Gellan gum fluid gels. Influence of the nature and concentration of gel-promoting ions on rheological properties.

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Abstract

Low-acyl gellan gum fluid gels were obtained using two different gel-promoting cations under the same processing conditions and their rheological properties were investigated. For that reason, stress and frequency sweeps measurements and flow curves tests were carried out. Small amplitude oscillatory shear assays demonstrated that these materials exhibit weak gel behaviour despite the shape of their mechanical spectra being similar to those obtained from strong gels. However, the existence of a weak gel structure was confirmed by the fact that the difference between the elastic and viscous components was of only one order of magnitude. In addition, a reduction in the storage and lost modules and the viscosity as a function of the applied shear was observed with increasing cation concentration. Finally, in order to produce fluid gels, a higher concentration of the monovalent cation was required than when divalent cations were employed in the low-acyl gellan gum fluid gels formulation.

Keywords

Low-acyl gellan gum, fluid gel, Rheology, Viscoelasticity, Very shear thinning, Gel-promoting cation.

Introduction

It is well known that fluid gels can be produced by polysaccharides capable of forming strong gels. This is possible when a strong gel manufactured under quiescent conditions is disturbed by submitting the sample to mechanical energy [1]. Consequently, the resulting sample shows a heterogeneous microstructure consisting of an irregularly-shaped cluster with gel-like behaviour suspended in an aqueous phase whose polysaccharide concentration is smaller than that present in the microgels formed. Among the biopolymers which can produce fluid gels are gellan gum [2, 3], agar, K-carrageenan, whey protein [4] or alginate [5]. Norton et al. [6] proposed a model to explain the form and stability of fluid gels. The latter model establishes a as a consequence of a gelation

stage takes place the particles or clusters form when the biopolymers aqueous solution is cooled under mechanical treatment. The cluster sizes are dependent of the shear conditions. Following, the molecular ordering is attained. The particle size and volume fraction achieved are as a function of the applied shear during process and the polymer concentration in the fluid gel formulation. In addition, the fluid gels stability is maintained while it is not submitted at the melting temperature.

Although the sample presents rheological behaviour somewhere between that of a strong gel and weak gel, it is closer to the latter. These rheological properties make possible the current and future applications of fluid gels as suspension [3] and satiety [7] agents, emulsion stabilizers [8]. Additionally, other applications can be mentioned in pharmaceutical and biomedical fields such topical administration of diclofenac [9] or in the paint formulation [10]. In the food industry, low-acyl gellan gum, as a fluid gel, is widely used, since this biopolymer has been utilized as a food additive in the USA from 1992 and, in addition, its use is currently authorized in other countries. The code established by The International Numbering System for food additives for gellan gum is INS 418 [11].

Gellan gum is a biopolysaccharide obtained by microbial fermentation from Sphingomonas elodea (ATCC 31461) [3] which can produce strong gels when gel-promoting ions are added to the gellan gum solution under cooling conditions. The disturbance of the formation of this strong gel gives rise to the development of a fluid gel, as mentioned above. The nature and ionic strength of gel-promoting ions chosen to prepare the fluid gels determine their final rheological properties. The main applications of gellan gum as a fluid gel are as a suspending agent in some drinks, such as citrus drinks or chocolate milk. On another hand, it is also utilized to suspend coloured particles in translucent drinks [12].

The main objectives of this work are the study of the effect of the nature of the salt employed to provide gel-promoting ions and the influence of the cation concentration on the rheological properties of fluid gels containing 0.2 wt% gellan gum. For these purposes, small amplitude oscillatory shear and steady-state measurements were carried out.

Materials and methods

Materials

Low-acyl gellan gum (Kelcogel® F^{TM}) cordially provided by CP-Kelco (San Diego, USA) was employed as obtained and it has molecular weight of $2\text{-}3\cdot10^5$ Da. This substance will be designated as LA-gellan in the rest of this paper. Its concentration in the fluid gels formulation was 0.2 wt %. To acquire Na^+ or Ca^{2+} gel-promoting ions, 99.5% purity NaCl [3] supplied from Panreac (Barcelona, Spain) and 98% purity $CaCl_2$ provided by Merck were used. $CaCl_2$ concentrations assessed were $9.0\cdot10^{-3}$ M, $1.1\cdot10^{-2}$ M, $1.3\cdot10^{-2}$ M, $1.6\cdot10^{-2}$ M and $1.8\cdot10^{-2}$ M, and NaCl concentrations studied were 0.22 M, 0.24 M and 0.27M. Deionised water was always utilized and 0.1 wt % sodium azide was used to preserve the fluid gels.

Fluid gel preparation

LA-gellan fluid gels were prepared in batches of 600 g following the steps suggested by Sworn (2009), as was done in a previous work [13]. In order to disperse the LA-gellan gum powder, it was added slowly to a vessel placed within a water-bath at 80º C. The hydration step was carried out at 80º C while stirring at 700rpm for 25 min was maintained using an Ika-Visc MR-D1 homogenizer (Ika, Germany) equipped with a sawtooth-type impeller. The impeller diameter/container diameter ratio was 0.85. Once the 25 minutes had elapsed, the required amount of $CaCl_2$ or NaCl was added and the solution was maintained under mechanical treatment at 80º C for 5min. Water loss by evaporation was corrected by adding the appropriate quantity of deionised water. Afterwards, the sample vessel was placed in a thermostatic bath at 20ºC and the gelation step was carried out by submitting the solution to mechanical treatment under 700 rpm with the aforementioned

Ika-Visc homogenizer for 1500s [13, 14, 15]. The cooling rate was 2.4ºC/min. Finally, the fluid gels were stored at 4.5 ºC for at least 48 h before performing the rheological study.

Rheological Characterization

In order to perform stress sweep and frequency sweep measurements, a controlled-stress rheometer AR2000 (TA Instruments, Crawley, United Kingdom) was employed. These tests were carried out at 20 ºC. A parallel plate with serrated surfaces, 40mm diameter and a measuring gap of 1mm was used as a sensor system. It should be noted that in order to avoid wall depletion phenomena, sensor systems with rough surfaces were required, since in previous works it was demonstrated that the gellan gum fluid gel structure consists of microgels in aqueous phase, this being a heterogeneous microstructure [1]. To prevent losses as a consequence of evaporation during measurements, a thin film of Dow-Corning 200® (Dow Chemical Co.) silicon oil fluid (kinematic viscosity, 20 cSt) was applied to enclose the plate rim. The estimation of the dynamic linear viscoelastic range (DLVR) was performed by stress sweeps under oscillatory shear measurements at three different frequencies (0.1, 1, 3 Hz), from 0.008 to 3 Pa. The frequency sweep tests were conducted in the 3-0.01 Hz frequency range as this is within the linear range of response. Flow behaviour was studied using a Haake RS100 controlled stress rheometer (Thermo Scientific, Karlsruhe, Germany), with a parallel plate sensor system with serrated surfaces (60mm diameter and a measuring gap of 1mm). The shear rate variation with the plate radius in the flow curves data was corrected by using the following equations [16]:

$$\eta_{corr}(\dot{\gamma}_R) = \eta_N [1 + (m/4)] \quad (1)$$

$$\tau_{corr}(\dot{\gamma}_R) = \eta_N [1 + (m/4)] \cdot \dot{\gamma}_R \quad (2)$$

where, $\eta_{newt} = (2 \cdot H/(\pi \cdot R^4)) * (M/\Omega)$; $m = d(\log \eta_{newt})/d(\log \dot{\gamma}_R) = n_{PL} - 1$; $\dot{\gamma}_R$ is the rim shear rate; τ_{corr} is the corrected shear stress; H is the gap between plates; Ω is the angular velocity; R is the plate radius, M is the torque applied, η_{newt} is the viscosity calculated at the rim of the parallel plate geometry and n_{PL} is the power law flow index.

The measurements were carried out in the 0.5-33Pa shear stress range by a step-wise procedure.

The samples were maintained in a rest state in the measuring gap for 600 s of equilibration time, before conducting the rheological test, in order to avoid any effects of recent mechanical history after the loading procedure.

Each type of measurement was carried out at least 4 times and in all of them, fresh sample was used.

In order to determine the existence of the significant differences between the results in this work, the standard deviations of all assessed parameters are shown in each table. For this purpose, the ANOVA ONE WAY method using Statgraphic Plus software was used.

Results and discussion

Dynamic linear viscoelastic range (DLVR)

Fig. 1 shows the influence of the Ca^{2+} concentration on the stress sweep results obtained to determine the DLVR at the three studied frequencies chosen in order to avoid destruction of the sample structure [12]. This Figure exhibits constant values of G' and G'' up to a certain shear stress, the critical stress, which is related to the inception of the non-linear zone characterized by the dependence of the shear stress applied on the viscoelastic moduli. The microstructural reorganization before breakdown entails energy dissipation which brings about an increase in G'' values up to a peak value at the beginning of the non-linear response [16, 17]. It is interesting to mention that, from that moment, the G' value began to decrease. As can be observed in Fig.1, the Ca^{2+} concentration had no influence on the extension of the linear viscoelastic range. The critical stress values shown in Table 1 demonstrate that there is a slight decrease in their values as the frequency increases. However, this tendency is not clear in the critical strain values. Additionally, data show a decrease in the viscoelastic modules with an increase in the Ca^{2+} concentration.

Figure 1

Table 1

Similar behaviour is observed when the stress sweep measurements were carried out over the gellan gum fluid gels containing Na^{+} as a gel-promoting cation (Fig.2), that is, there was a decrease in the G' and G'' values with an increase in the cation concentration.

However, there was a slight reduction in the DLVR with increasing-Na^+ concentration. This is also supported by Table 2.

Figure 2

Table 2

Mechanical spectra

The frequency sweep results are displayed in Fig.3. The data show the storage module ($G´$) is larger than the loss module ($G´´$) over the whole frequency range studied. In addition, the mechanical spectra of gellan gum fluid gels containing both gel-promoting cations exhibited the typical behaviour shown by strong gels which present a) a slow frequency dependence on $G´$ characteristic slopes and b) a minimum of $G´´$in the mid-section of the frequency range. However, they cannot be considered strong gels since there is only a difference of one order of magnitude between the storage module values and the loss module values. Additionally, as can be observed, both an increase in Ca^{2+} concentration (Fig.3a) and Na^+ concentration (Fig.3b) provoked a fall in the viscoelastic moduli. However, this trend started to be significant when the value of Ca^{2+} reached $1.8 \cdot 10^{-2}$ M, while significant differences in the case of Na^+ were found for the sample containing 0.27 M NaCl.

Figure 3a

Figure 3b

This effect of the concentration of the gel-promoting ions on the mechanical spectra is due to the fact that the gellan gum is an anionic biopolymer and an increase in the cation concentration causes a rise in the charge screen effect resulting in a decrease in the repulsive interactions between the gellan gum macromolecules. Previous works have reported that the existence of cations in solutions of polyelectrolyte provokes the screening of the charge along the chains of polysaccharide involving a little and closely packed structure resulting in a decrease in their rheological parameters [18, 19]. In addition, the presence of inorganic salts with a degree of hydration causes the thickness formation around the polysaccharide molecules provoking a reduction in these parameters [20].

Fig.3a shows the occurrence of a minimum peak in the $G´´$ curves of the order of magnitude of 0.6 rad/s which makes it possible to estimate the plateau module value, G_N^0, [21, 22]. The plateau module gives an idea of the level of the interactions among the gelled particles forming the fluid gel. Fig.3c illustrates the plateau module, G_N^0, as a

function of the $CaCl_2$ concentration. The decrease in the G_N^0 in $1.8 \cdot 10^{-2}$ M $CaCl_2$ indicates that the concentration needed to form the gels is exceeded. This fact can be associated with the charge screen effect between the gellan macromolecules since it is an anionic polyelectrolyte.

Figure 3c

Additionally, it can be observed that the mechanical spectra shape did not change in the $CaCl_2$ concentration range studied, indicating the existence of the same microstructure. This fact is supported by the representation of exponent ($n´$) of the power equation which relates $G´$ to the angular frequency ($G´ \sim \omega^{n´}$) (Fig.3d). The value of $n´$ was practically constant at about 0.02 which is very close to zero. This result is typical of strong gels. However, according to the criteria proposed by Ross-Murphy [23], the gellan gum fluid gels cannot be classified as strong gels since the strong gels undergo shear-induced fracture under flow, their linear viscoelastic region is broad and the differences between G' and G" are great enough to support the occurrence of a self-supporting gel. Here, the difference between $G´$ and $G´´$ was of only one order of magnitude, which is more characteristic of weak gels and justifies the fluid gel consistency.

Figure 3d

Moreover, it must be noted that smaller Ca^{2+} concentrations lead to similar, or even higher, $G´$ and $G´´$ values in the mechanical spectra than those shown by the samples involving higher Na^+ concentrations in their formulation (Fig.3). This fact has been attributed to the ionic strength and the nature of the salt employed [24]. The single divalent ion is capable of substituting each monovalent ion-water-monovalent ion interaction between two carboxylates [25].

Steady state test

The influence of the concentration of gel-promoting ions can be observed in Fig.4 (Ca^{2+} cations in Fig.4a and Na^+ cations in Fig.4b) where the viscosity is plotted against the shear stress.

It must be mentioned that the most noticeable aspect of the flow curves, for both Ca^{2+} and Na^+, is their "very shear thinning" [26] behaviour for all concentrations studied. This behaviour is characterized by showing high plateau viscosity values at low shear stresses and zero shear viscosity. However, as reported in several works [14,15] the high time necessary to achieve the real steady state at low shear stresses or rates makes it necessary

to appeal to creep compliance measurements. Therefore, in most cases, the apparent Newtonian viscosity observed in the flow curves, which must be obtained by means of creep compliance tests [27]. The viscosities shown at the smallest shear stresses represent the tendency to reach an apparent Newtonian viscosity as a result of the experimental design, which was flow curve with a protocol with 5 minutes per point. Nevertheless, this apparent Newtonian viscosity obtained from flow curves do not correspond with the steady state response at low shear stresses since at least 60 minutes per shear stress test are required to reach it [28]. In addition, it is possible to observe in Fig.4 the existence of a critical shear stress or "yield stress" from which a little increase in the shear stress value provokes a decrease in viscosity of 5 orders of magnitude for Ca^{2+}, and 6 orders of magnitude in the case of Na^{+}.

Figure 4

Table 3a

Table 3a exhibits the practical yield stress as a function of the concentration of gel-promoting ions. These results indicate a general tendency of decreasing practical yield stress as cation concentrations increase.

In Fig.5 the influence of the corrected shear stress was plotted as a function of shear rate. In addition, the fit of the results to a Herschel-Bulkley equation (3) has been included:

$$\tau - \tau_0 = k \cdot \dot{\gamma}^{n} \quad (3)$$

Moreover, this equation becomes the following (4) when $\dot{\gamma} = 1\ s^{-1}$ and $K = \tau_1 - \tau_0$:

$$\tau = \tau_0 + (\tau_1 - \tau_0) \cdot \dot{\gamma}^{n} \quad (4)$$

Where K is the consistency index ($Pa \cdot s^{-n}$) and its units are dependent of the flow index, n, τ is the shear stress and τ_0 is the yield stress predicted by the Herschel-Bulkley equation (Pa). The parameters obtained from this equation are shown in Table 3.

Figure 5

Table 3

Both Fig.5 and Table 3 support the fact that the data were fairly well fitted to the Herschel-Bulkley equation. The yield stresses obtained from Herschel-Bulkley were smaller than those estimated from the graph. The yield stress values of the Herschel-Bulkley equation

exhibited a slight tendency to decrease as the concentration of gel-promoting ions increased for both cations studied. This result is coherent with those observed in frequency sweep measurements due to the increase in the charge screen effect when the cation concentration increases, as mentioned above [18,19]. Additionally, the index flow values shown in Table 3b were typical of materials presenting shear thinning behaviour. Moreover, a slight tendency to increase with Ca^{2+} concentration was observed. However, this effect was not so evident in the case of Na^{+}.

Conclusions

In this work, the influence of the nature of the gel-promoting cations and their concentration on the gellan gum fluid gel rheological behaviour was assessed. The extent of the dynamic lineal viscoelastic range was not affected by the Ca^{2+} concentration. However, increasing Na^{+} concentration provoked a slight fall in the DLVR extension. On the other hand, critical shear stresses were smaller as the frequency increased. Mechanical spectra of fluid gels containing both cations, Ca^{2+} or Na^{+}, exhibited a typical strong gel shape. Nevertheless, the difference between the storage module and the loss module was more characteristic of weak gels. The data correspond to a rubber-like region of relaxation. In the case of Ca^{2+}, the plateau modulus showed a slight decrease with increasing concentration, but the decrease was significant at 0.2 wt % Ca^{2+}.

Steady state tests made it possible to determine that gellan gum fluid gel showed a "very shear thinning" behaviour for all formulations studied. This fact made it possible to estimate the practical stress values. In addition, the flow curves were well fitted to the Herschel-Bulkley equation. However, the yield stress values obtained from the latter equation were higher than those estimated from the graph.

This study confirms that the rheological properties of gellan gum fluid gels, such as the predominance of the storage module over the loss module, extremely great apparent viscosity at low shear and the existence of a yield stress, make it an excellent stabilizer of dispersions.

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Conflict of interest

There no was conflicts of interest to declare

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Table captions

Table 1. Determination of dynamic linear viscoelastic region at studied frequencies (0.1, 1 and 3 Hz) for fluid gels containing 0.2 wt% LA-gellan gum and $CaCl_2$ as gel-promoting ions. Temperature: 20ºC

Table 2. Determination of dynamic linear viscoelastic region at studied frequencies (0.1, 1 and 3 Hz) for fluid gels containing 0.2 wt% LA-gellan gum and NaCl as gel-promoting ions. Temperature: 20ºC

Table 3a. Determination of practical yield stress for fluid gels containing 0.2wt % and NaCl or CaCl2 as gel-promoting ions. T=20ºC

Table 3b. Fitting parameters of the Herschel-Bulkley equation for fluid gels containing 0.2 wt% LA-gellan gum and $CaCl_2$ or NaCl as gel-promoting ions, prepared by different mechanical protocols. Temperature: 20ºC. E stands for standard error of fitting parameters

Tables

Table 1. Determination of dynamic linear viscoelastic region at studied frequencies (0.1, 1 and 3 Hz) for fluid gels containing 0.2 wt% LA-gellan gum and $CaCl_2$ as gel-promoting ions. Temperature: 20ºC

[$CaCl_2$] M	τ_c (Pa)						γ_c					
	0.1Hz	SD (0.1Hz)	1Hz	SD (1Hz)	3Hz	SD (3Hz)	0.1Hz	SD (0.1Hz)	1Hz	SD (1Hz)	3Hz	SD (3Hz)
$9.0 \cdot 10^{-3}$	0.30	0.04	0.10	0.06	0.10	0.13	0.006	0.002	0.001	0.000	0.004	0.002
$1.1 \cdot 10^{-2}$	0.30	0.11	0.10	0.10	0.04	0.04	0.005	0.003	0.002	0.001	0.002	0.001
$1.3 \cdot 10^{-2}$	0.20	0.05	0.20	0.00	0.06	0.03	0.004	0.001	0.005	0.001	0.003	0.001
$1.6 \cdot 10^{-2}$	0.30	0.12	0.10	0.03	0.06	0.02	0.006	0.003	0.004	0.001	0.004	0.000
$1.8 \cdot 10^{-2}$	0.20	0.02	0.10	0.00	0.05	0.02	0.004	0.000	0.003	0.001	0.009	0.001

Table 2. Determination of dynamic linear viscoelastic region at studied frequencies (0.1, 1 and 3 Hz) for fluid gels containing 0.2 wt% LA-gellan gum and NaCl as gel-promoting ions. Temperature: 20ºC.

[NaCl] M	τ_c (Pa)						γ					
	0.1 Hz	SD (0.1Hz)	1 Hz	SD (1Hz)	3 Hz	SD (3Hz)	0,1 Hz	SD (0.1Hz)	1 Hz	SD (1Hz)	3 Hz	SD (3Hz)
0.22	1.60	0.50	0.80	0.34	0.80	0.37	0.061	0.001	0.039	0.002	0.035	0.000
0.24	1.60	0.45	0.64	0.12	0.20	0.01	0.075	0.003	0.022	0.001	0.038	0.001
0.27	0.64	0.03	0.40	0.09	0.16	0.03	0.029	0.001	0.021	0.000	0.017	0.002

Table 3a. Determination of practical yield stress for fluid gels containing 0.2wt % and NaCl or $CaCl_2$ as gel-promoting ions. T=20ºC.

$CaCl_2$ (M)	Practical yield stress (Pa)	**NaCl (M)**	Practical yield stress (Pa)
$9.0 \cdot 10^{-3}$	7.3	**0.22**	6.4
$1.1 \cdot 10^{-2}$	4.3	**0.24**	6.4
$1.3 \cdot 10^{-2}$	4.5	**0.27**	4.8

$1.6 \cdot 10^{-2}$	2.7
$1.8 \cdot 10^{-2}$	4.1

Table 3b. Fitting parameters of the Herschel-Bulkley equation for fluid gels containing 0.2 wt% LA-gellan gum and $CaCl_2$ or NaCl as gel-promoting ions, prepared by different mechanical protocols. Temperature: 20ºC. E stands for standard error of fitting parameters

$CaCl_2$ M	**τ_0 (Pa)**	**$E_{\tau 0}$**	**$\tau_1 - \tau_0$ (Pa)**	**$E\tau_1 - \tau_0$**	**n**	**En**	**R^2**
$9.0 \cdot 10^{-3}$	3.5	0.7	0.83	0.34	0.45	0.06	0,978
$1.1 \cdot 10^{-2}$	2.5	0.6	0.20	0.08	0.63	0.05	0,986
$1.3 \cdot 10^{-2}$	2.6	0.5	0.11	0.05	0.69	0.06	0,983
$1.6 \cdot 10^{-2}$	2.1	0.4	0.05	-	0.81	0.06	0,988
$1.8 \cdot 10^{-2}$	2.4	0.6	0.12	0.07	0.71	0.08	0,983
NaCl M	**τ_0 (Pa)**	**$E_{\tau 0}$**	**$\tau_1 - \tau_0$ (Pa)**	**$E\tau_1 - \tau_0$**	**n**	**En**	**R^2**
0.22	2.36	0.51	0.06	-	0.75	0.010	0.979
0.24	3.68	0.08	0.04	-	0.82	0.001	0.999
0.27	1.90	0.31	0.10	-	0.71	0.004	0.990

Figure captions

Fig.1a. Stress sweep tests performed at 0.1Hz for fluid gels containing 0.2 wt% LA-gellan gum and $CaCl_2$ as gel-promoting ions. Temperature: 20ºC

Fig.1b. Stress sweep tests performed at 1Hz for fluid gels containing 0.2 wt% LA-gellan gum and $CaCl_2$ as gel-promoting ions. Temperature: 20ºC

Fig.1c. Stress sweep tests performed at 3 Hz for fluid gels containing 0.2 wt% LA-gellan gum and $CaCl_2$ as gel-promoting ions. Temperature: 20ºC

Fig.2a. Stress sweep tests performed at 0.1Hz for fluid gels containing 0.2 wt% LA-gellan gum and NaCl as gel-promoting ions. Temperature: 20ºC

Fig.2b. Stress sweep tests performed at 1Hz for fluid gels containing 0.2 wt% LA-gellan gum and NaCl as gel-promoting ions. Temperature: 20ºC

Fig.2c. Stress sweep tests performed at 3Hz for fluid gels containing 0.2 wt% LA-gellan gum and NaCl as gel-promoting ions. Temperature: 20ºC

Fig.3a. Mechanical spectra obtained at fixed shear stress of 0.02 Pa for fluid gels containing 0.2 wt% LA-gellan gum and $CaCl_2$ as gel-promoting ions. The error bars at different frequencies have been included to indicate the reproducibility of the test. Temperature: 20ºC

Fig.3b. Mechanical spectra obtained at fixed shear stress of 0.1Pa for fluid gels containing 0.2 wt% LA-gellan gum and NaCl as gel-promoting ions. The error bars at different frequencies have been included to indicate the reproducibility of the test. Temperature: 20ºC

Fig.3c. $CaCl_2$ concentration dependence on the plateau module (G^0_N) for fluid gels containing 0.2 wt% LA-gellan gum and $CaCl_2$ as gel-promoting ions. Temperature: 20ºC

Fig.3d. $CaCl_2$ concentration dependence on exponent (n´) of the power equation which relates G´ to the angular frequency ($G' \sim \omega^{n'}$) for fluid gels containing 0.2 wt% LA-gellan gum and $CaCl_2$ as gel-promoting ions. Temperature: 20ºC

Fig.4a. Corrected shear stress dependence of viscosity for fluid gels containing 0.2 wt% LA-gellan gum and $CaCl_2$ as gel-promoting ions. Temperature: 20ºC

Fig.4b. Corrected shear stress dependence of viscosity for fluid gels containing 0.2 wt% LA-gellan gum and NaCl as gel-promoting ions. Temperature: 20ºC

Fig.5a. Shear rate dependence of corrected shear stress for fluid gels containing 0.2 wt% LA-gellan gum and $CaCl_2$ as gel-promoting ions and fitting curve of the Herschel-Buckley model. Temperature: 20ºC

Fig.5b. Shear rate dependence of corrected shear stress for fluid gels containing 0.2 wt% LA-gellan gum and NaCl as gel-promoting ions and fitting curve of the Herschel-Buckley model. Temperature: 20ºC

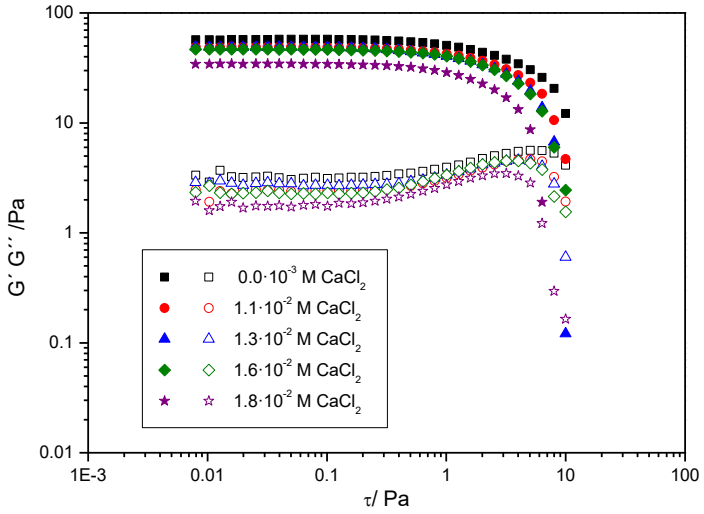


Figure 1a

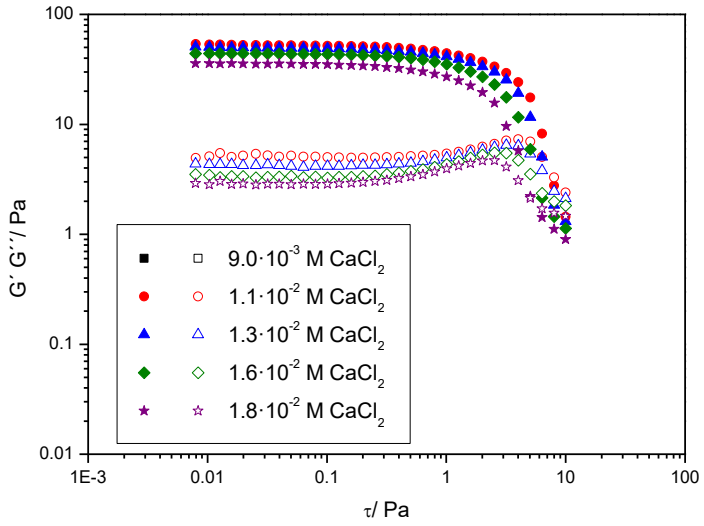


Figure 1b

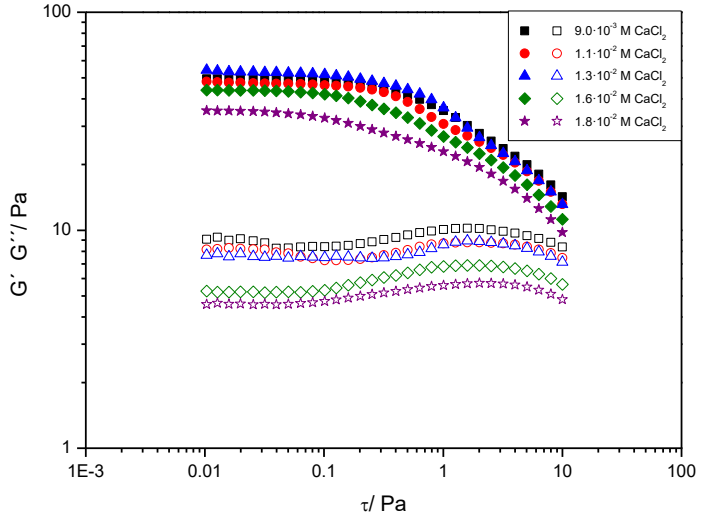


Figure 1c

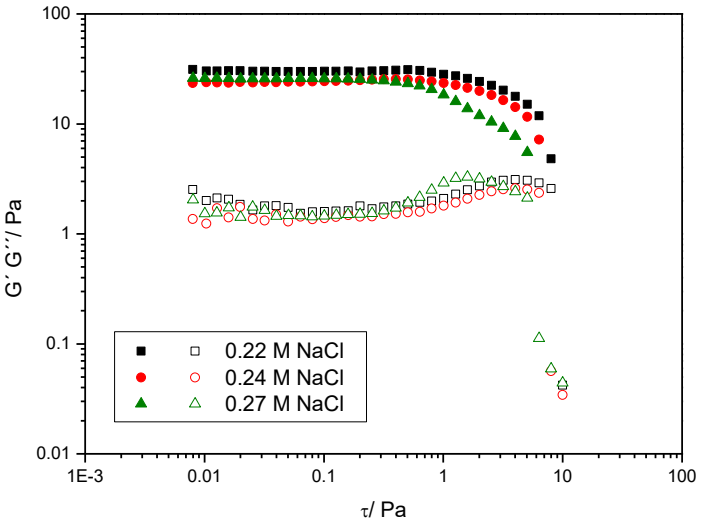
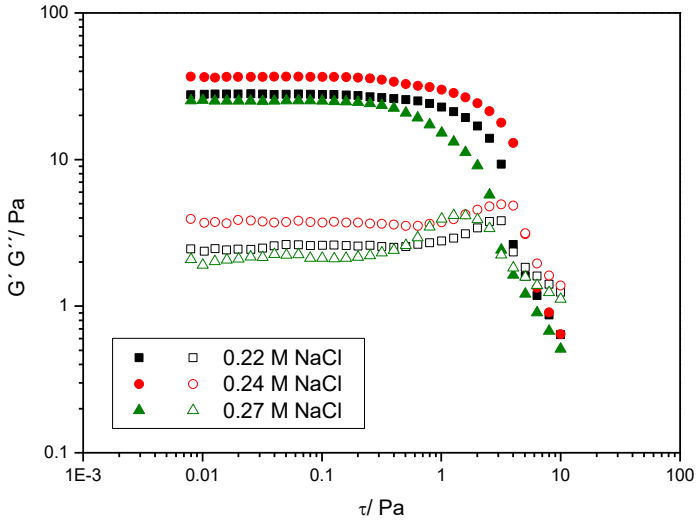


Figure 2a



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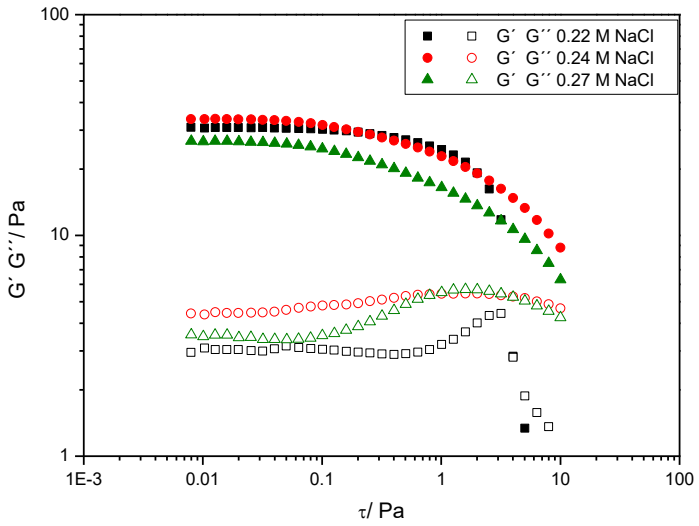


Figure 2c

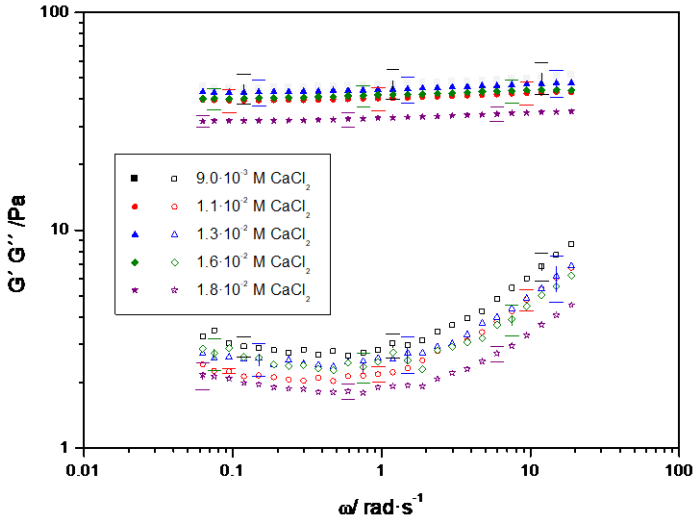


Figure 3a

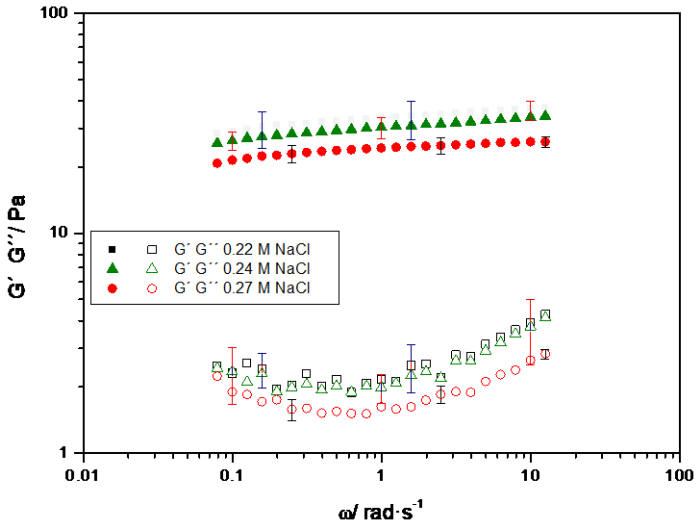
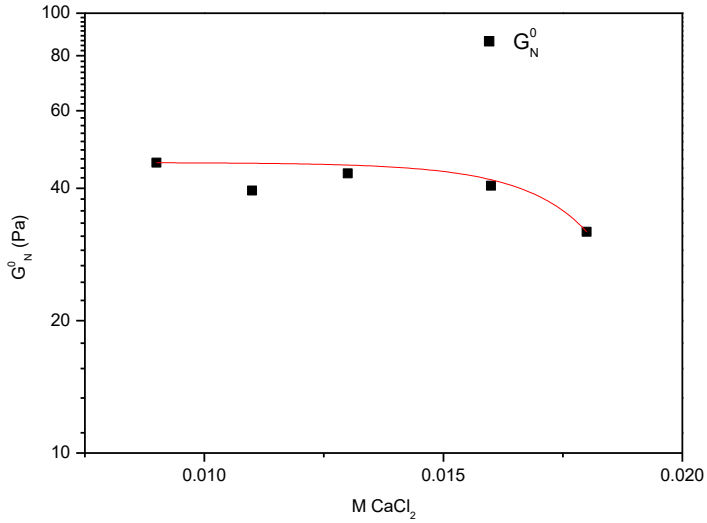


Figure 3b



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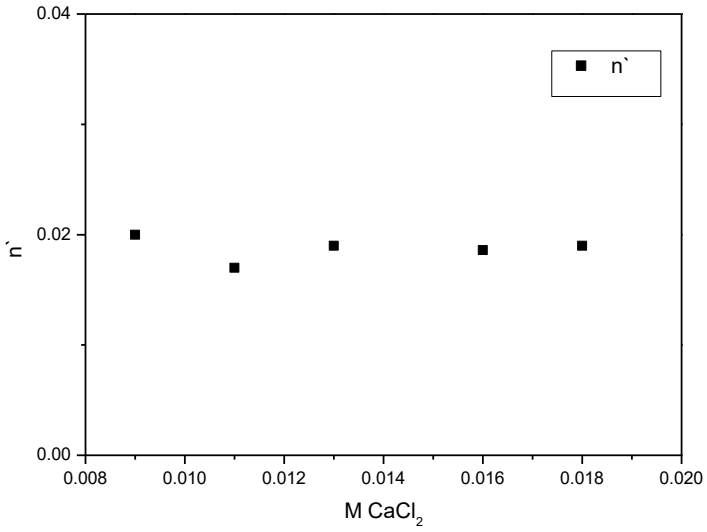

Figure 3d

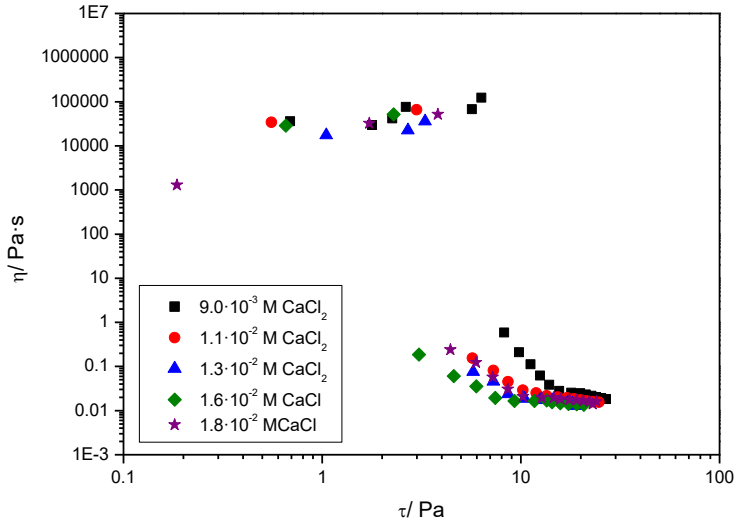

Figure 4a

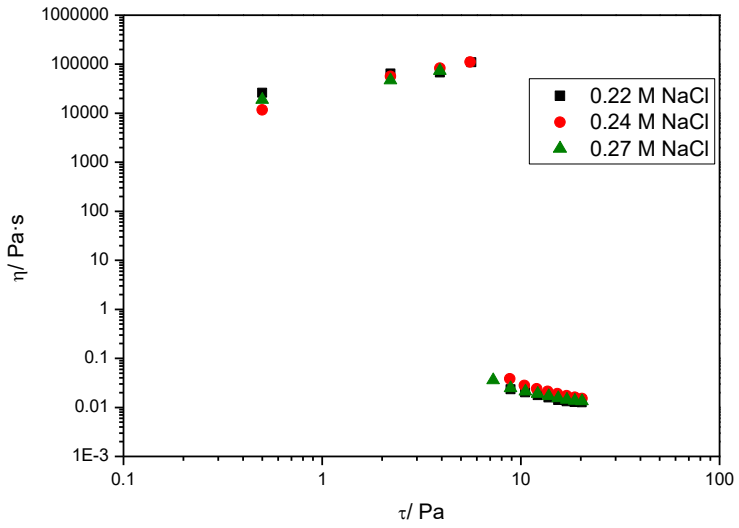

Figure 4b

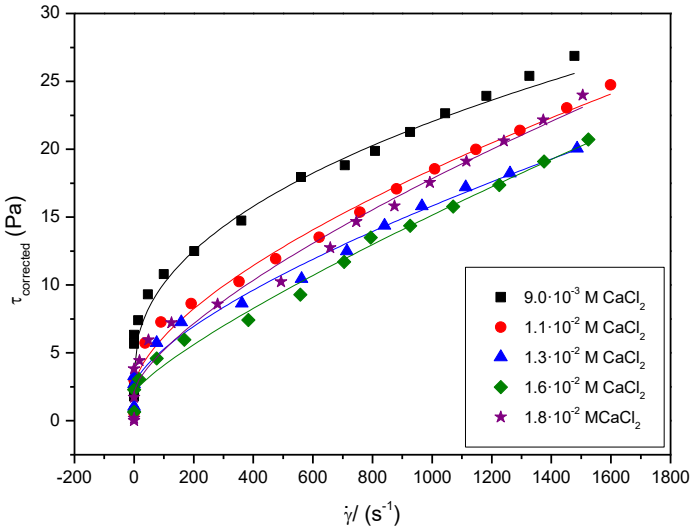

Figure 5a

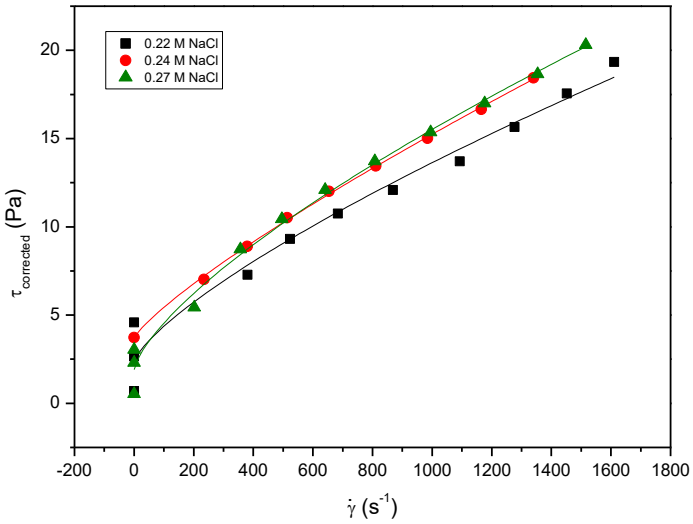

Figure 5b