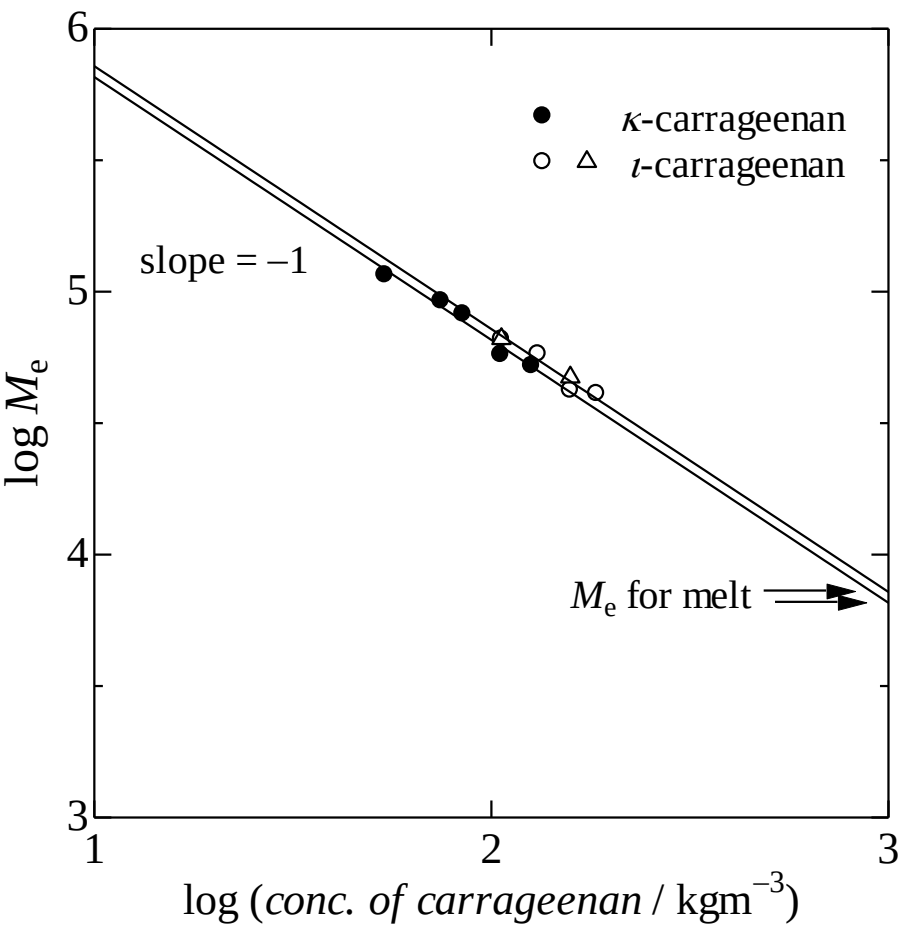


The molecular weight between entanglements ( $M_e$ ) for  $\kappa$ - and  $\iota$ -carrageenans, sulfated galactans, was examined in concentrated solutions using an ionic liquid 1-butyl-3-methylimidazolium acetate as a solvent. The dynamic viscoelasticity data for the solutions measured at different temperatures were overlapped according to the time-temperature superposition principle, and the obtained master curves exhibited the flow and rubbery plateau zones, being typical of concentrated polymer solutions having entanglement coupling. The values of  $M_e$  for  $\kappa$ - and  $\iota$ -carrageenans in the solutions were determined from the plateau moduli. Then the values of  $M_e$  in the molten state ( $M_{e,melt}$ ) estimated as a material constant to be  $6.6 \times 10^3$  and  $7.2 \times 10^3$ , respectively. The close values of  $M_{e,melt}$  for  $\kappa$ - and  $\iota$ -carrageenans indicate that 4-sulfate group of  $\iota$ -carrageenan are not so influential for the entanglement network. Compared with agarose, a non-sulfate galactan, carrageenans have larger values of average spacing between entanglements.



## **Molecular Weight between Entanglements for $\kappa$ - and $\iota$ -Carrageenans in an Ionic Liquid**

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## 1. Introduction

Sulfated polysaccharides have attracted a great deal of attention because of their desirable bioactivities, and many of the natural as well as synthetic sulfated polysaccharides have been obtained and tested until now [1-6]. In industry, many of sulfated polysaccharides are utilized as thickening or gelling agents, but there are few studies on the fundamental aspect of the polysaccharides [7,8]. The chain properties are fundamental characteristics of the polymers which affect the bioactivities as well as the gelling ability, and therefore become indispensable for the further application of the polysaccharides.

Carrageenan is one of the familiar sulfated polysaccharides used as a thickening (gelling) agent, and can be classified into several types:  $\kappa$ - and  $\iota$ -carrageenans have a common chemical structure of alternating  $\alpha$ -(1-3)-D-galactose-4-sulfate (S) and  $\beta$ -(1-4)-3,6-anhydro-D-galactose (A) units; the difference is that  $\iota$ -carrageenan has an additional sulfate group in A unit to be 2-sulfate [9]. Examining chain properties of the two types of carrageenans ( $\kappa$ - and  $\iota$ -carrageenans) reveals, of course, the characters of respective sulfate polysaccharides, but also gives the information on the effect of the number of sulfate groups. By computer simulation, the chain properties such as the characteristic ratio ( $C_\infty$ ) for the polysaccharides have been obtained to show a flexible nature for both the carrageenans [9,10]. Characterization of  $\kappa$ - and  $\iota$ -carrageenans has been performed by several research groups, and their results lead to a stiffer

chain nature compared with the simulation using the dimer model [11-13].

The molecular weight between entanglements ( $M_e$ ) in the molten state ( $M_{e,melt}$ ) is also a fundamental parameter [14,15] reflecting polymer chain properties, and can be estimated by examining the concentration dependence of the plateau modulus of solutions although the molten states of  $\kappa$ - and  $\iota$ -carrageenans cannot be realized [16]. However, to our knowledge, there have been no reports on  $M_e$  for the carrageenans even in concentrated solutions, partly because aqueous solutions of  $\kappa$ - and  $\iota$ -carrageenans form gels with increasing polymer concentration owing to the aggregation of helical part of polymer chains [11]. This means that preparation of concentrated solutions of  $\kappa$ - and  $\iota$ -carrageenans is almost impossible using water as the solvent. Now, it is well known that ionic liquids work as good solvents for several polysaccharides insoluble to conventional solvents [17-19]. For some polysaccharides we have actually obtained concentrated solutions with ionic liquids, and have estimated the values of  $M_e$  successfully from the rheological properties of the solutions [18-22]. In this study, the idea that using an ionic liquid to determine  $M_e$  in solutions has been applied to  $\kappa$ - and  $\iota$ -carrageenans. The values of  $M_{e,melt}$  have been estimated from the concentration dependence of  $M_e$ .

## 2. Experimental

### 2.1 Materials

Powdery  $\kappa$ -carrageenan (lot #: 108301, MRC-Polysaccharide, Japan) ( $\kappa$ -M) and  $\iota$ -carrageenan (lot #: 105204, MRC-Polysaccharide, Japan) ( $\iota$ -M) were used in this study. The manufacturer characterized the samples as follows: The viscosity for 1.5% aqueous solutions of  $\kappa$ -M and  $\iota$ -M at 75 °C were 35 and 56 mPas, respectively; the metal content (%) regarding  $\text{Ca}^{2+}$ ,  $\text{Na}^+$ , and  $\text{K}^+$  species were respectively 0.9, 0.3, and 5.1 for  $\kappa$ -M and 3.3, 2.3, and 3.0 for  $\iota$ -M. For  $\iota$ -carrageenan another sample purchased from Funakoshi, Japan (sample-coded as  $\iota$ -F) was also employed. All samples were used without further purification, although  $\iota$ -M and  $\iota$ -F were dried in a vacuum oven at 80 °C for more than 12 h just before use. The solvent, 1-butyl-3-methylimidazolium acetate (BmimAc; BASF, Germany), was used as received. The melting point of BmimAc has been reported to be below  $-20$  °C [23], and thus the solutions have remained in the liquid state over a temperature range examined. Concentrated solutions of the carrageenans were prepared in the following way. Each carrageenan sample was added into the solvent (BmimAc) in a dry glass vessel on a hot plate at 80 °C and the mixture was quickly stirred with a stainless spatula at 80 °C. Then the glass vessel was sealed and the mixture was further stirred overnight on a hot plate at 80 °C. The concentration of carrageenan ( $c$ ) ranged from  $5.4 \times 10^1$  to  $1.3 \times 10^2 \text{ kgm}^{-3}$  (ca. 5 to 12 wt%) for  $\kappa$ -M, from  $1.0 \times 10^2$  to  $1.8 \times 10^2 \text{ kgm}^{-3}$  (ca. 10 to 18 wt%) for  $\iota$ -M, and from  $1.0 \times 10^2$  to  $1.6 \times 10^2 \text{ kgm}^{-3}$  (ca. 10 to 15 wt%) for  $\iota$ -F. In the calculation of  $c$ , the reported value of the density of  $1.055 \times 10^3 \text{ kgm}^{-3}$  at room temperature was

used for BmimAc; while a common value of  $1.0 \times 10^3 \text{ kgm}^{-3}$  was assumed for the densities for the carrageenans [18], since the molten states of carrageenans cannot be attained.

## 2.2 Measurements

Dynamic viscoelasticity was measured for the concentrated solutions using an ARES rheometer (now TA Instruments, USA) under a nitrogen atmosphere. A cone-plate geometry with the diameter of 25 mm and the cone angle of 0.1 rad was used. The storage modulus ( $G'$ ) as well as the loss modulus ( $G''$ ) was measured as a function of angular frequency ( $\omega$ ) with an amplitude of oscillatory strain ( $\gamma$ ) of 0.1 which ensures the linear viscoelasticity. The measured temperature ( $T$ ) ranged from 20 to 80 °C for  $\kappa$ -M, and from 0 to 100 °C for  $\iota$ -M and  $\iota$ -F.

## 3. Results and Discussion

Fig. 1 shows the master curves of  $G'$  and  $G''$  for the  $\kappa$ -M solutions, where the  $\omega$  dependence of  $G'$  and  $G''$  measured at different temperatures have been superposed at the reference temperature ( $T_r$ ) of 80 °C only by using a horizontal shift factor  $a_T$ . The curves for the different solutions are shifted upwards by a factor of  $A$  to avoid overlapping. As seen in the figure, the time-temperature superposition principle holds well for all the  $\kappa$ -M solutions measured, meaning that no conformational change such as coil-helix transition occurs in

BmimAc over the  $T$ -range examined. The master curves for all solutions have two zones typical of polymer liquids: First one is the flow zone observed in the low  $\omega a_T$  region where the  $G''$  curve holds the relation  $G'' \propto \omega$ , and the second one is the zone at high  $\omega a_T$  where the  $G'$  curve shows a plateau called the rubbery plateau. Every plateau in the figure tilts because of the polydispersity of the carrageenan sample. The plateau, originating from the entanglement coupling between polymer chains, becomes higher with increasing  $c$ , although the vertical shift may make it difficult to notice the change. The  $T$ -dependence of  $a_T$  used for the master curves in Fig. 1 is shown in Fig. 2. The values of  $a_T$  at a given  $T$  are almost independent of  $c$  and all data points fall on a single line, indicating that the  $T$ -dependence of  $a_T$  obeys an Arrhenius-type equation.

Fig. 3 shows the similar curves of  $G'$  and  $G''$  for the  $\iota$ -M solutions. It is seen that the time-temperature superposition principle also holds for the  $\iota$ -M solutions. The flow zone as well as the rubbery plateau exists for all solutions. The  $\iota$ -F solutions showed the similar curves to those of the  $\iota$ -M solutions if the comparison was made at the same  $c$ . The  $T$ -dependence of  $a_T$  at  $T_r = 80^\circ\text{C}$  is shown in Fig. 4. The data can also be represented by an Arrhenius-type equation. It should be noted that the data for the  $\iota$ -F solutions are also consistent with those for the  $\iota$ -M solutions shown here.

For a tilted rubbery plateau, as observed in this study, there exist several definitions for the

plateau modulus ( $G_N^0$ ). Among them we adopt here a definition that the  $G'$  value at  $\omega$  where the loss tangent ( $\tan\delta$ ;  $\tan\delta = G''/G'$ ) vs.  $\omega$  curve shows a minimum should be taken as  $G_N^0$  [18-22].

Then the value of  $M_e$  for a polymer in concentrated solution can be calculated by eq 1 as

$$M_e = \frac{10^3 cRT}{G_N^0} \quad (1)$$

where  $R$  is the gas constant [14,15,24]. Since  $G_N^0$  for the  $\kappa$ -M solution at  $c = 1.3 \times 10^2 \text{ kgm}^{-3}$  is estimated to be  $7.1 \times 10^3 \text{ Pa}$  (Fig. 1), we have  $M_e = 5.2 \times 10^4$ . The values of  $M_e$  for the other solutions were determined in a similar manner. Fig. 5 shows double logarithmic plots of  $M_e$  vs.  $c$ . Straight lines in the figure commonly have a of  $-1$ , which is based on the well-known relation  $M_e \propto c^{-1}$  for concentrated polymer solutions [14,16], and a line is drawn to be the best fit for each type of carrageenans. The data points for each sample appear to fall on the line, recalling that the  $M_e \propto c^{-1}$  relation also holds for the carrageenan solutions. Therefore,  $M_{e,\text{melt}}$  for  $\kappa$ - and  $\iota$ -carrageenans can be estimated as the value of  $M_e$  at  $c = 1.0 \times 10^3 \text{ kgm}^{-3}$ , the density assumed for carrageenans (in the molten state) in this study. This leads to the values of  $M_{e,\text{melt}}$  for  $\kappa$ - and  $\iota$ -carrageenans of  $6.6 \times 10^3$  and  $7.2 \times 10^3$ , respectively, and these can be considered as the material constants. For comparing the chain properties of various saccharides, we used the number of monosaccharide units between entanglements in the molten state  $N_{\text{unit}}$  instead of  $M_e$ . The values of  $N_{\text{unit}}$  for  $\kappa$ - and  $\iota$ -carrageenans are calculated to be 34 and 31, respectively, if each polysaccharide is assumed to be composed of uniform repeating units stated in the introduction.

It is revealed that  $\kappa$ - and  $\iota$ -carrageenans have similar chain properties regarding entanglement coupling; from the point of chemical structure, this result suggests that 2-sulfate group of A unit does not affect the chain property significantly.

It has been shown by several research groups [25-27] that  $M_{e,melt}$  is related to the characteristic ratio ( $C_\infty$ ), a measure of chain stiffness. The explicit expression has not been established yet, and therefore, we cannot estimate  $C_\infty$  from  $M_{e,melt}$ . However, we can say at least that closer values of  $M_{e,melt}$  for  $\kappa$ - and  $\iota$ -carrageenans imply closer values of  $C_\infty$  for these polysaccharides. This is actually consistent with the simulation results described in the introduction that both types of carrageenans are flexible.

We now compare  $N_{unit}$  for carrageenan, represented here by  $\kappa$ -carrageenan, with that for agarose. Agarose is a non-sulfated galactan composed of  $\alpha$ -(1-3)-D-galactose and  $\beta$ -(1-4)-3,6-anhydro-L-galactose units. Although A unit of  $\kappa$ -carrageenan is replaced with the corresponding L-galactose unit, the chemical structure of agarose is quite similar to that of  $\kappa$ -carrageenan except for the sulfate group. In our previous study,  $N_{unit}$  for agarose has been determined to be 15 [20], which is appreciably smaller than that for  $\kappa$ -carrageenan. This may suggest that 4-sulfate group of S unit of  $\kappa$ -carrageenan is influential in  $N_{unit}$ .

#### 4. Conclusions

The values of  $M_e$  for  $\kappa$ - and  $\iota$ -carrageenans in concentrated solutions were determined by dynamic viscoelasticity measurements using BmimAc as a solvent. It was assured that rheological behavior of the carrageenan solutions is typical of concentrated polymer solutions with entanglement coupling. From the  $c$ -dependence of  $M_e$ , the material constants  $M_{e,melt}$  for  $\kappa$ - and  $\iota$ -carrageenans was determined to be  $6.6 \times 10^3$  and  $7.2 \times 10^3$ , respectively. The close values of  $M_{e,melt}$  or  $N_{unit}$  mean that 2-sulfate group of A unit does not affect the chain properties significantly, while 4-sulfate group of S unit might be influential.

## References

1. Z. Osawa, T. Morota, K. Hatanaka, T. Akaike, K. Matsuzaki, H. Nakashima, N. Yamamoto, E. Suzuki, H. Miyano, T. Mimura, Y. Kaneko, *Carbohydr. Polym.* 21 (1993) 283-288.
2. D. Ngo, S. Kim, *Int. J. Biol. Macromol.* 62 (2013) 70-75.
3. M. Neushul, *Hydrobiol.* 204/205 (1990) 99-104.
4. X. Liu, T. Chen, Y. Hu, K. Li, L. Yan, *Biopolymers* 101 (2014) 210-215.
5. M. Jin, Y. Wang, M. Huang, Z. Lu, Y. Wang, *Carbohydr. Polym.* 99 (2014) 624-629.
6. N. Volpi, *Carbohydr. Polym.* 82 (2010) 233-239.
7. H.J. Vreeman, T.H.M. Snoeren, T.A. Payens, *J. Biopolymers* 19 (1980) 1357-1374.
8. E. Eteshola, M. Gottlieb, S. Arad, *Chem. Eng. Sci.* 51 (1996) 1487-1494.
9. J.Y. Le Questel, S. Cros, W. Mackie, S. Perez, *Int. J. Biol. Macromol.* 17 (1995) 161-175.
10. R. Urbani, A. Di Blas, A. Cesaro, *Int. J. Biol. Macromol.* 15 (1993) 24-29.
11. M. Bosco, A. Segre, S. Miertus, A. Cesaro, S. Paoletti, *Carbohydr. Res.* 340 (2005) 943-958.
12. F. Cuppo, H. Reynaers, S. Paoletti, *Macromolecules.* 35 (2002) 539-547.
13. D. Sloodmaekers, C.D. Jonghe, H. Reynaers, F.A. Varkevisser, C. Bloys van Treslong, *J. Int. J. Biol. Macromol.* 10 (1988) 160-168.
14. M. Doi, S.F. Edwards, *The Theory of Polymer Dynamics*, Clarendon: Oxford, 1986.
15. J.D. Ferry, *Viscoelastic Properties of Polymers*, John Wiley and Sons, New York, 1980.

16. T. Masuda, N. Toda, Y. Aoto, S. Onogi, *Polym. J.* 3 (1972) 315-321.
17. R.P. Swatloski, S.K. Spear, J.D. Holbrey, R.D. Rogers, *J. Am. Chem. Soc.* 124 (2002) 4974-4975.
18. J. Horinaka, R. Yasuda, T. Takigawa, *J. Polym. Sci. B: Polym. Phys.* 49 (2011) 961-965.
19. J. Horinaka, Y. Urabayashi, T. Takigawa, M. Ohmae, *J. Appl. Polym. Sci.* 130 (2013) 2439-2443.
20. J. Horinaka, R. Yasuda, T. Takigawa, *J. Appl. Polym. Sci.* 123 (2012) 3023-3027.
21. J. Horinaka, R. Yasuda, T. Takigawa, *Carbohydr. Polym.* 89 (2012) 1018-1021.
22. J. Horinaka, A. Okuda, R. Yasuda, T. Takigawa, *Colloid Polym. Sci.* 290 (2012) 1793-1797.
23. The product information on BmimAc given by BASF (accessed March 26, 2014).  
[http://www.basf.de/basf2/img/produkte/intermed/nbd/products/ionicliquid/Ionic\\_Liquids\\_Product\\_Range.pdf?MTITEL=Brochure%3A+BASIONICS+TM+and+BASIL+TM+-+Solutions+for+Your+Success%3A+Product\\_Range&](http://www.basf.de/basf2/img/produkte/intermed/nbd/products/ionicliquid/Ionic_Liquids_Product_Range.pdf?MTITEL=Brochure%3A+BASIONICS+TM+and+BASIL+TM+-+Solutions+for+Your+Success%3A+Product_Range&)
24. S. Onogi, T. Masuda, K. Kitagawa, *Macromolecules* 3 (1970) 109-116.
25. W.W. Graessley, S.F. Edwards, *Polymer* 22 (1981) 1329-1334.
26. L.J. Fetters, D.J. Lohse, D. Richter, T.A. Witten, A. Zirkel, *Macromolecules* 27 (1994) 4639-4647.
27. S. Wu, *J. Polym. Sci. B: Polym. Phys.* 27 (1989) 723-741.

## Figure Captions

**Fig. 1** Master curves of  $\omega$  dependence of  $G'$  and  $G''$  for  $\kappa$ -M solutions at  $T_r = 80$  °C. The curves are shifted upwards by  $A$ .

**Fig. 2** Shift factor for  $\kappa$ -M solutions plotted against the reciprocal of  $T$ . All data points fall on a single line.

**Fig. 3** Master curves of  $\omega$  dependence of  $G'$  and  $G''$  for  $\iota$ -M solutions at  $T_r = 80$  °C. The curves are shifted upwards by  $A$ .

**Fig. 4** Shift factor for  $\iota$ -M solutions plotted against the reciprocal of  $T$ . All data points fall on a single line.

**Fig. 5** Double-logarithmic plot of  $M_e$  vs.  $c$  for  $\kappa$ - and  $\iota$ -carrageenans in solution. Each line is the best fit one with a slope of  $-1$ .  $M_{e,\text{melt}}$  is determined as  $M_e$  at  $c = 10^3 \text{ kgm}^{-3}$ .

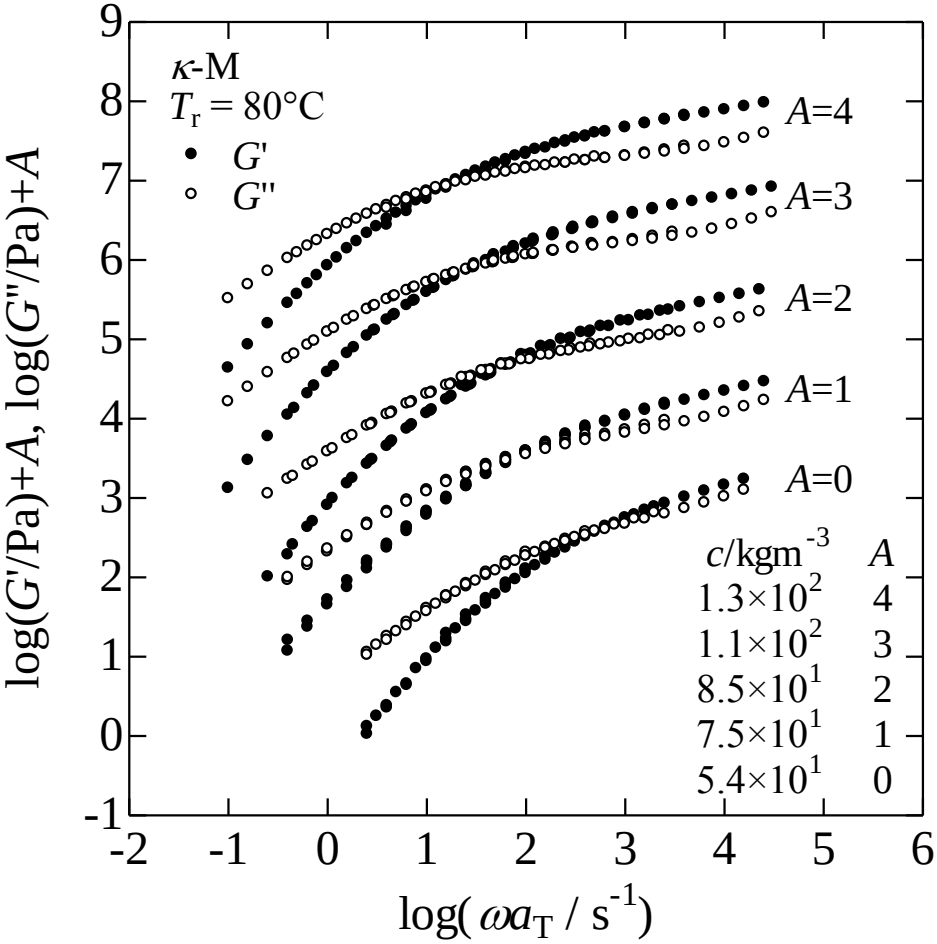


Fig. 1

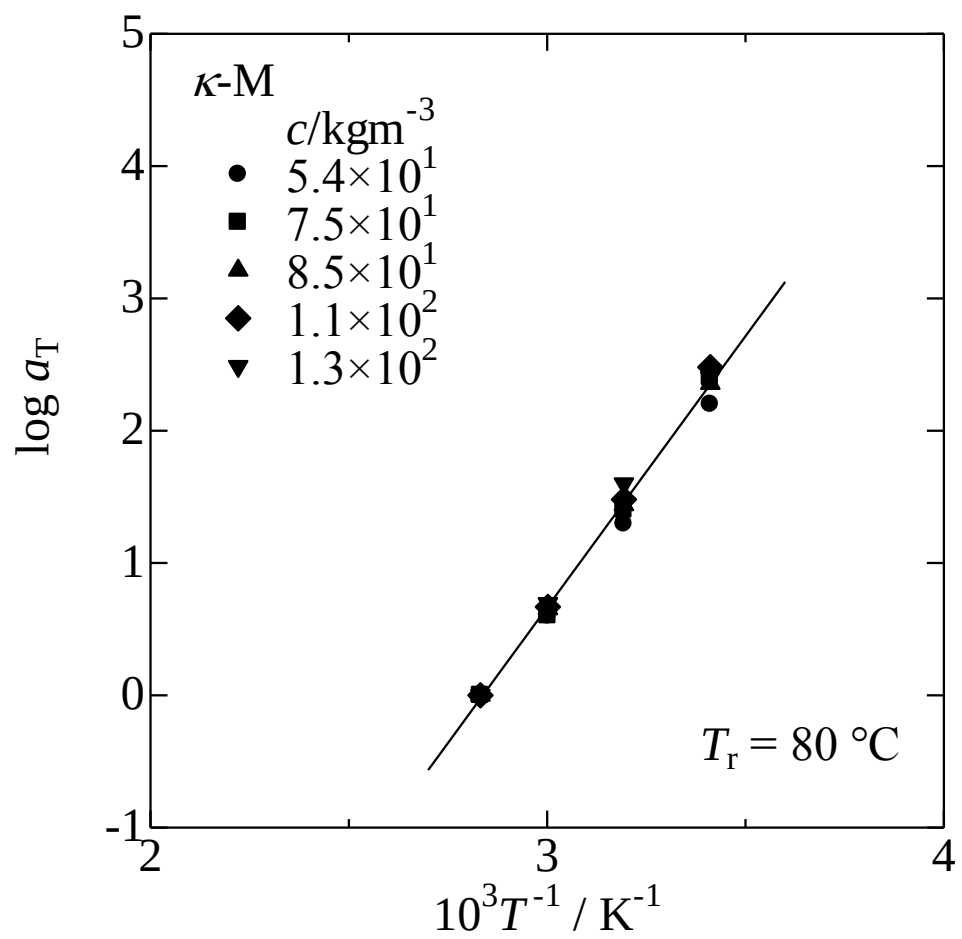


Fig. 2

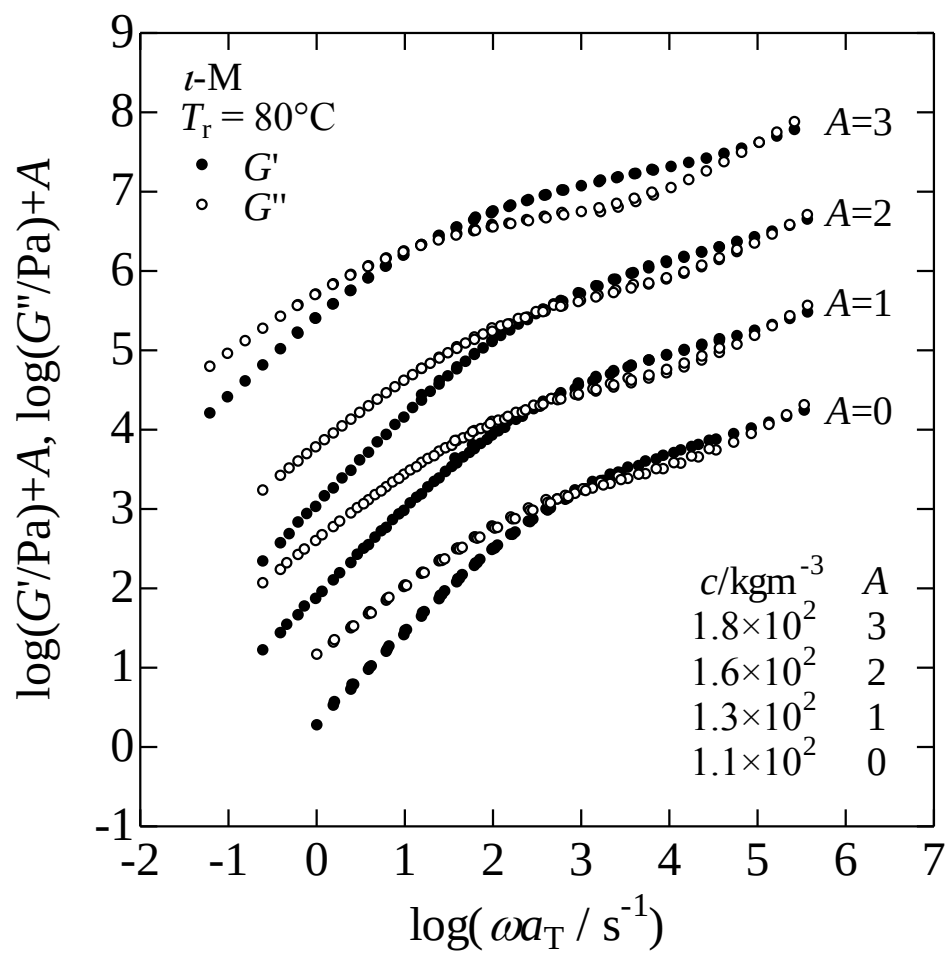


Fig. 3

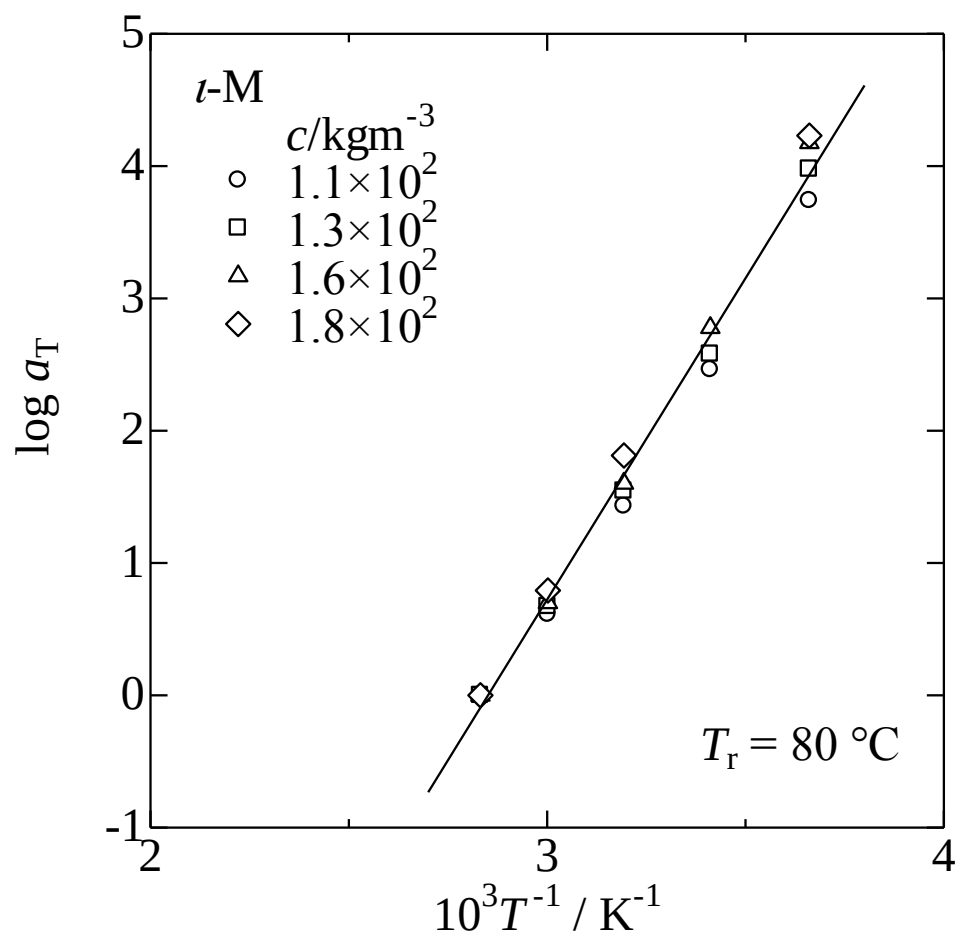


Fig. 4

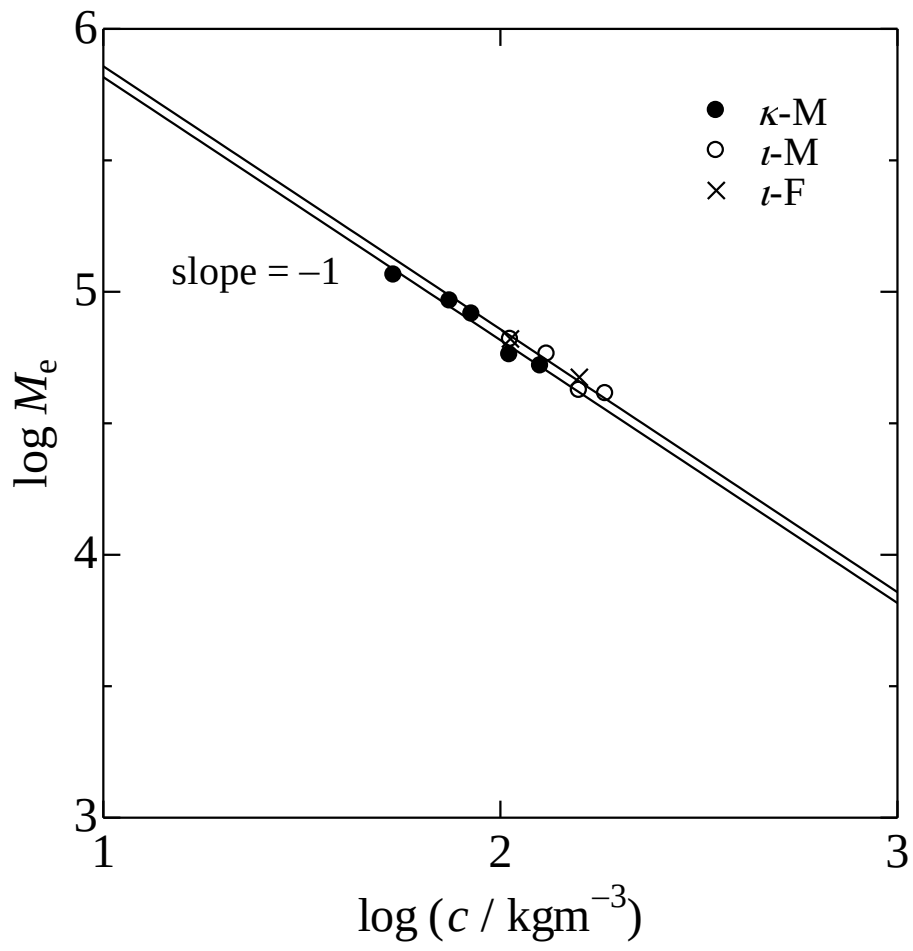


Fig. 5