Rheological properties of gels formed with furcellaran and globular proteins
bovine serum albumin and β-lactoglobulin

Katrin Laos¹, Geoffrey J. Brownsey², Margus Friedenthal¹ and Stephen G. Ring²

¹ Department of Food Processing, Tallinn University of Technology, Ehitajate tee 5, Tallinn 19086, Estonia
² Division of Food Materials Science, Institute of Food Research, Norwich Research Park, Colney, Norwich NR4 7UA, UK

ABSTRACT

The effect of the addition of the globular proteins, bovine serum albumin and β-lactoglobulin, on the properties of furcellaran gels was studied. The gels were found to be physically cross-linked networked gels. Proteins strongly influence the shear modulus. At low pH the phase-separation occurred with the change in loss tangent.

INTRODUCTION

Both proteins and polysaccharides contribute to the structural properties of foods through their aggregation and gelation behaviour. The development of novel gelled products from proteins and polysaccharides and their control needs a better understanding of gelation mechanisms and physical properties of mixed gels. When gelation occurs between two different polymers, three basic types of gel structure can be observed, namely interpenetrating, associative, and phase-separated networks. Interpenetrating networks form when the two components gel separately and form independent networks. Both networks are continuous throughout the sample but any interaction between them is only topological. Associative networks are formed when there are direct associations between polymers prior to network formation. Phase-separation can be segregative (also called thermodynamic incompatibility) and associative (also called complex coacervation). In associative phase separation one of the separating phases is enriched in both polymers, whilst, in a segregative phase separation each phase is enriched in one of the polymers. When phase separation takes place, a competition between the phase separation and gelation process generally takes place, resulting in an increase in the complexity of the system.

The understanding of the mechanisms of interaction and the effect of changing conformation on these interactions is of great interest for predicting the structure and the properties of mixed systems.

Furcellaran is an anionic sulphated polysaccharide extracted from the red alga Furcellaria lumbricalis. It is currently considered to be a copolymer of β- and κ-carrageenan and usually represented structurally as a repeating unit of alternating 3-linked β-D-galactopyranose and 4-linked α-D-galactopyranose residues, with part of the latter existing as a 3,6-anhydro derivate (Figure 1). Hydroxyl groups in the polysaccharide chain may be substituted (sulphated, methylated, etc.) and other monomer residues such as xylose and glucose may be found. Furcellaran is a

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polyelectrolyte that carries sulphate groups and it is negatively charged over a wide range of pH. The charge density is usually one sulphate per three or four monomer units.

A characteristic of furcellaran is its ability to form gels in the presence of specific ions which is associated with a conformational change from coil to helix. Gelation of furcellaran is believed to proceed like κ-carrageenan via a two-step mechanism, as shown in Figure 2. Carrageenan chains associate themselves by the formation of intermolecular double helices, but these do not in themselves produce a gel network. Gelation occurs with the subsequent aggregation of these helices mediated by specific binding of gel promoting cations (particularly K⁺ and Ca²⁺).

Bovine serum albumin (BSA) is one of the most widely studied and applied proteins in biochemistry. It is an important, globular blood protein with molecular mass of 66,000. Serum albumins comprise about 580 amino acid residues and are characterized by a low content of tryptophan and a high content of cystine and charged amino acids, such as aspartic and glutamic acids, lysine and arginine.

β-lactoglobulin (BLG) is a major protein of the whey fraction of milk in many mammals. At physiological conditions, bovine β-lactoglobulin forms dimer, with each monomer consisting of 162 amino acid residues and characterized by a molecular mass 18,300. The conformation of BLG is pH dependent. At pH 3.5 the protein dimerizes, at pH 4.6 the dimers may further aggregate to form an octamer and at pH 7.5 the protein conformation undergoes a reversible transition which leads to a swelling of the monomeric unit.

The aim of this study is to investigate the rheological behaviour of mixed gels formed with furcellaran and globular proteins, BSA and BLG.

EXPERIMENTAL

Materials
The furcellaran was a gift from FMC Food Ingredients.
BSA and BLG were supplied by Sigma-Aldrich. They were used without further purification. The potassium acetate and potassium phosphate buffer solutions were prepared with analytical grade reagents.

Purification of furcellaran
The furcellaran preparation (3g) was dissolved in 2 L milliQ water at ~100°C. The solution was passed through diatomaceous earth (Sigma-Aldrich Co, Ltd., UK) and dialyzed (yield 80%). The Na⁺ furcellaran was obtained by elution through an ion-exchange (Amberlite IR-120) column in the Na⁺ form at 4 °C. The eluant was freeze-dried.

Preparation of gels
Protein and furcellaran samples were dispersed separately in water or buffer solutions and then mixed. The gels were...
prepared by dialysing the solutions against 1M KCl solution in water or buffer solution at 4°C for overnight.

Rheometry

The stiffness of the gels at 25°C was determined as the shear modulus at 200 Hz calculated from the measured velocity of a shear-wave passing through the gel using a Rank pulse shearometer. The rheological properties of the gels were analysed by dynamic oscillatory controlled strain measurements using the Advanced Rheometric Expansion System (ARES-LS2). The viscoelastic properties of the gels were analysed by recording the storage modulus ($G'$), loss modulus ($G''$), and loss tangent (tanδ) during strain and frequency sweeps at 25°C. A parallel plate measuring geometry was used with gel diameter 4mm. The gel pieces were carefully placed on the lower plate of the rheometer, and a compression of not more than 0.5% was applied to the gel by the upper plate. Strain sweep measurements were performed at a constant frequency of 1 Hz whilst frequency measurements were performed using 0.1% strain, which was within the linear viscoelastic region for furcellaran and mixed gels.

RESULTS AND DISCUSSION

The dependence of shear modulus on the furcellaran concentration is shown in Figure 3. The shear modulus increased with increasing concentration of furcellaran. In Figure 4 is shown dependence of shear modulus on the KCl concentration (0.1-1M) for the 1.5% furcellaran gel. The shear modulus increased with KCl concentration, and was more marked in the concentration range 0 to 0.4 M KCl.

Dynamic oscillatory rheology was used to monitor more detailed gel characteristics. To ensure that the gel properties were measured within the linear viscoelastic region, strain sweep measurement were first carried out (Figure 5). It can be seen that

![Graph](image1)

Fig.3. Dependence of shear modulus on furcellaran concentration.

![Graph](image2)

Fig.4. Dependence of shear modulus on KCl concentration.
dependence of $G'$ but no $G'$-$G''$ crossover and can be categorised as a typical physically cross-linked network gel (Figure 6). A physical gel is a polymer network in which junctions can break and recombine due to thermal fluctuation. The variation of storage modulus and loss modulus was small with added protein (Figure 6B) or changing pH.

For the shear modulus in mixed furcellaran/protein gels, complex behaviour was observed. The initial addition of 0.1% w/w protein to the 1.5% furcellaran solution increased shear modulus, further increase in protein content lead to a decrease in gel stiffness (Figure 7). In the range 0.5% to 2.5% (w/w) BSA and 0.75 to 2.5% (w/w) BLG, increase in modulus was observed. From a protein content of 2.5% (w/w) the gel stiffness decreased again. Similar behaviour in $G'$ was recently reported by Oakenfull et al. with gels made with κ-carrageenan and sodium caseinate. Considering their work, the behaviour between furcellaran and protein can be explained as follows:

1. When small amounts of protein are added, the dry matter content is increased and the $G'$ increases.
2. When more protein is added, some of the furcellaran is bound to the protein. Bound furcellaran is no longer available to contribute to the furcellaran network. Thus $G'$ decreases.

3. As the concentration of protein increases, protein aggregates with bound furcellaran become sufficiently abundant to form a continuous network, $G'$ then increases.

In figure 7 (dotted curves) is shown the separate contributions to $G'$ from the complex and furcellaran. The contribution of furcellaran decreases, as with increasing concentration of protein the furcellaran forms the complex with protein; the contribution from the complex increases, once it has passed the gel threshold.

![Figure 7](image1.png)

**Figure 7.** Dependence of shear modulus, $G'$, 1 Hz, on BSA or BLG concentration in 1.5% w/w furcellaran gels.

Studying the dependence of pH on the gels, we observed that the structure of the mixed furcellaran/protein gels was pH dependent. At pH 7 the gels were translucent but became turbid with decreasing pH (Figure 8). This change indicates a phase separation between furcellaran and the protein. Looking the furcellaran/BSA mixed gel at pH=3.4 under the microscope we can see a coarse, phase separated structure (Figure 9).

![Figure 8](image2.png)

**Figure 8.** 1.5% w/w furcellaran gels with 1.5% w/w BSA at different pH’s.

![Figure 9](image3.png)

**Figure 9.** Optical micrograph of a 1.5% w/w furcellaran gel containing 1.5% w/w BSA at pH 3.

The dependence of shear modulus on the pH of furcellaran gels is shown in Figure 10. The shear modulus is increasing with increasing pH of medium, goes through maximum at pH 4.3 and begins to decrease. The gel stiffness starts to increase again from pH 6.2. The mixed systems behave in a similar way but the shear modulus values are higher. This behaviour indicates that low pH increases the stiffness of the gel but from pH 4.3 it starts to decrease again.

As in these measurements there wasn’t a marked behaviour difference between furcellaran and furcellaran/protein gels, dynamic oscillatory rheology was applied. In Figure 11 it can be seen that for furcellaran gels the loss tangent increased linearly with increasing pH. But for mixed systems there was decrease in loss tangent between pH 3.4 and 4. From pH 4 the loss tangent increased linearly with increasing pH.
The results obtained show that when gelation occurs in furcellaran globular protein systems, at pH’s in the vicinity of neutrality, an associative network forms. On decreasing the pH of the medium to pH 3.4 a phase separated structure forms.

CONCLUSIONS
This study shows that furcellaran and globular proteins form physically cross-linked network gels. The initial addition of protein to furcellaran solution increased shear modulus, further increase in BSA content leads to a decrease in gel shear modulus. Studying the dependence of pH on the gels we observed that the structure of the mixed furcellaran/protein gels was pH dependent. At low pH the associated phase separation occurred and loss tangent changed.

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