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Rheology and characteristics of sulfated polysaccharides from chlorophytan seaweeds *Ulva fasciata*

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ABSTRACT

The rheological characteristics of polysaccharides which were extracted and separated from *Ulva fasciata* (UFP) were investigated in aqueous solutions under conditions of concentration, temperature, solution pH and salt concentrations. It was described by the power-law model with a consistency index (k) and a flow behavior index (n). The rheology results showed UFP exhibited as a shear-thickening fluid and a possible mechanism was proposed to explain this phenomenon that might be the collapse of UFP necklace-type structures. UFP characteristics were evaluated by determining the chemical analysis and zeta potential. The findings indicated UFP may consist of partially ulvan, as the results were in accordance with the ulvan structure. Additionally, a rod-climbing effect and cold-set gelation were observed in the UFP semidilute solution. Therefore, the cold-set gelling properties and unique shear-thickening fluid properties in this work could be valuable for the exploration of *U. fasciata* as a new source of water-soluble gelling polysaccharides.

1. Introduction

Food hydrocolloids obtained from different sources have been widely used in food industry to improve the food rheological properties, extend food shelf life, and encapsulate flavor compounds (Nwokocha & Williams, 2009). They have also been used to emulsify oil (water) in water (oil) systems (e.g. ice cream, yogurt) enhance the food elasticity and thickness, retain moisture, and manufacture food gels (Xiu, Zhou, Zhu, Wang, & Zhang, 2011). From a chemical point of view, they are polysaccharides (carrageenan, starch, pectin) or proteins (gelatin) (Koocheki, Mortazavi, Shahidi, Razavi, & Taherian, 2009). *Ulva fasciata* commonly known as 'sea lettuce', is an abundantly growing green seaweed in coastal seashore of South China (Chakraborty, Lipton, Paul, & Vijayan, 2010). It is an important food in South China and has been used in soups and vegetables. Polysaccharides extracted from *U. fasciata* (UFP) are a group of sulfated heteropolysaccharide, which attracted particular interest because of their effective bioactivities, such as antimicrobial, hemolytic activities and the antibacterial properties (Qi et al., 2012). Earlier studies reported that seaweed extracts such as agar, alginate and carrageen have been widely used for food hydrocolloids (Rajapakse & Kim, 2011), *U. fasciata* is belonging to the family of Ulvaceae, and it has the potential to be applied to food hydrocolloids.

According to the type of flow, most food hydrocolloids solutions are shear-thinning, meaning the viscosity decreases when the shear rate is increased (Marcotte, Taherian, Trigui, & Ramaswamy, 2001). While shear-thickening meaning the viscosity of a hydrocolloid increases with the increase of flow rate (Garg et al., 2009). An example is uncooked corn starch paste where shear stress squeezes the water from between the starch granules allowing them to grind against each other, this property is often used in sauces, for example, tomato sauce(Krystyjan, Sikora, Adamczyk, & Tomasik, 2012; Sikora, Kowalski, Tomasik, & Sady, 2007). It is indicates shear-thickening hydrocolloids has been widely used for food to gain the desired functionalities.

In the past decade, remarkable of studies have been reported focusing on the separation, purification and structural analysis of plant polysaccharides (Gupta & Abu-Ghannam, 2011). As the demand for hydrocolloids with specific functionalities has been increased recently, it is of highly interesting for food scientists and technologists to search for new sources of polysaccharides (Yadav, Johnston, Hotchkiss, & Hicks, 2007). The separation and purification of UFP has been conducted in our group (Shao, Chen, & Pei, 2013). We have found UFP exhibited unique shear-thickening fluid properties, but no literature has been done on its rheological properties. Therefore, the objectives of this study were to determine the chemical component of polysaccharides separated from *U. fasciata*, and

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investigate the effects of concentration, temperature, solution pH and salt concentrations on the rheology and characteristics, which might provide useful information on the potential utilization of this new hydrocolloid source in food industry.

2. Materials and methods

2.1. Materials and chemicals

The *U. fasciata* was collected on the coast of Nanji Archipelago (Zhejiang province, China). Prof. Xinqian Ye (Zhejiang University, Hangzhou, China) did the authentication of species. The collected sample was washed with seawater and deionized to remove extraneous matter such as epiphytes and contamination from other algae. Then sample was again washed with deionized water and air shade dried. Finally, the sample was sealed in plastic bags and stored at room temperature.

2.2. Analytical methods

The contents of total sugar, protein, sulfate and uronic acid were determined by phenol-sulfuric acid method (Dubois, Gilles, Hamilton, Rebers, & Smith, 1956), coomassie brilliant blue method (Bradford et al., 1976), barium chloride-gelatin method (Dodgson & Price, 1962), and sulfuric acid carbazole colorimetry method (Blumenkrantz & Asboe-Hansen, 1973), respectively.

2.3. Extraction of polysaccharides

Five hundred gram of dried *U. fasciata* cut into 5 cm × 5 cm slices and soaked with 5 L of 95% ethanol (v/v) for 12 h and repeated for three times to remove lipids and colored ingredients including free sugars, amino acids and some phenols. The residue was dried in the air for 12 h and ground into powder and passed through a 100 mm sieve. The powder sample was extracted in 5 L of distilled water at 100 °C for 3 h. The slurry was separated by gauze and filtered. The extraction was repeated three times and the filtrate was combined, and then centrifuged at 4500 rpm for 10 min. The supernatant was decanted and concentrated to about 1000 ml under reduced pressure. Ethanol (95%, v/v) was added slowly to a final alcohol concentration of 80%. The mixture was allowed to stand overnight at room temperature. The precipitate was collected and washed twice with absolute ethanol and the crude polysaccharides were obtained.

2.4. Radial flow chromatography

According to the method of Jiang, Sun, He, and Shao (2012), radial flow chromatography was used for purification of the crude polysaccharides. A 250 ml bed-volume radial flow column packed with ion-exchange resin (A103S, Purolite International Ltd, USA) was used for the separation and purification. After preliminary experiments, the optimal conditions for the purification were: crude polysaccharide concentration 10 mg/ml, solution flow-rate 2 ml/min, solution volume 100 ml and elution flow-rate 40 ml/min. The liquid collected through the radial flow column was concentrated under reduced pressure. Finally, the polysaccharides (UFP) were obtained after freeze drying.

2.5. Monosaccharide composition analysis

The monosaccharide compositions of UFP were determined by reductive hydrolysis using the same procedure as described in the previous paper (Shao et al., 2013). About 20 mg sample and standard monosaccharide were hydrolyzed with trifluoroacetic acid (TFA) and NaBH4. Then alditol acetates were analyzed by gas chromatography (GC) using an Agilent 7890N instrument equipped with an HP-5 capillary column.

2.6. Visual observation of viscoelastic properties

Visual observation were obtained using Constant Speed Stirrer (Shen Sheng Bio-tech Co. ltd, Shanghai, China) equipped with a 5 mm rod, a semidilute solution of UFP (10%, w/w) prepared by dispersing the freeze-dried UFP in deionized water and kept in 50 ml beaker. In the experiment this rod was rotated with its end immersed in the fluid and the rotation was 50 r/min, then fluid would rose up with the rod at different time.

2.7. Rheology measurement

Rheology measurements were carried out using a rotational viscometer (R/S Plus, Brookfield Engineering Laboratories, USA) equipped with CC48 measuring spindles (based on viscosity of dispersion). For each test, approximately 50 ml sample was transferred to the sample compartment followed by 3 min pre-shearing at 1000 s^{-1} to obtain a uniform solution. A computer controlled program (Rheo 2000, USA) in a rotational mode was used to shear samples at a linear rate from 0 to 4000 s^{-1} to obtain the viscosity curves. The flow behavior index (n) and consistency index (k) values were computed by fitting the power law model:

$$\tau = k \cdot \gamma^n \quad (1)$$

where k is the consistency coefficient (Pa s^n), n is the flow behavior index (dimensionless), τ is the shear stress (Pa) and γ is the shear rate (s^{-1}). When these flow curves were plotted in double logarithmic scales, they presented straight lines, indicating the two-parameter Ostwald–de Waele or power-law model was a suitable equation to fit the τ–γ relationships (Xiu et al., 2011). In the case of Newtonian behavior, Eq. (1) becomes Newton's law of viscosity, with viscosity equal to k. But in the case of non-Newtonian behavior with $n \neq 1$, the flow characteristic was termed as the shear-thinning behavior if $n < 1$ and the shear-thickening behavior if $n > 1$ (Koocheki et al., 2009).

2.7.1. Determination of flow properties at different concentrations

UFP solutions were prepared at concentrations of 0.1%, 0.3%, 0.5%, and 1% by dispersing the required amount in deionized water, under slow stirring at room temperature, and stored at 4 °C for 12 h for complete hydration prior to assessment. Prepared samples were loaded into the viscometer sample compartment and maintained at 25 °C for 20 min in a water bath, and then the viscosity was measured as describe above concentrations.

2.7.2. Determination of flow properties at different temperatures

A 0.5% UFP solution was prepared as Section 2.7.1 then were loaded into the cup and cylindrical cup and allowed to equilibrate at a set-point temperature for 20 min in a water bath. Experiments were carried out at five temperatures: 10, 20, 30, 40 and 50 °C.

2.7.3. Determination of flow properties at different pH

A 0.5% UFP solution was prepared as Section 2.6.1 and adjusted the pH values to 1, 3, 5, 7, 10 and 12 by using 6 M NaOH and HCl before the viscosity measurement, the temperature was also controlled at 25 °C in a water bath.

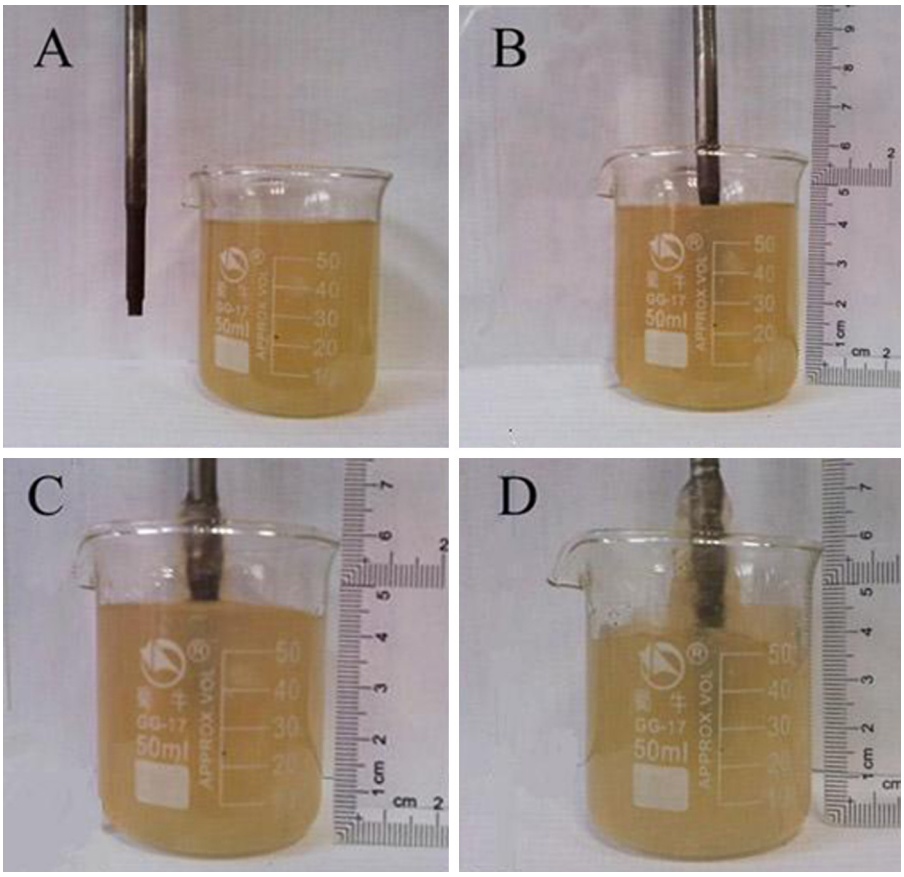

Fig. 1. The rod-climbing effect (also known as The Weissenberg Effect) of 10% (w/w) solution of UFP. ((A) and (B) shows solution of UFP with the rod was stationary; (C) and (D) shows rob-climbing effect of the same solution when the rod was rotated).

2.7.4. Determination of flow properties at different salt concentrations

A 0.5% UFP solution was prepared as Section 2.6.1. Monovalent (NaCl) and divalent ($CaCl_2$) salts were added to the solution to give final concentrations of 0.1–0.5 M. The viscosity measurements were performed at 25 °C as described above.

2.8. Particle size and ξ-potential measurements

Particle size and ξ-potential measurements were carried out on a Microtrac Zetatrac (Beckman Coulfor Inc., USA) using Microtrac FLEX Operating Software for data analysis. The freeze-dried UFP samples were dispersed in deionized water at 0.5% concentration and stored at 20 °C for 48 h with a final pH adjustment between 1 and 12 using 6 M HCl or 6 M NaOH. The samples were centrifuged at $3100 \times g$ for 30 min at 20 °C and 3 ml of sample was transferred to a measurement vessel for particle size and ξ-potential analysis.

2.9. Statistical analysis

All experiments were performed in triplicate and the results were the average of three independent experiments. Statistical analyses were carried out by using the Statistical Analysis Systems (OriginPro 8.5, OriginLab Corporation, MA, USA) software package. The results were analyzed using one-way ANOVA to determine significant differences ($p \leq 0.05$) for the means among the samples.

3. Results and discussion

3.1. Chemical analysis

The chemical analysis indicated that the UFP was consisted of about 42% sugars, 1% proteins, 19% sulfate, and 35% uronic acid (Table 1) and it was suggested UFP were a highly sulfated acidic heteropolymers. The large proportion of uronic acid in UFP is of particular interesting as normally this component is no more than 20% in most of the reported seaweed polysaccharides (de Souza et al., 2007; Percival, 1979; Rioux, Turgeon, & Beaulieu, 2007). The GC analysis of the monosaccharides revealed that UFP were composed of rhamnose, xylose, glucose and mannose, which was in agreement with the monosaccharide composition of water-soluble polysaccharides from other members of Ulvacese family (Costa et al., 2012), with small quantitative differences. From the component of view, the UFP may contain partially ulvan which was

Table 1
Chemical composition and monosaccharide composition of UFP.

	Compositions	W%
Chemical	Total sugar	42.63 ± 0.46
	Uronic acid	35.06 ± 0.39
	Sulfate	19.41 ± 0.17
	Protein	1.20 ± 0.01
Monosaccharide	Rhamnose	42.37 ± 0.05
	Xylose	36.25 ± 0.06
	Glucose	11.74 ± 0.05
	Mannose	9.64 ± 0.01

a complex water-soluble acidic polysaccharide extracted from the cell-walls of the green seaweeds.

3.2. Visual observation of viscoelastic properties

A semidilute solution of UFP (10%, w/w) prepared by dispersing the freeze-dried UFP in deionized water exhibited a rod-climbing ability (Fig. 1). The rod-climbing effect (also known as Weissenberg effect) was due to the normal stresses present in the polymer fluid and was thus a purely non-Newtonian effect. While the rod-climbing effect has been observed in some polymers and crude oils (Bonn et al., 2004), but rarely observed in natural polysaccharide polymers (Goh, Matia-Merino, Hall, Moughan, & Singh, 2007; Bird, Armstrong, & Hassager, 1987). What is more, no literature has been reported about the rod-climbing effect in Ulvacese family.

Interestingly, the UFP solution was found to be a cold-set gelation as well, that means it could be kept at a solution state at high temperature while turned to a gelation state when the temperature was decreased. This was similar to carrageenan and gelatin although the source of polysaccharides was different (Costa et al., 2012). Percival and McDowell (1967) were the first to mention the formation of a stiff gel on concentrating about *Ulva pertusa* extracts. Later on, Haug (1975) discovered that boric acid, calcium ions, and a pH between 7.5 and 8.0 were required to form a weak gel with the extract from *Ulva lactuca*. In this paper, such gel was also obtained in *U. fasciata* extract without any addition.

The cold-set gelling properties of *U. fasciata* offered potential applications where texture need to be precisely controlled by temperature, pH, or salts. It could be used to design gels able to improve the food properties under specific physicochemical conditions which may be applied to food hydrocolloids (Lahaye & Robic, 2007).

3.3. Rheology measurement

3.3.1. Effect of concentration on the UFP flow properties

Many macromolecules in solutions exist as conformational disordered random coil, whose shapes fluctuate continually under Brownian motion (Lapasin, De Lorenzi, Pricl, & Torriano, 1995). In the dilute regime, the individual polymer coils or rods are so far apart that they have negligible influence on each other and are free to move independently. However, with increasing concentrations, molecular collisions become more frequent and a stage will be eventually reached at which the molecules begin to contact with one another (Lai, Tung, & Lin, 2000). The transition from a dilute solution of independently moving coils or rods to an entangled network is usually accompanied by a very marked change in the concentration dependence of solution viscosity. As showed in Fig. 2A, the apparent viscosity of purified UFP varied from 1.27 to 10.37 mPa s, and the viscosity was observed to have a slight increase when the UFP concentration increased from 0.1 to 1.0% (w/v), showing the viscosity was greatly depend on concentration. What is more, solutions extracted from Ulvacese family often develop low viscosities, the viscosity in saline solutions was about several mPa s for ulva extracts (Lahaye, Jegou, & Buleon, 1994), such low viscosity may reflect the polymolecularity with high proportions of short-chain polysaccharides or highly branched structure as proposed. However, the structure and the branching pattern so far were not in support of a highly branched polysaccharide (Lahaye & Robic, 2007).

The consistency index (k) and flow behavior index (n) values of different concentration UFP solutions were present in Table 2. The coefficients of determination (R^2) were 0.94 or higher for all tested samples indicating the appropriateness of the power-law model to describe the flow properties of the UFP solutions. The results indicated that the n values decreased continuously when

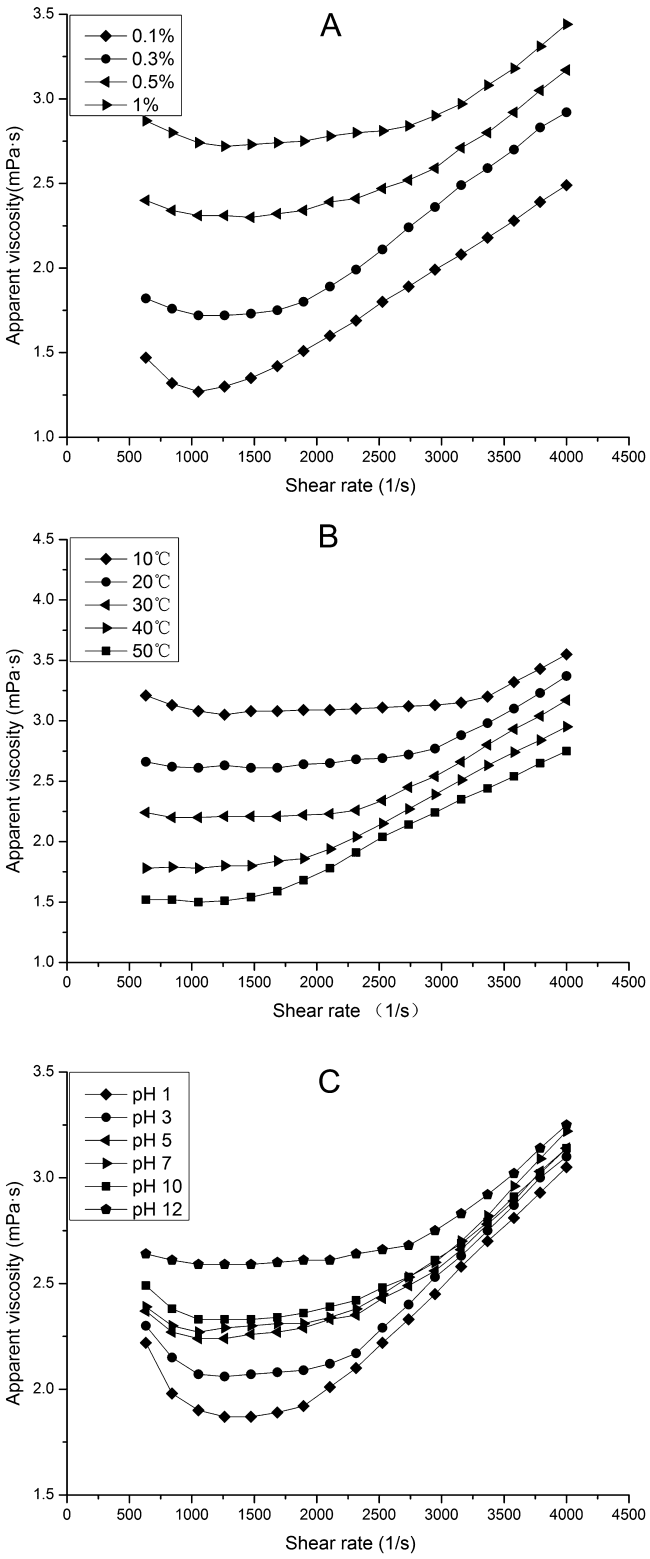

Fig. 2. Effect of several factors on the flow behavior of aqueous UFP solutions: (A) UFP concentration, 25 °C, pH 5.0; (B) temperature, UFP concentration was 0.5%, pH 5.0; (C) pH, UFP concentration was 0.5%; 25 °C.

the UFP concentration was increased. Besides, Fig. 2A showed the occurrence of the thickening at lower shear rate with ~1000 s^{-1} at 0.1%, compared to ~2500 s^{-1} at 1% where the thickening effect was less pronounced. All these showing a weakened shear-thickening behavior. The n values of all other lower concentration solutions

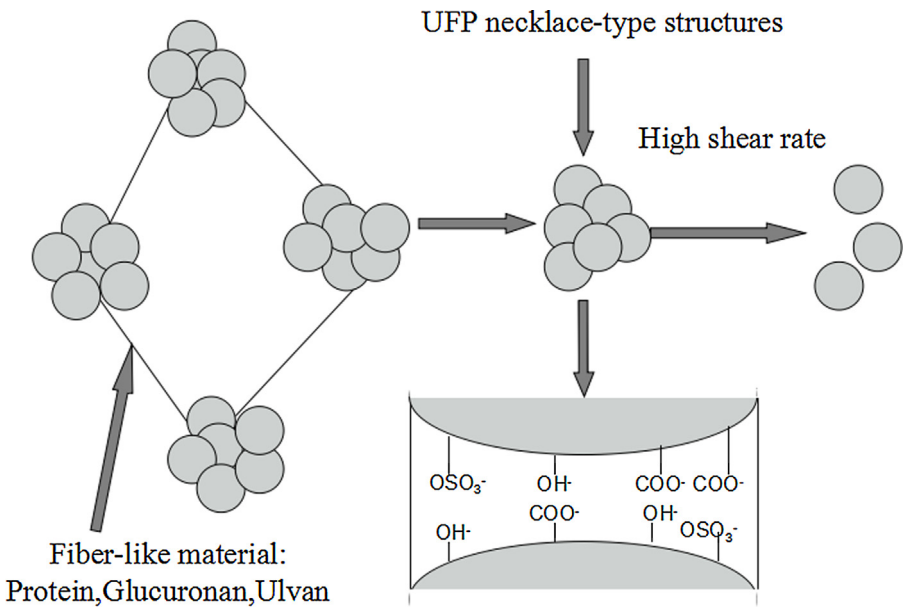

Fig. 3. Schematic representation of the UFP shear-thickening mechanism.

were above 1, showing that these polysaccharide solutions at lower concentrations behaved as shear-thickening fluids.

3.3.2. *Effect of temperature on the UFP flow properties*

The apparent viscosities of 0.5% (w/v) UFP solutions versus shear rate at temperatures between 10 and 50 °C were present in Fig. 2B. As expected, the viscosity was decreased with the temperature increment. Table 2 also showed that the *k* values increased with the temperature while the opposite trend was observed with the *n* values, which decreased from 1.1824 to 0.9704.

A possible reason might due to UFP ultrastructural were collapsed and polysaccharide molecules were driven together to form agglomerates which cause the solution to shear-thicken. Robic, Gaillard, Sassi, Lerat, and Lahaye (2009) observed ulva extraction by cryo-TEM, scanning electron microscopy, and atomic force microscopy, it was found the ultrastructure departed from the classical rod-shape or fiber-shape structures of gel-forming polysaccharides. It rather resembled necklace-type structures formed by a polyelectrolyte in a water solvent condition (Dobrynin, 2008), such as those observed for DNA, hyaluronan, or synthetic polyelectrolytes in solutions containing solvent perturbing compounds (Cowman & Matsuoka, 2005). So in UFP solution when the shear rate was increased, this necklace-type structures maybe gradually damaged, which eventually leaded to the viscosity increased.

Table 2
Concentration, temperature, pH dependence of flow behavior index (*n*) and consistency index (*k*).

	n	*k*	R^2
Concentration (%)			
0.1	1.1952 ± 0.0033	0.00086 ± 0.00009	0.9438
0.3	1.1251 ± 0.0013	0.00083 ± 0.00006	0.9719
0.5	1.0534 ± 0.0027	0.0013 ± 0.00005	0.9888
1	1.0154 ± 0.0014	0.0026 ± 0.00001	0.9924
Temperature (°C)			
10	1.1824 ± 0.0032	0.00054 ± 0.00006	0.9735
20	1.1506 ± 0.00021	0.00069 ± 0.00009	0.9799
30	1.0761 ± 0.0028	0.0014 ± 0.00006	0.9849
40	1.0242 ± 0.0026	0.0023 ± 0.00003	0.9903
50	0.9704 ± 0.0035	0.0041 ± 0.00003	0.9939
pH			
1	1.0663 ± 0.0021	0.0017 ± 0.00001	0.9931
3	1.1126 ± 0.0036	0.00097 ± 0.00009	0.9538
5	1.2118 ± 0.0005	0.00098 ± 0.00007	0.9704
7	1.1185 ± 0.0036	0.0010 ± 0.00003	0.9864
10	1.1050 ± 0.0038	0.0011 ± 0.00006	0.9859
12	1.0988 ± 0.0020	0.012 ± 0.00003	0.9893

3.3.3. *Effect of pH on the UFP flow properties*

The *k* and *n* values of the UFP solution under different pH conditions were also given in Table 2. The *k* value of the UFP solution was the smallest near pH 5, where was its natural pH value, but *n* value was the biggest. The results showed that both acidic conditions (pH 1–2) and alkaline conditions (pH 10–12) changed the rheological behavior of the solution, where the *n* values were decreased but *k* values were increased. The shear-thickening effect was observed through the whole range of pH (Fig. 2C). The viscosities were similar between the samples of pH 5 and 10. The solutions exhibited higher viscosity at pH ≥ 10 and lower apparent viscosity at pH ≤ 5.

The mechanism underlying the shear-thickening of UFP was not completely understood, but it might be related to several structure properties including its spherical-based morphology and necklace-type structures (Fig. 3). The line represented fiber-like material, which could be constituted by proteins, glucuronan or extended ulvan segments, the aggregation represented UFP necklace-type structures. In general, there had four types of interactions contributed to this aggregation, including hydrophobic interactions, hydrogen bonding, electrostatic interactions, and covalent bonds (Bryant & McClements, 1998). When UFP solution was sheared at high shear rate, the interactions between necklace-type structures were disrupted, the sulfate esters, carboxylate groups and hydroxyl were exposed on spherical surface, thus leaded to polysaccharide molecule driven together to form agglomerates, the visual performance was viscosity increased.

3.3.4. *Effect of salt on the UFP flow properties*

The effect of salt concentration on hydrocolloid viscosity was important to estimate its functional rheological properties. The apparent viscosity decreased when the NaCl concentration was increased from 0.1 to 0.5 M (Fig. 4A), which suggested that the monovalent NaCl was unable to increase the apparent viscosity of UFP solution. However, the divalent $CaCl_2$ was found to be more

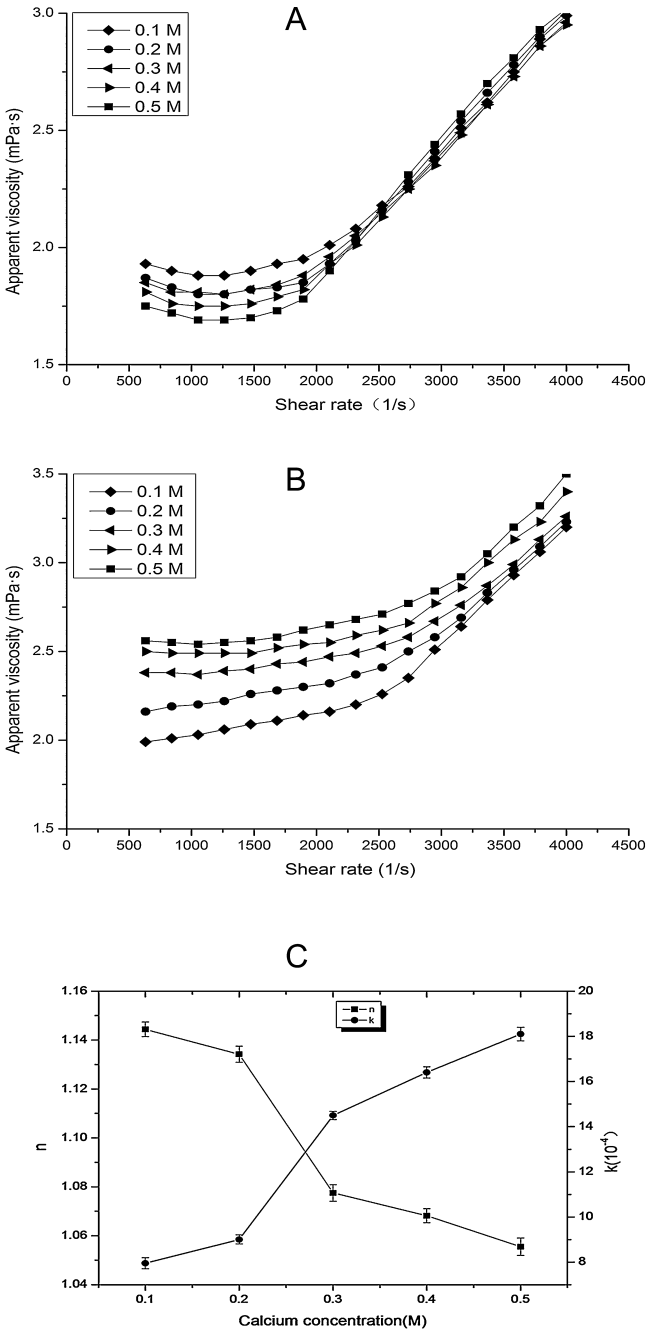

Fig. 4. Effect of salts on the flow behavior of aqueous UFP solutions: (A) NaCl; (B) $CaCl_2$; (C) $CaCl_2$ concentration of power law model (UFP concentration was 0.5%, pH 5.0, 25 °C).

efficient at enhancing the shear-thickening and resulted in higher viscosities at higher salt concentrations (Fig. 4B).

The results suggested that the rheological behavior of the UFP was strongly affected by salt type and ionic strength, possibly due to the presence of uronic acid in the polysaccharide structure (Goh et al., 2007). When the NaCl concentration was low, the electrostatic interactions dominated in the solution and the UFP molecules were existed in a more extended and rigid conformation that resulted in a higher viscosity of the UFP solution. In contrast, when the ionic strength was higher, the raised concentrations of counter-ions made the molecules contracted and expressed as lower viscosity due to the charge shielding effect (Qun & Ajun, 2006). However, the UFP viscosity with the addition of $CaCl_2$ was completely different, i.e. the viscosities of UFP solutions were significantly increased

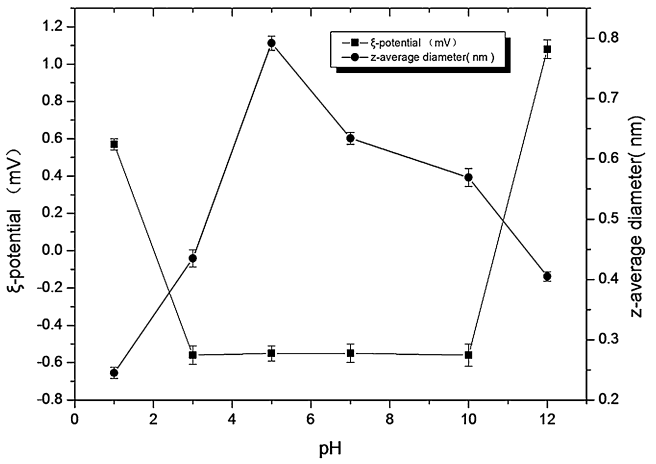

Fig. 5. ξ-Potential (mV) and z-average diameter (nm) measurements at 25 °C of aqueous UFP solutions (UFP concentration was 0.5%) dialyzed with pH adjusted between 1.0 and 12.0.

with the $CaCl_2$ concentration increase (Fig. 4B). The mechanism of these two different salts on the UFP solution viscosity was not clear, which was under investigation.

In the salt concentrations of 0.1–0.5 M, NaCl was not fit to the power-law model (data not shown), while with the addition of $CaCl_2$, the *n* values were decreased but *k* values were greatly increased, as shown in Fig. 4C. In the case of divalent cations such as calcium, salt addition may have also promoted the formation of salt bridges between negatively charged groups (Bryant & McClements, 1998). Haug (1975) investigated the influence of calcium ions on the viscosity and proposed that the calcium ions may have formed bridges between other ions or have helped in stabilizing other ions linkages.

3.3.5. *Zeta potential and the z-average diameter measurements*

The effect of pH on the UFP zeta potential (ξ-potential) and polymer particle size (*z*-average diameter) was also studied under dilute conditions (0.5%). At its natural pH of around 5.0, the UFP polymer was negatively charged at a ξ-potential value of −0.55 mV (Fig. 5). The ξ-potential values varied only slightly (−0.55 to −0.56 mV) between pH 5 and 10, but increased considerably when the pH values were below 3 and above 10. As for the polymer size, the polymer particle was the largest at its natural pH of 5 (754 nm) and turned smaller when the pH values became either above or below this point.

As presented in Table 1, about 35% of the polymer fraction was uronic acid and 19% was sulfate, therefore the two types were likely to be the origin of the negative charge. While two major repeating disaccharides of ulvan were aldobiuronic acids designated as type A: ulvanobiuronic acid 3-sulfate (A_{3S}) and type B: ulvanobiuronic acid 3-sulfate (B_{3S}). Other minor repeating units contain glucuronic acid as a branch on O-2 of rhamnose 3-sulfate or partially sulfated xylose replacing the uronic acid (see Fig. 6) (Robic et al., 2009). Since ulvan contains two types of negatively charged groups: sulfate esters and carboxylate groups, which indicated UFP may containing a part of ulvan. In basic conditions (pH 1 and pH 12) the necklace-type structures resulted collapse into a dense homogeneous network likely prompted by the interactions of carboxylate and sulphate groups. This may also suggested that some sort of disaggregation had taken place under extreme pH conditions in the dilute solutions (Matia-Merino, Goh, & Singh, 2012). Tischer, Iacomini, Wagner, & Gorin, 2002 observed that some insoluble fractions of the polysaccharides may become soluble under extreme pH conditions. In the present study, this phenomenon may also have

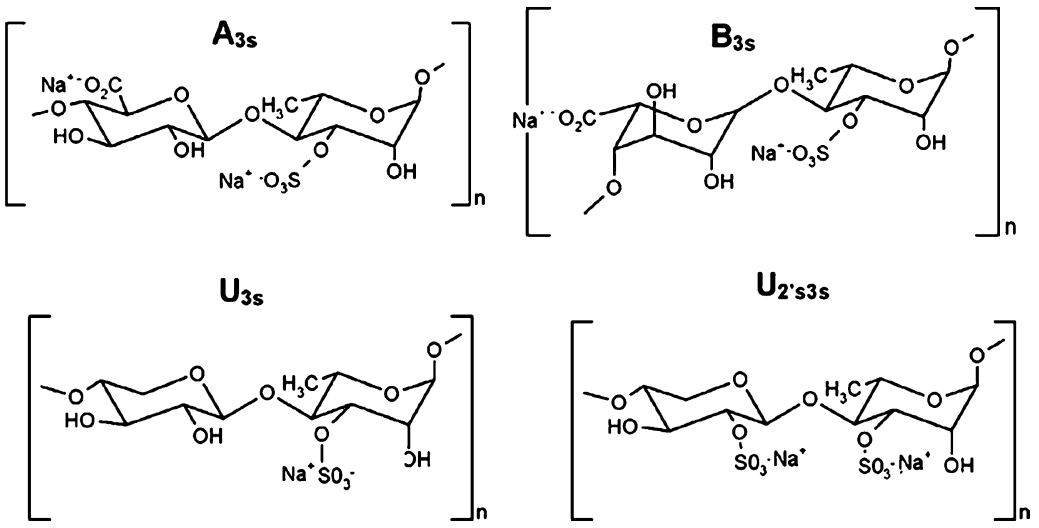

Fig. 6. Structure of the main repeating disaccharides in *Ulva* ulvan: ulvanobiuronic acids A_{3S} and B_{3S} and ulvanobioses U_{3S} and $U_{2'S,3S}$.

happened, and then, caused the polymer particle size smaller under extreme high or low pH conditions.

4. Conclusions

A sulfated polysaccharides was extracted and purified from *U. fasciata* and it behaved as a shear-thickening fluid under different concentration, temperature, solution pH and salt concentrations. A possible mechanism was proposed for shear-thickening that might be the collapse of UFP ultrastructural. Analysis of chemical composition and zeta potential confirmed the UFP may contain a part of ulvan, which were a water-soluble cell wall polysaccharides extracted from green seaweeds. However, a rod-climbing effect and cold-set gelation were also observed which was different from the findings from other members of Ulvacese family. Additionally, the more accurate chemical structure and the mechanism of gelation are under investigation. The cold-set gelling properties and unique shear-thickening fluid properties indicated that the UFP could be a new source of water-soluble gelling polysaccharides in food industry.

Acknowledgments

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