aqueous dispersions of hydrophilic bio-polymers: welan, gellan, and carboxymethyl cellulose were examined at low polymer concentrations. Different types of rheological responses were achieved by varying polymer concentration and by preparing different mixtures of the polymers at various mutual ratios. Dispersions of polymer blends were prepared at constant overall polymer concentration. These systems were prepared in order to study the influence of different structural conditions of the samples on rheological properties. The transition from sol-to-gel behaviour was achieved by changing the polymer concentration, or by changing the composition at constant polymer concentration. The viscoelastic properties of the systems were measured under non-destructive shear conditions of oscillatory shear, by using the controlled stress rheometer. The analysis of experimental data was performed by using the generalized Maxwell model and the Friedrich - Braun model for describing the mechanical spectra in linear viscoelastic regime.

Introduction

Aqueous polymer solutions, especially those of natural biopolymers are very important material source in various industrial branches because they exhibit high stability level, good compatibility and are biodegradable. In recent years, the production and the application of such environmental friendly materials considerably increase. Industrial uses of the carbohydrate systems center on their ability to thicken or structure many times their own weight of water, or in other words they control the rheology of hydrated systems. The solution properties of these carbohydrates are of considerable interest for a number of practical commercial applications such as thickening, suspending and gelling agents.[1-3] For example, hydrophilic polymers represent one of the most used materials in the production of almost all pharmaceutical dosage forms; as gelling agents structuring hydrogels, or as thickeners of the continuous phase in dispersions (emulsions and suspensions). The natural polysaccharides used as carrier materials in the encapsulation technology have the great advantage to be non-toxic, bio-compatible and biodegradable. Furthermore, aqueous dispersion of gellan is used in medicine to prepare eye lens. Due to a specific rheological properties of hydrophilic biopolymers, are of great interest from scientific and technological point of view in the field of food science and technology,[4,5] as well as in the other industrial branches (pharmacy, ceramics,[10] paints, textile, etc.). Aqueous dispersions of carbohydrates can be successfully used also as model fluids in order to simulate different rheological properties of real systems in various technological processes like mixing,[12] pumping etc.

Rheological behaviour of hydrophilic polymer dispersions in aqueous media in general exhibit the rheological behaviour characteristic for polymers or polymer solutions, but at certain circumstances also some specific rheological properties. Aqueous carbohydrates or bio-polymers, and synthetic systems (like cellulose ethers) can behave like pure liquids or like elastic solids.[1] The transport properties and, specifically, the rheological behaviour of real and complex materials such as carbohydrate polymers can be significantly affected by several factors, mainly related to molecular and supermolecular features. Most of these factors are common to all polymeric systems, others are peculiar to carbohydrate polymers.[4] Relevant forces to intermolecular associations of carbohydrate systems and, the formation of 3D structural network or gel structures, are chain associations, hydrogen bonding, Coulombic, dipole-dipole, Van der Waals charge and hydrophobic interactions. All these fluctuate with time, temperature and environmental conditions. Since the mechanical properties hydrophilic polymer dispersions depend on their physical and chemical conditions, their network structural formations depend on the polymer concentration, ionic strength, presence of organic solvents, pH etc.[1]

In general, hydrophilic polymers are able to form in aqueous media three-dimensional network structures, or gel structure, already at very low polymer concentrations.[1,5] The systems with gel structure exhibit elastic solid behaviour under the conditions of small deformations. Through a rheological study it is not only possible to evaluate the time evolution of the macroscopic properties of a given system, but also that of its structural and/or molecular characteristics.[1] The structural conditions of hydrophilic polymer dispersions can be classified as: dilute polymer solutions, weak gels, micro gels and strong gels. Weak gels generally result from the co-operative action of physical non-covalent interactions between polymer chains in the formation of extended intermolecular junction zones. The whole system is composed by more or less extended stiff junction zones that involve two or more chains and by flexible chain segments between the junction zones. Its rheological properties lies between those of ordinary polymer solutions and strong gels, depending on the balance between these entropic and enthalpic contribution, as well as on the degree of connectivity and heterogeneity of the network.[1] With increasing stress the intermolecular junctions breaks down, leading to strong decrease in viscosity and permitting the flow of the system. Thanks to the physical nature of the interaction bonds, this situation is reversible, but sometimes takes time.

Our study is focused on the examination of the systems, which form physical gels, i.e. without the chemical crosslinking of the polymer molecules. At low polymer concentration such materials exhibit liquid like behaviour, Newtonian or non-Newtonian. The rheological properties of hydrophilic polymer dispersions can be changed by changing physical and chemical conditions, and under the proper conditions they can exhibit the behaviour characteristics for semi-solids.[5] At higher polymer concentrations overlapping and associations of the polymer molecules result in formation of an extended junction zones, and consequently a three-dimensional network is formed, where the junction zones play the part of the point crosslinks in covalent gels. Strong gel behaviour can be observed when the polymer association is strong. Under small deformation conditions the mechanical spectra of strong gels approximate closely to solid like behaviour. When subjected to large deformation or continuous flow conditions, the gel network ruptures into small gel regions. The flow conditions then become heterogeneous. This is not the case for weak gels, which may flow homogeneously, even under continuous shear conditions. They exhibit marked non-Newtonian properties, strictly connected to the progressive disruption of the network into smaller flow units as the shear rate increases.[1] Also weak gels exhibit elastic solid behaviour under the conditions of small deformations, but the elastic contribution to the viscoelastic response is in this case not so pronounced, as for strong gels. The stability and macroscopic integrity of the gel structure depend on the balance between polymer-polymer and polymer-solvent interactions. When polymer aggregation is favoured, segregation into two phases may take place or inter-chain association may be restricted to small microgel clusters dispersed in a macromolecular solution. The rheological behaviour of the microgels, depend on the polymer concentration. At high concentration of the aggregates they exhibit solid like behaviour at low stresses and their rheological properties cannot be easily distinguished from those of weak gels.

Correlation of rheological data and modeling constitute a complementary step, necessary for the exploitation of the experimental results. All approaches to date modeling fall into two main categories: the phenomenological and microrheological (molecular) approaches. The former deals with the development and definition of the model according to the principles of continuum mechanics. It based upon achievement the maximum agreement between predicted and experimental data. The latter is based on the definition of rheological properties, starting from molecular or microscopic parameters which identify the components of the system.

The analysis of viscoelastic data in our work is based on the phenomenological approach. Starting point of the modeling is to consider the fluid's rheology equivalent to a parallel series of Maxwell elements as shown in Figure1.

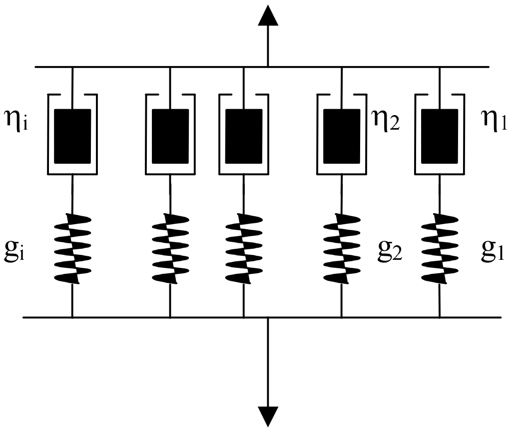

Figure 1:The generalised Maxwell model, g_i: spring constants, η_i: viscosities

Each spring and each dashpot has a characteristic relaxation time λ, given by the ratio of the viscosity η and the elastic modulus g of the element ($\lambda = \eta/g$). By considering a discrete array of springs and dashpots it is possible to incorporate a discrete range of relaxation times within the model. The differential equation governing a single Maxwell element for a simple shear is:

$$\frac{d\tau}{dt} + \frac{\tau}{\lambda} = \frac{d\gamma}{dt} \cdot g\ , \qquad (1)$$

where $d\gamma/dt$ is the strain rate of the element and τ the current shear stress. Under the condition of oscillatory shear the strain rate and the shear stress can be written as:

$$\frac{d\gamma}{dt} = \omega\gamma_0 \cdot \cos(\omega t) \qquad (2)$$

$$\tau = G^*\gamma_0 \cos\delta \cdot \sin(\omega t) + G^*\gamma_0 \sin\delta \cdot \cos(\omega t) = \gamma_0\left[G'\sin(\omega t) + G''\cos(\omega t)\right] \qquad (3)$$

where ω is angular frequency, G’ and G’’ are storage and loss moduli, respectively. The moduli in a single Maxwell element can be written:

$$G' = \left[\frac{g\lambda^2\omega^2}{1+\lambda^2\omega^2}\right] \quad \text{and} \quad G'' = \left[\frac{g\lambda\omega}{1+\lambda^2\omega^2}\right] \qquad (4)$$

Usually the single Maxwell element is not sufficient for describing linear viscoelastic response of real liquids under oscillatory shear conditions. More general response is obtained by putting any number of the Maxwell elements in parallel series.[6] In this case the values of overall G’ and G’’ at any frequency are given by the sum of i contributions from i th Maxwell elements:

$$G''(\omega) = \sum_i \frac{g_i\lambda_i^2\omega^2}{\left(1+\lambda_i^2\omega^2\right)} \qquad (5)$$

$$G''(\omega) = \sum_i \frac{g_i\lambda_i\omega}{\left(1+\lambda_i^2\omega^2\right)} \qquad (6)$$

The dynamic response of viscoelastic liquid over a range of frequencies can be modeled by choosing a range of Maxwell elements with appropriate values of g and λ chosen to cover the range used in experiment for which G’ and G’’ values are available.

Frequency dependence of storage and loss moduli can be also described with the model, suggested by Friedrich and Braun which belong to the class of the fractional derivative models.[7] The model is able to describe a wide range of viscoelastic responses, starting from pure viscous liquid to elastic solid by a limited number of parameters. In the differential form the model can be expressed as:

$$\overline{\overline{\tau}} + D^{c}\left[\overline{\overline{\tau}}\right] = G_{\infty}\left\{D^{0}\left[\overline{\overline{\gamma}}\right] + D^{c}\left[\overline{\overline{\gamma}}\right]\right\} + \Delta G\, D^{d}\left[\overline{\overline{\gamma}}\right] \qquad (7)$$

The equation correspond to 'solid model' when c = d = 1 and for $G_\infty > 0$. On the basis of fractional derivative analysis the mechanical spectra can be expressed with the following relations:

$$G'(\omega) = G_{\infty} + \Delta G \frac{(\lambda_{FB}\omega)^{d}\left[\cos\left(\frac{\pi}{2}d\right) + (\lambda_{FB}\omega)^{c}\cos\left(\frac{\pi}{2}(d-c)\right)\right]}{1 + 2(\lambda_{FB}\omega)^{c}\cos\left(\frac{\pi}{2}c\right) + (\lambda_{FB}\omega)^{2c}} \qquad (8)$$

$$G''(\omega) = \Delta G \frac{(\lambda_{FB}\omega)^{d}\left[\sin\left(\frac{\pi}{2}d\right) + (\lambda_{FB}\omega)^{c}\sin\left(\frac{\pi}{2}(d-c)\right)\right]}{1 + 2(\lambda_{FB}\omega)^{c}\cos\left(\frac{\pi}{2}c\right) + (\lambda_{FB}\omega)^{2c}} \qquad (9)$$

Parameter G_∞ represent the equilibrium modulus when the frequency tends to zero. The model describes liquid like response, if $G_\infty = 0$. Parameter λ_{FB} is a characteristic time of a material, which determine the relative contribution of the elastic and viscous components in the viscoelastic response and, consequently, the extension of the frequency region where the elastic or viscous contribution prevail. When c = d = 1 and $G_\infty = 0$ the fractional derivative model coincide the Maxwell model and, correspondingly, λ_{FB} becomes relaxation time of the fluid. Hence, λ_{FB} can be named as fractional relaxation time. The models for describing G'(ω) and G''(ω) suggested by Friedrich and Braun generalize the relation introduced by Tschoegl [8] for the relaxation of the Cole - Cole behaviour by introduction an additional parameter d (the exponent). The exponent c in Eqs. (8) and (9) originally comes from Cole - Cole functions. When d = 1 the decrease of the exponent c ($c \leq 1$) influences the function G'(ω) over the whole frequency range, whereas the material function G''(ω) is appreciably modified only at higher frequencies. This is due to appearance of asymmetry of G''(ω) which is often observed for various real materials and is not possible to describe with original form of Cole - Cole behaviour.[8]

In the present work the viscoelastic properties of hydrophilic biopolymers dispersed in water at low polymer concentrations were studied. The analysis of viscoelastic data in linear viscoelastic regime was examined in order to study sol-gel transition by changing the polymer concentration, or by changing the composition of polymers in water. The application of the discussed viscoelastic models proved satisfactory fitting results for all studied systems. The transition from polymer solution to weak gel behaviour for the systems under examination was followed by the variation of the model parameters.

Experimental

Materials:

Welan (K1C376 – Kelco - CRETE) is an acidic microbial polysaccharide produced by Alcaligenes spp. ATCC 31555. **CMC** is a purified sodium carboxymethyl cellulose (BLANOSE Cellulose gum 7HF). The powdered polymers welan and CMC were dissolved in distilled water by mechanical stirring at ambient temperature. The samples of pure polymers and those of polymer mixtures (W/CMC) were prepared, having the same overall polymer concentration, (1wt. %). All the samples were stored for two days to ensure a complete wetting of the polymer, before the rheological tests was carried out.

Gellan gum (KELCOGEL) is a microbial polysaccharide produced by fermentation of the organism Pseudomonas elodea. The gellan is soluble in water at temperature above 90 °C. The aqueous gellan solutions undergo thermally induced sol – gel transition. At higher temperatures they exhibit sol behaviour.[4] The samples at different polymer concentrations, from 0.3 to 0.8 wt. % were dissolved at 96 °C in distilled water by mechanical stirring. When the solutions were cooled the gelation appeared at temperature about 29 °C.

The rheological tests were performed under steady and oscillatory shear conditions at 20 °C. The controlled stress rheometer Haake, RheoStress RS 150 was used and equipped with a cone and plate sensor system (C 6/°4). The flow curves were obtained by stress sweep tests under destructive shear conditions. The upper limit of linear viscoelastic response (LVR) under oscillatory shear conditions were determined from stress sweep at frequency of 1Hz. The mechanical spectra in LVR were measured at constant strain amplitude of 0.03.

Results and discussion

The major part of present work is concerned with the viscoelastic properties of aqueous solutions of biopolymers. These systems are capable to form complex structures at low polymer concentrations. Two type of systems were prepared in order to study sol-gel transition. The aqueous dispersions of CMC, welan and mixtures of both polymers CMC-welan were prepared at the same polymer concentration of 1wt. %. The other systems contained gellan at different polymer concentrations.

The flow curves in Figures 2 and 3 illustrate only the first impression about different structural conditions in examined aqueous biopolymer solutions. They also demonstrate the differences between the flow properties typical for polymer solution and those peculiar to weak gel behaviour. Polymer solutions, like CMC in Figure 2 and gellan at low polymer concentration (up to 0.5 wt. %) in Figure 3 exhibit a first newtonian plateau at low shear stress conditions followed by shear thinning behaviour. The presence of welan in the composition (Figure 2) or increase of gellan concentration (Figure 3) is reflected in more complex flow properties. These systems exhibit more pronounced decrease of viscosity in a narrow shear stress range and time dependent effects on flow properties. Furthermore, Figure 3 demonstrates a strong variation of viscosity with increasing gellan concentration in narrow range from 0.3 to 0.75 wt. %.

More exact information about structural conditions in examined systems can be obtained from the tests under non-destructive conditions of oscillatory shear. The upper limit of linear viscoelastic response (LVR) is determined from stress sweep experiment at frequency of 1 Hz. When the system passes from polymer solution to more complex structural conditions, the critical strain amplitude which determines the upper limit of linearv viscoelastic response decreases appreciably. In the LVR the dynamic functions are independent on applied amplitude of shear stress (or strain) at constant frequency. At the exit of LVR the dynamic moduli decrease and the phase lag increases with further increasing strain amplitude as shown in Figure 4 for CMC – welan systens and in Figure 5 for aqueous gellan systems at different polymer concentrations.

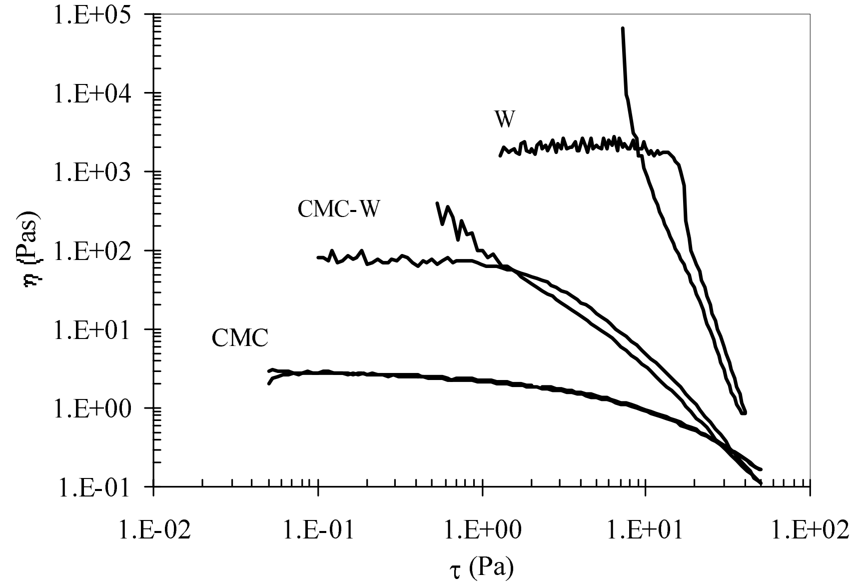

Figure 2: Flow curves of CMC, CMC-W (ratio 1:1) and welan in 1 wt. % of polymer solution.

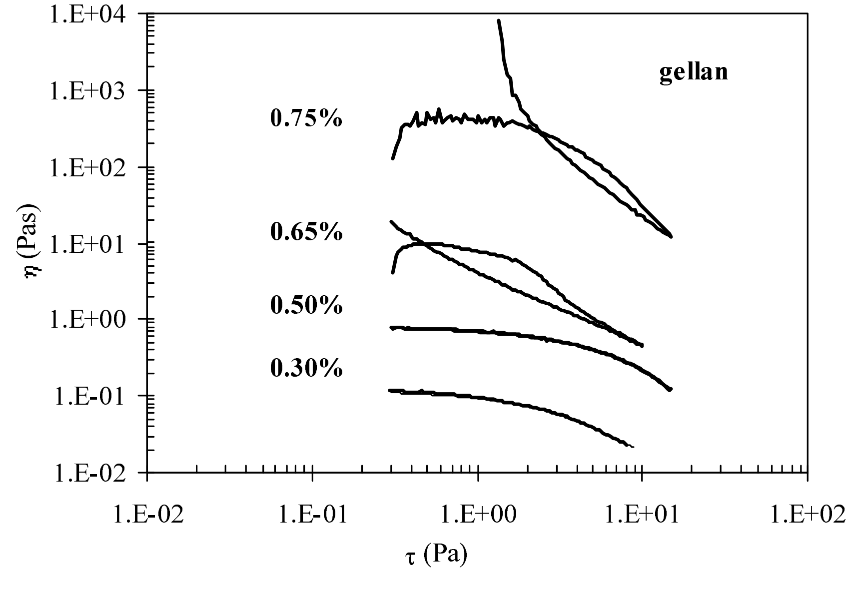

Figure 3: Flow curves of aqueous gellan systems at different polymer concentrations.

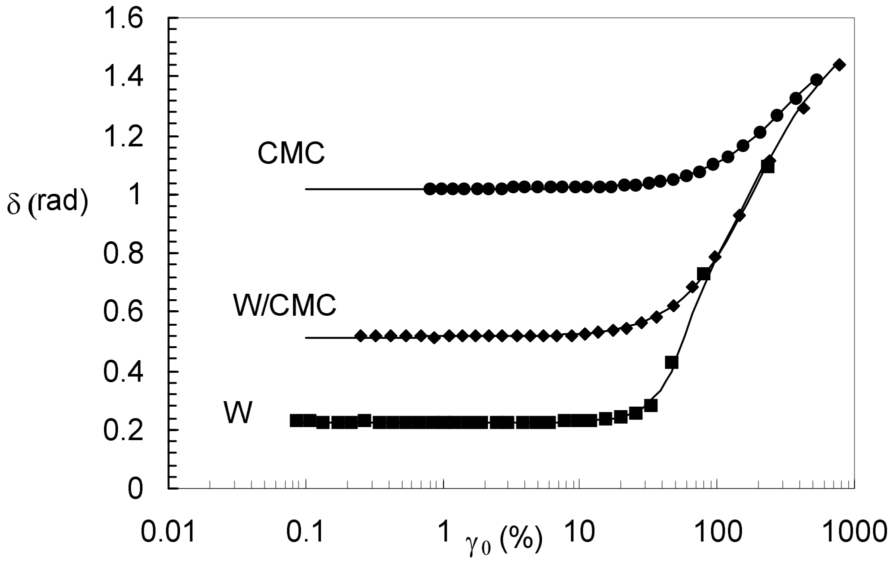

Figure 4: Phase lag vs. strain amplitude at 1Hz from stress sweep tests of CMC-welan systems. W/CMC represents the system with both polymers at ratio of 1:1.

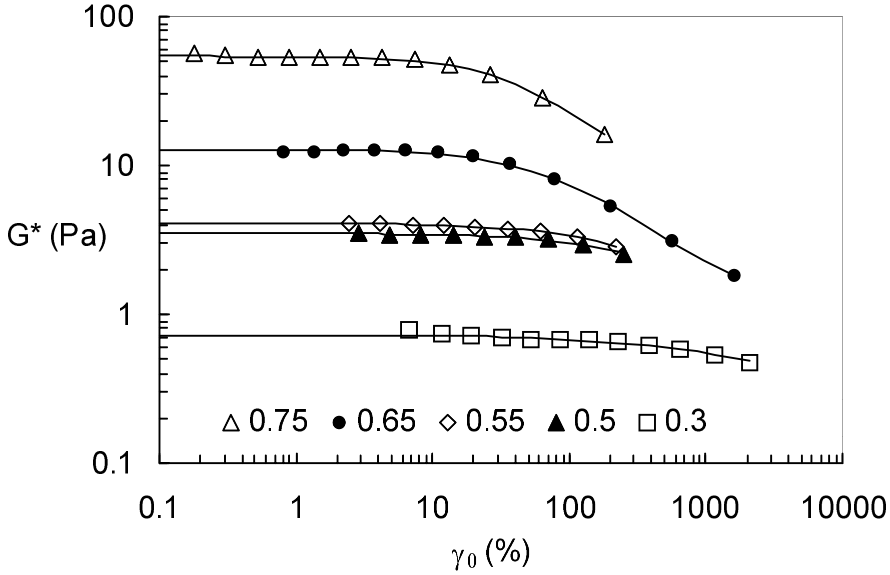

Figure 5: Complex modulus vs. strain amplitude at 1Hz obtained by stress sweep tests of aqueous gellan systems at different polymer concentrations

For a certain material the same critical strain amplitude (γ_c), which define the upper limit of LVR, should be determined from the dependence of complex modulus, complex viscosity or phase lag on applied strain amplitude. In general also critical strain amplitude depends on applied frequency, but it often does not change appreciably. Often stress sweep tests are used in order to determine the strain conditions of materials under which LVR can be measured when frequency sweep tests are performed. For aqueous systems under examination the critical strain amplitude indicates different structural conditions. When the systems exhibit the rheological properties, typical to polymer solution, γ_c is higher (about 60 %) and progressively decreases with increasing gellan concentration or, when two polymers (CMC and welan) are mixed at the same overall polymer concentration of 1 wt. % as shown in Figure 6.

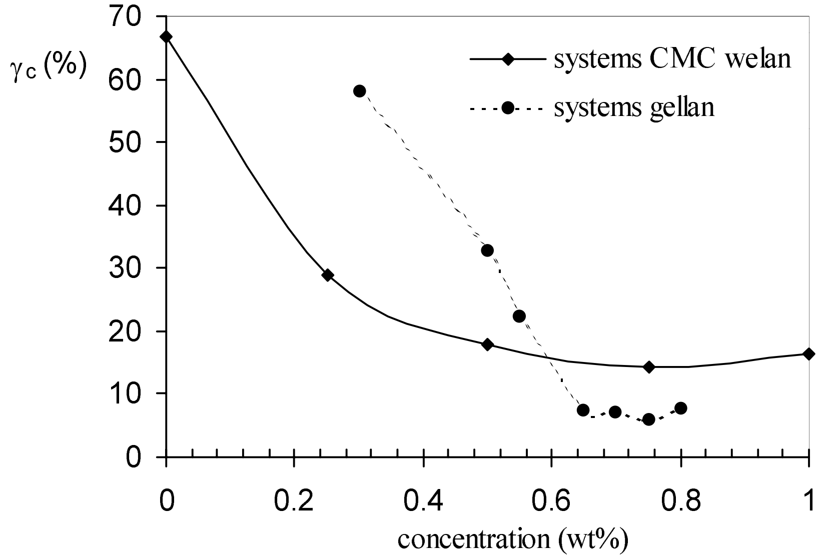

Figure 6: Critical strain aptitude vs. polymer concentration for gellan systems; and vs. welan concentration for CMC- welan mixtures at 1wt % of overall polymer concentration.

The mechanical spectra of all examined systems, i.e. frequency dependence of loss and storage moduli, are measured under the conditions of LVR. Since the stress sweep tests are performed only at frequency of 1Hz, the frequency sweep tests are carried out at very low, constant, strain amplitude of 3%. The mechanical spectra of CMC–welan systems are shown in Figure 7. In the examined frequency range the viscous contribution to viscoelastic response (loss modulus) is predominant for CMC at 1wt. %. The elastic contribution (storage modulus) becomes more important only at higher frequencies. Both moduli appreciably increase with increasing frequency. The elastic contribution becomes predominant in the whole frequency range examined when the system is composed of CMC and welan (1:1). For pure aqueous welan system at 1 wt % of polymer, the elastic contribution dominates and both moduli are almost independent of applied frequency which is usually found for weak gel behaviour.

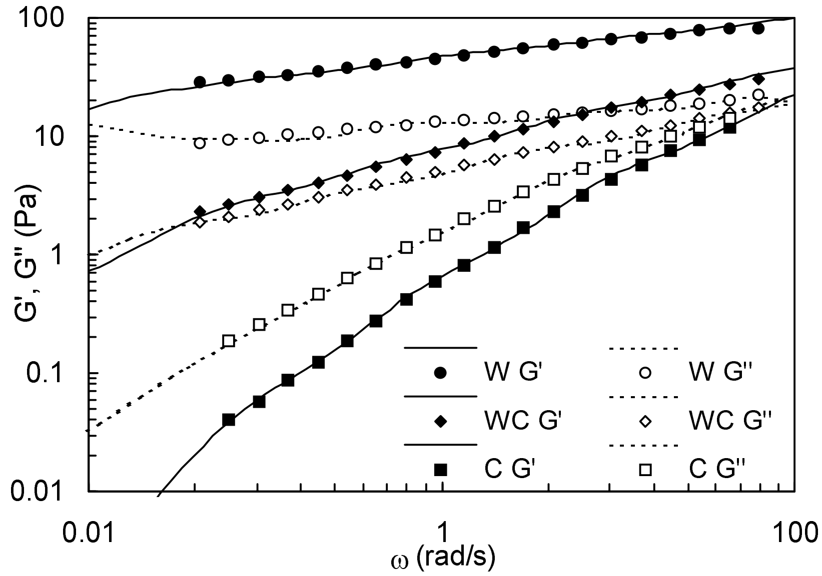

Figure 7: Frequency dependence of loss (G'') and storage (G') moduli for CMC–welan systems, curves are calculated from the generalised Maxwell model.

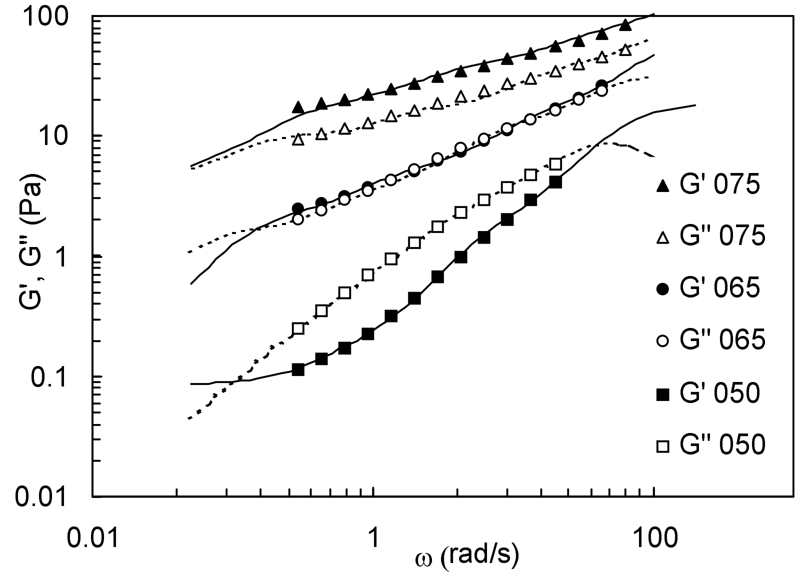

Figure 8: Frequency dependence of loss (G'') and storage (G') moduli for gellan at different concentrations, curves are calculated from the generalised Maxwell model.

Similar frequency dependencies of the dynamic moduli can be found also in the case of gellan systems at increased polymer concentration, as shown in Figure 8. Last two figures also show that with increasing welan content (in the composition of CMC-welan), or with increasing gellan concentration (> 0.65 wt. %) the dependencies of G'(ω) and G''(ω) become parallel to each other and G' is by one order of magnitude higher than G''. Such a condition corresponds to an apparent sol/gel transition according to the criterion suggested by Winter and Chambon.[9] For the analysis of viscoelastic behaviour the experimental data are correlated according to the generalised Maxwell model. To avoid the problems concerning the evaluation of fitting parameters □i and gi from the experimental data, it is necessary to fix a maximum number of elements in a series and to set a constraint which allows only positive values of the parameters. The curves passing the experimental data in Figures 7 and 8 are evaluated by using the Eqs. (5) and (6).

As a result of this modelling procedure a relaxation spectra of each sample are evaluated. For CMC and for gellan systems at low polymer concentrations the elastic modulus, g_i, continuously decreases with increasing relaxation time λ_i. Such edge-type distribution of relaxation times is typical for polymer solutions.[1]

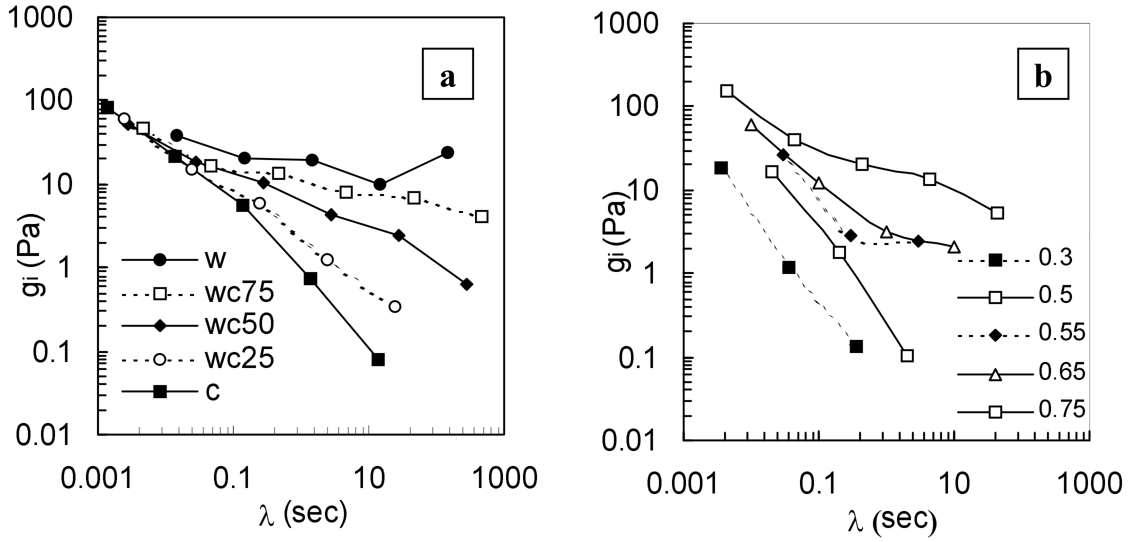

Figure 9: The relaxation spectra of CMC-welan systems at constant overall polymer concentration (a) and of aqueous gellan systems at different concentrations (b).

When the structure of material becomes more complex, the decrease g_i (λ_i) is less pronounced and is shifted toward longer relaxation times. The increase of welan in the CMC-welan system and increase of gellan concentration in Figures 9a and 9b leads to a gradual shifting of the relaxation spectrum towards higher values with the appearance of a box-type distribution of relaxation times which is characteristic for structured systems like dense entanglement polymeric networks.[10, 11]

In order to analyse the viscoelastic behaviour of studied systems and to determine a sol – gel transition of the systems, the experimental data are examined with an another approach suggested by Friedrich and Braun.[7] A fractional derivative model under the condition of oscillatory shear leads to Eqs. (8) and (9). The model parameters are determined by applying the fitting procedure simultaneously for both $G'(\omega)$ and $G''(\omega)$, in the same way as follows when the Eqs. (5) and (6) are used. In both cases, as an objective function in the minimisation procedure the mean square relative deviation is used. Frequency dependence of loss and storage modulus at different polymer composition of CMC-welan systems together with the curves thorough the experimental data calculated by applying Eqs. (8) and (9) are shown in Figures 10a and 10b, respectively. Evidently the model with five adjustable parameters (G_∞, ΔG, λ_{FB}, c, d) provides a satisfactory fitting, which is comparable with (or even better than) the results obtained with the generalised Maxwell model with five elements. Similarly high fitting quality is attained also when the model was applied for the analysis of gellan systems at different polymer concentration.

At the same polymer concentration of CMC-welan systems in Figures 10a and 10b, the viscous contribution to the viscoelastic response in the high frequency range tends toward the same value, whereas at low frequencies the differences due to different structural conditions are well noticeable. The elastic contribution (G') increases more markedly than the viscous one (G'') with increasing welan concentration in the composition of the systems. This effect is more pronounced in low frequency region. All these gradual changes are well described by the corresponding variations of the Friedrich and Braun model parameters, as shown in Figure 11.

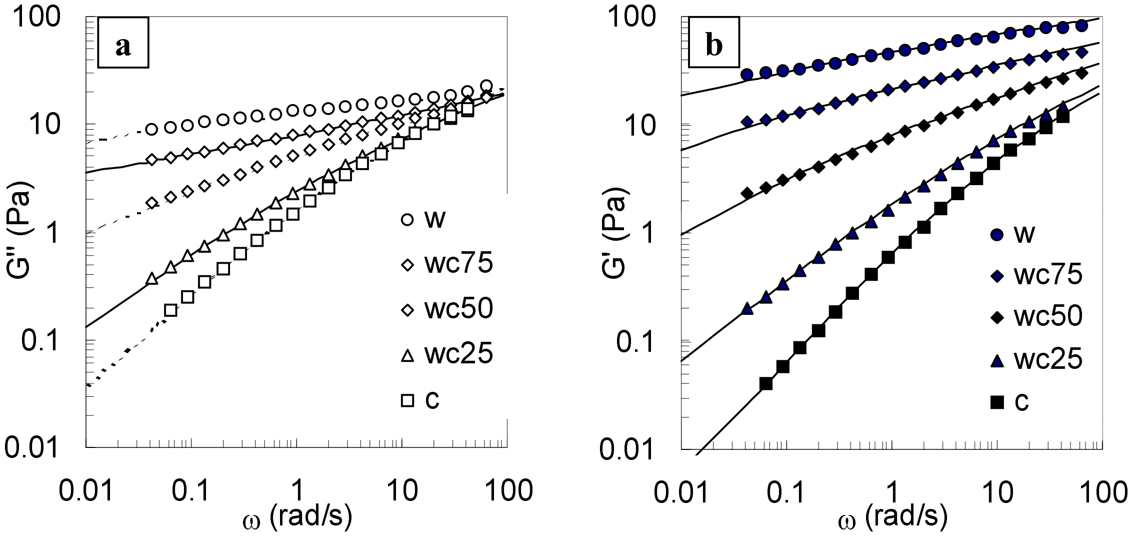

Figure 10: Frequency dependence of (a) loss (G’’) and (b) storage modulus (G’) for CMC-welan systems. The curves throughout the experimental data are calculated using the Friedrich and Brown model.

Although the transition from polymer solution to weak-gel behaviour of gellan systems with increasing polymer concentration is not exactly the same as it is observed for CMC-welan systems, the variation of model parameters exhibit similar trends. Since the mechanical spectra of gellan systems have been already shown in the Figure 8 only variations of the model parameters (G_∞, ΔG, λ_{FB}, c, d) are reported in Figure 12. For both systems the characteristic time of the material, □FB, which determine the role of the relative contribution of the elastic and viscous components in the viscoelastic response strongly increases when material passes from polymer solution to weak gel behaviour. For both systems ΔG remains nearly constant, even if the viscosity under destructive shear conditions and the dynamic moduli under non-destructive shear conditions appreciably increase with increasing welan content, or gellan concentration. When the materials pass from polymer solution to weak gel behaviour a gradual decrease of fractional derivative order d is observed in both cases, whereas a sharp minimum of derivation order c at sol-gel transition point is found only for gellan systems.

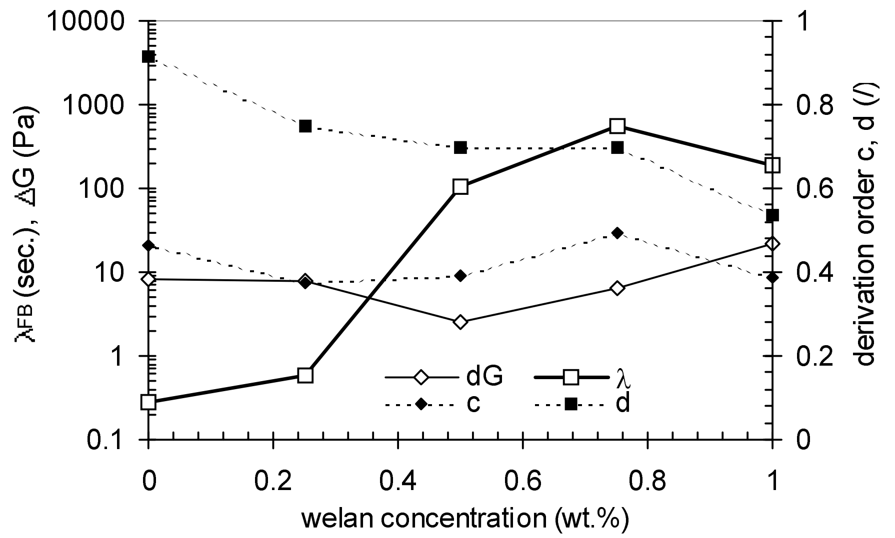

Figure 11: Parameters of the Friedrich and Braun model (Eqs. (8),(9)) for CMC-welan systems

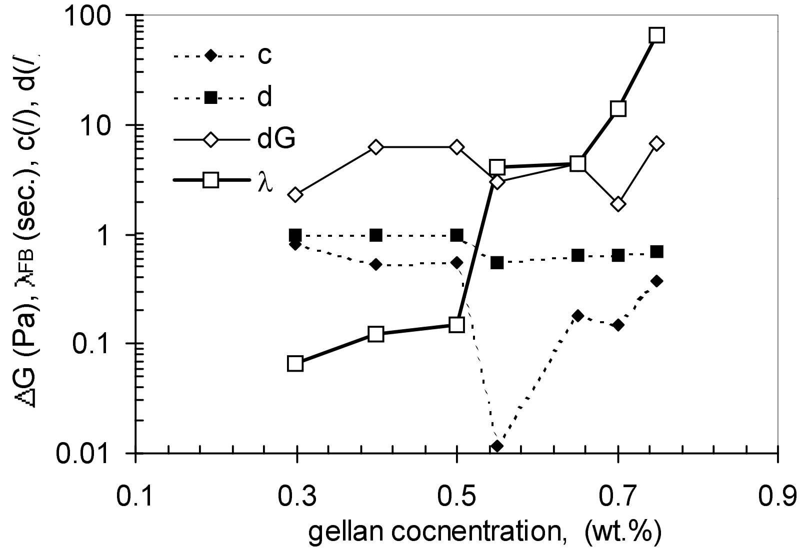

Figure 12:Parameters of the Friedrich and Braun model (eqs. (8),(9)) for gellan systems at different polymer concentrations.

Conclusions

Hydrophilic polymers in aqueous media are capable to form a complex structures which are, at certain circumstances already at low polymer concentrations, responsible for a weak gel behaviour.

Due to great interest of this materials a number of detailed investigations can be found in literature, but they are often focused only on a specific material and with a specific purposes. A detailed rheological analysis in this field prove uniform characterisation of the materials and is not limited only to a certain class of materials.

Prepared samples exhibited different types of rheological behavior. A gradual transition from the behavior characteristics for polymer solution to those peculiar for weak gels was observed for both classes of investigated systems. The analysis of viscoelastic data under non-destructive shear conditions enable to distinguish between those different types rheological properties, which are a consequence of different structural conditions in the samples. More exactly, from experimental data in linear viscoelastic regime a wide range of information about material functions can be evaluated. Application of different suitable viscoelastic models to the experimental data allows to follow the structural changes by changing the composition (or concentration) of the systems through the parameter analysis. The model parameters in this case are actually physical properties and (or) a discrete material functions. Both models used in the present work: the generalised Maxwell model and the Fruedrich Braun model correlate the experimental data very well. They have been already successfully applied for describing the rheological behaviour of different complex fluids, for example.[3,6,10,11] Also in this study the sol-gel transition was possible to determine from the analysis of the parameters involved in the applied models.

Nomenclature

c	fractional derivative order in Eqs. (8) and (9) (-)
d	fractional derivative order in Eqs. (8) and (9) (-)
G^*	complex shear modulus (Pa)
G'	storage modulus (Pa)
G''	loss modulus (Pa)
G_∞	equilibrium modulus in Eqs. (8) and (9), (Pa)
ΔG	parameter in Eqs. (8) and (9) (Pa)
g_i	elastic modulus of the ith Maxwell element
t	time (sec)

Greek letters

δ	phase lag (rad)
γ_0	strain amplitude (-)
γ_c	critical strain amplitude (-)
λ_i	the relaxation time of the ith Maxwell element (s)
λ_{FB}	the relaxation time of the Friedrich and Braun model in Eqs. 8 and 9 (s)
η	viscosity (Pa.s)
τ	shear stress (Pa)
ω	frequency (rad/s)

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Povzetek

Proučevali smo reološke lastnosti vodnih disperzij naslednjih hidrofilnih biopolomerov: welan, gellan in karboksi metil celuloza pri nizkih koncentracijah polimera. Še posebej smo se osredotočili na analizo viskoelastičnih lastnosti. Izkazalo se je, da omenjeni polimeri pri enaki koncentraciji izkazujejo različne reološke lastnosti, od takih značilne za polimerne raztopine do lastnosti šibkih gelskih struktur. Z mešnjem vodnih disperzij biopolimerov smo pripravili raztopine z enako celokupno koncentracijo, ki so izkazovale različne reološke lastnosti. Spreminjanje reološkega obnašanja smo proučevali tudi v primeru spreminjanja koncentracije gellana v vodi. Namen našega dela je bil doličiti prehod iz polimerne raztopine v šibek gel na osnovi reoliških lastnosti. Postopno spreminjanje reoloških lastnosti z mešanjem dveh biopolimerov (welan-CMC) ali s spreminjanjem koncentracije polimera v vodi je posledica različne strukturiranosti proučevanih vzorcev. Za analizo viskoelastičnih lastnosti smo uporabili splošen Maxwellov model in model Friedrich Brauna. Izkazalo se je, da oba modela zelo dobro opišeta eksperimentalne podatke. Analiza parametrov modelov pa omogoča kvantitativno optrdeliti spremembe v strukturi vzorcev (glede na sestavo ali koncentracijo polimera v vodi), torej opredeliti sol-gel prehod.