

1 **Sulfated cellulose pulp with ultra-high water** 2 **retention characteristics**

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18 Technology (MEXT).

19 **Abstract:** A sulfated cellulose pulp (SCP) exhibiting ultra-high water retention
20 properties has been developed, and its water retention mechanisms have been
21 analyzed based on molecular structures determined by solid-state ^{13}C nuclear
22 magnetic resonance (NMR). Cellulose pulp (CP) from wood is sulfated using a
23 sulfamic acid and urea reaction system with varying concentrations of sulfamic
24 acid. SCP has 1.04–1.93 mmol/g of sulfate groups and exhibits a high water
25 retention value (WRV) of 16000%, which is approximately 100 times greater than
26 that of CP. After the sulfate reaction, new peaks at 69 ppm are observed in the ^1H -
27 ^{13}C cross-polarization/magic angle spinning (CPMAS) and dipolar
28 decoupling/MAS (DDMAS) ^{13}C NMR spectra, which are assigned to the sulfated
29 C6. Quantitative evaluation of area ratios of the corresponding peaks in the ^{13}C
30 DDMAS NMR spectra indicates that approximately 18% of C6 in CP is maximally
31 converted to sulfated C6 when $R = 4.19$. The present work demonstrates that the
32 WRV is related to the amount of sulfated C6, which guides the design of future
33 absorbent materials based on CP.

34
35 **Keywords:** Cellulose, Sulfated cellulose pulp, Water retention, Solid-state ^{13}C
36 NMR, Sulfate group

37 Introduction

38 Sulfated cellulose pulp (SCP) has attracted considerable attention in recent years
39 because it affords cellulose nanofibers, which are fibers isolated to the smallest unit
40 that constitutes a cellulose pulp (CP). Several synthetic methods for SCPs have been
41 proposed, such as sulfuric acid hydrolysis (Rånby et al. 1949), the
42 $\text{HSO}_3\text{Cl}/(\text{CH}_3\text{CO})_2\text{O}$ system (Zhang et al. 2011), the sulfamic acid/urea/*N,N*-
43 dimethylformamide system (Huang and Zhang 2010), the $\text{HSO}_3\text{Cl}/N,N$ -
44 dimethylformamide system (Zhao MW et al. 2007), and the deep eutectic solvent
45 system (DES, CP/sulfamic acid/urea system without water) (Sirviö et al. 2019). In
46 a similar manner to CP modified by carboxyl (Saito et al. 2007) and phosphate
47 groups (Ghanadpour et al. 2015; Noguchi et al. 2017; Zhao M et al. 2021), SCP is
48 also defibrillated via mechanical treatment in a high-pressure homogenizer,
49 affording in nanofibers. Nanofibers have been applied to functional materials such
50 as O_2 gas barrier films (Fukuzumi et al. 2009), rheology control agents (Wang et al.
51 2019), and metal ion adsorbents (Liu et al. 2015; Liu et al. 2016; Riva et al. 2024;
52 Lehtonen et al. 2020). Thus, cellulose nanofibers possess various characteristics
53 that allow them to be used in various industries with expanding applications.

54 Superabsorbent polymers (SAPs), known for their high absorbency, are a widely
55 recognized functional material. They are commonly used in products such as
56 disposable nappies (Zhang et al. 2021), concrete admixtures (He et al. 2019), and
57 soil conditioners (Hou et al. 2018). These polymers can absorb more than 1,000
58 times their own weight in water (Meshram et al. 2020). However, the components
59 of SAPs, such as polypropylene, polyester, and polyacrylic acid, are not
60 biodegradable, posing significant environmental and health issues. Therefore, there
61 has been a growing demand for environmentally friendly and highly absorbent
62 materials.

63 Recently, our group has presented the synthesis of SCP using a CP/sulfamic
64 acid/urea system, affording a water retention value (WRV) of approximately
65 3000% (Nishimura and Otsuka 2024), with enhancing water dispersion stability and
66 transparency in aqueous dispersions (submitted). Furthermore, the mechanism by
67 which SCP appears transparent in water is attributed to the swollen fiber structure
68 of the SCP fibers (Nishimura and Otsuka 2024). The molecular structure of SCP
69 has been analyzed using ^{13}C solid-state nuclear magnetic resonance (NMR), which
70 shows that the sulfation reaction occurs at the hydroxy groups in the C2, C3, and

C6 positions. However, the relationship between its molecular structure, fiber swelling, and WRV is not completely clear. While SCP has the potential to solve the environmental issues of conventional petroleum-derived SAPs, further improvements in its water retention capacity are required. Therefore, understanding the molecular structure of SCP, particularly the influence of the distribution of sulfate groups on WRV, is important for enhancing its water retention capacity. The sulfate group of SCP was previously investigated using the ^1H - ^{13}C cross-polarization/magic angle spinning (CPMAS) method (Zhang et al. 2011), which can provide useful structural information. CPMAS is a technique that enhances sensitivity by transferring the magnetization of ^1H , which has a natural abundance of 99%, to ^{13}C , which has a natural abundance of 1%. However, it is well known that its quantitative reliability is low because the signal intensities are affected by the distance to the ^1H and molecular mobility of the measurement. On the other hand, dipolar decoupling/magic angle spinning (DDMAS) is highly quantifiable because ^{13}C can be measured directly without passing through ^1H magnetization. One of the disadvantages of DDMAS is that it takes a long analysis time because five times the relaxation time T_1 is required for the recycle time to make the quantification reliable (Snape et al. 1989). To the best of our knowledge, no studies have reported ^{13}C DDMAS experiments on SCP. In this study, a novel SCP exhibiting an ultra-high water retention capacity was synthesized using the CP/sulfamate/urea reaction system. The molecular structure of SCP was examined via CPMAS, while DDMAS was employed for the quantification of the sulfate groups, elucidating the relationship between the water retention capacity and the molecular structure of SCP. Our findings provide essential information for the development of environmentally friendly absorbent materials that can be used in sustainable products such as agricultural water retention materials and biodegradable hygiene products.

Materials and methods

Materials

The cellulose pulp (CP) used in this study was never-dried softwood-bleached kraft pulp (Marusumi Paper Co., Ltd., Japan). The concentration of the CP slurry was

adjusted to 25 wt%, and the water used for the CP slurry was replaced from industrial to pure water. Sulfamic acid ($\text{H}_2\text{NSO}_3\text{H}$), urea ($(\text{H}_2\text{N})_2\text{C}=\text{O}$), sodium hydroxide (NaOH), and sodium hydrogen carbonate (NaHCO_3) were purchased from FUJIFILM Wako Pure Chemical Co. All the materials were used without further purification. The ion-exchange resin (Amberlite HPR1024H) was purchased from Organo Co., Japan. Pure water (distilled by Marusumi Paper Co., Ltd., Japan, conductivity < 0.1 mS/m, pH 5–8) was used in all the experiments.

Sulfation of cellulose pulp

The sulfate reaction solution was prepared by adding and stirring sulfamic acid (1.25–5.00 g, 0.013–0.051 mol) and urea (2.50 g, 0.042 mol) with pure water (12 g) at room temperature (296 K). The 25 wt% CP (8 g, BD2 g) was immersed in the sulfate reaction solution for 10 min, spread thinly and uniformly on an acrylic plate, and dried at 358 K for 3 h using a constant-temperature dryer (DKN602, Yamato Scientific Co. Japan). The dried CP reacted when heated to 413 K for 30 min. The reactants were neutralized with NaHCO_3 and washed with pure water on a 330-mesh sieve (Sampo Co., Japan). The sulfated cellulose pulp slurry was adjusted to a concentration of 1.0 wt% with pure water and then refrigerated at 277 K. The reaction conditions were determined at 5 different molar ratios (R), where R was determined by dividing the number of moles of sulfamic acid by the number of moles of the glucose residues units in CP. The moles of glucose residues units were calculated from the dry weight of the pulp/162.

Water retention value

The water retention value (WRV) was measured using the TAPPI method and 10 g of the 0.5 wt% SCP slurry. The SCP slurry was centrifuged at 3000 g for 15 min and the WRV was calculated using the following Equation (1).

$$\text{WRV}(\%) = \frac{W_w - W_d}{W_d} \times 100 \quad (1)$$

where W_w is the mass after centrifugation and W_d is the mass after drying the sample at 358 K for 24 h.

134

135 **X-ray diffraction measurements**

136 The X-ray diffraction (XRD) patterns of samples were measured by a X-ray
137 generator (Empyrean, Spectris Co., Ltd. United Kingdom) at a power level of 45
138 kV and 40 mA with Cu-K α radiation ($\lambda = 1.54 \text{ \AA}$) in the range $2\theta = 10\text{--}30^\circ$. The
139 crystallinity index (CI) of CP and SCP was calculated according to the following
140 Equation (2): (Segal et al. 1959)

$$141 \quad \text{CI}(\%) = \frac{I_{200} - I_{am}}{I_{200}} \times 100\% \quad (2)$$

142 where I_{200} is the overall intensity of the peak at 2θ about 22.4° , and I_{am} represents
143 the intensity of the minimum at 2θ about 18.5°

144

145 **Scanning electron microscopy**

146 The morphology observation of CP and SCP was observed by field emission-
147 scanning electron microscopy (FE-SEM, JSM-6701F, JEOL Ltd., Japan) with an
148 acceleration voltage of 3 kV. The samples were freeze-dried and coated with
149 platinum.

150

151 **Solid-state ^{13}C NMR**

152 Freeze-dried SCP was powdered using a blender (WB-1; Osaka Chemical Co.,
153 Osaka, Japan). ^1H and ^{13}C NMR experiments were performed at 500.194 and
154 125.774 MHz, respectively, on an 11.7 T spectrometer (JEOL ECZ 500, JEOL Ltd.,
155 Japan) using a 4 mm magic-angle spinning (MAS) probe at room temperature.
156 Potassium bromide was used to adjust the magic angle, and adamantane was used
157 as the reference. Standard ramped cross-polarization (CP), dipolar decoupling, and
158 Torchia sequences (Torchia 1978) were used with a MAS frequency of 15 kHz and
159 high-power irradiation to achieve heteronuclear decoupling during each detection
160 period. The broadening factor of 80Hz was applied to all the NMR spectra. For ^{13}C
161 CPMAS, the following parameters were used: $\pi/2$ for ^1H , 3.3 μs ; mixing time, 5
162 ms; spectral width, 400 ppm; data points, 1024; recycle delay time (RD), 5 s;

163 accumulations, 1000–1200 scans. For ^{13}C DDMAS, the following parameters were
164 used: $\pi/2$ for ^{13}C , 3.3 μs ; RD, 1200 s; accumulations, 260–300 scans; the other
165 parameters were the same as those of ^{13}C CPMAS. For Torchia experiments of T_1
166 measurements, the following parameters were used: RD, 4 s; accumulations, 700
167 scans; interval time, 1, 1.39, 1.95, 2.71, 3.79, 5.25, 7.37, 10.28, 14.34, 20.0, 50.0,
168 80.0, 125.0, and 200 s; the other parameters were the same as those of the ^{13}C
169 CP/DDMAS experiments. All NMR spectra were processed and analyzed using
170 DELTA software (JEOL USA, Inc.).

171

172 **Elemental analysis of sulfur contents**

173 The amount of sulfate groups in SCP was determined by a CHNS/O elemental
174 analyzer (Flash EA1112, Thermo Finnigan, USA). The samples were used freeze-
175 dried SCP (10 mg). The amount of sulfate groups in the samples (mmol/g) was
176 calculated from the sulfur content (%) in the sample and sulfur atomic mass. The
177 degree of substitution (DS) was calculated using the following Equation (3): (Sirviö
178 et al. 2019).

$$179 \quad \text{DS} = \frac{S \times 162}{3206 - (S \times 97)} \quad (3)$$

180 where S is the sulfur content (%).

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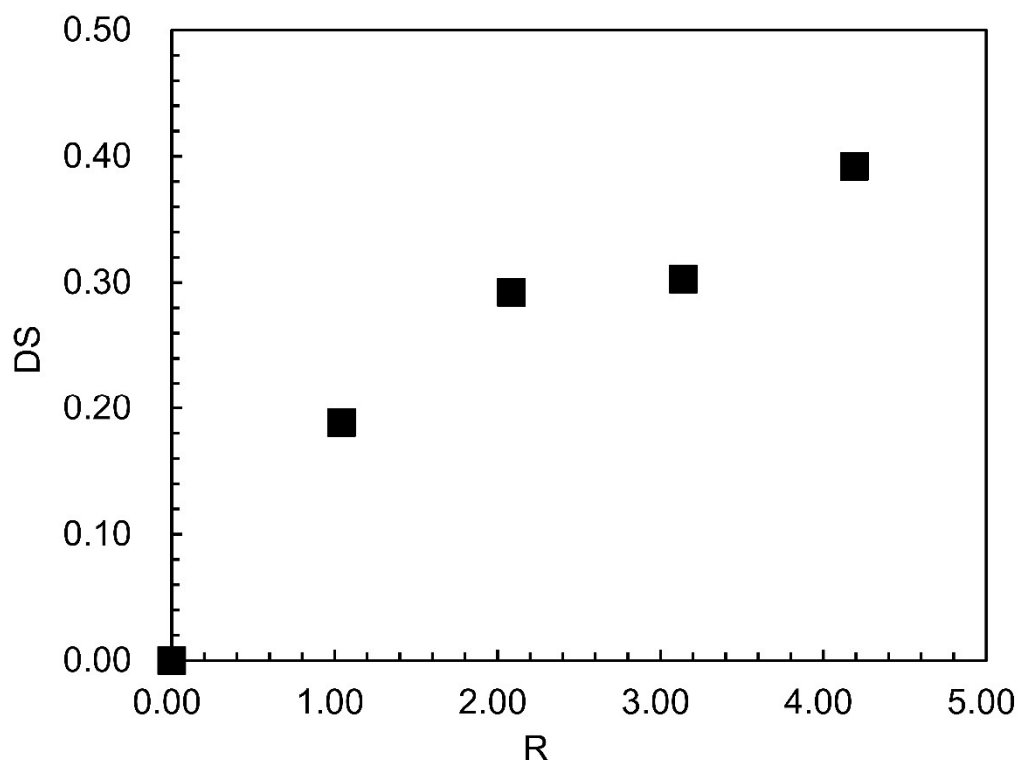
182 **Fourier-transform infrared spectroscopy**

183 The Fourier-transform infrared (FTIR) spectra of CP and SCP were recorded on a
184 Fourier transform infrared spectrometer (IRTracer-100, Shimadzu Corp., Japan) in
185 transmission mode, with a resolution of 4 cm^{-1} .

186

187 **Results and discussion**

188 Figure 1 shows the relationship between the R value and the degree of substitution
189 (DS). DS increased as the R value increased. The sulfated cellulose pulp (SCP) with
190 a degree of substitution ranging from 0.20 to 0.40 was obtained by adjusting the
191 amount of sulfamic acid used in the reaction with cellulose pulp, showing the
192 significant role of sulfamic acid in this modification process.



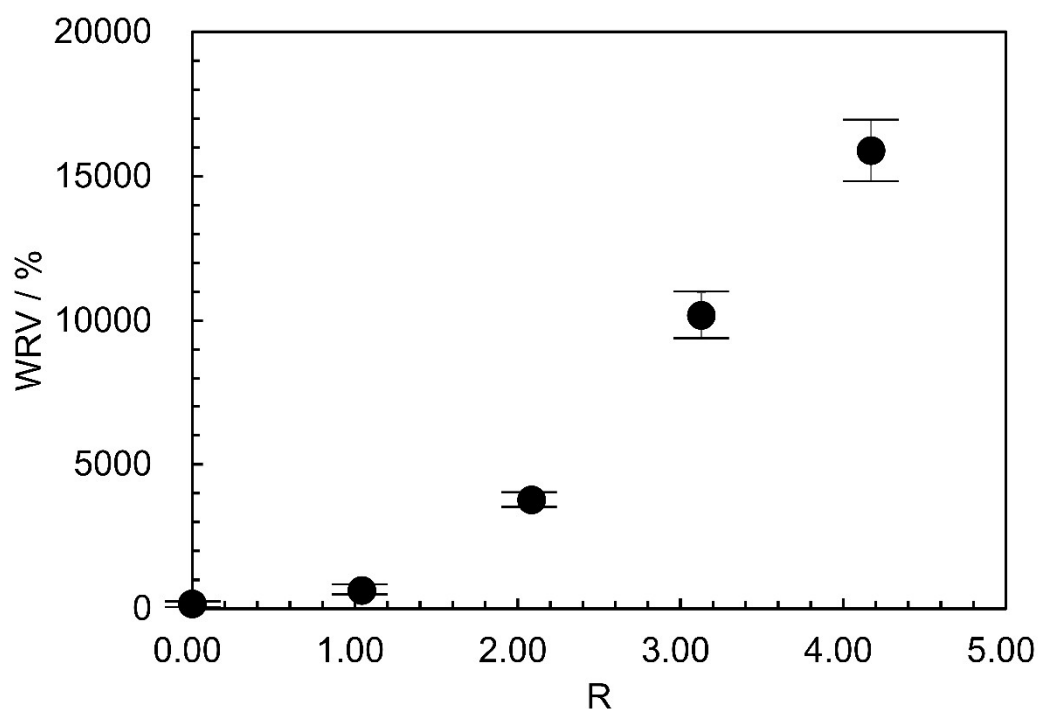
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194 **Fig. 1** Relationship between the molar ratio (R) and the degree of substitution (DS). R is the molar
 195 of sulfamic acid divided by the molar of cellulose pulp (CP)

196

197 Figure 2 shows the WRV results of SCP for different R values. WRV increased
 198 slightly as the R value increased from 0 to 1.05, and increased almost linearly as
 199 the R value increased above 1.05. The maximum WRV reached approximately
 200 16000% when the R value was 4.19, which is approximately 5 times greater than
 201 the value reported by Nishimura and Otsuka for SCP and approximately 100 times
 202 greater than that of CP. Furthermore, previous studies have shown that the WRV of
 203 TEMPO-oxidized CP is approximately 400% at about 1.5 mmol/g of carboxyl
 204 groups (Saito et al. 2007) and phosphorylated CP has a WRV of approximately
 205 900% at about 1.9 mmol/g of phosphorus groups (Hou et al. 2022). Such a result
 206 suggests that the developed SCP in this study has a higher WRV than other

207 chemically modified cellulose pulps with a similar amount of functional groups.



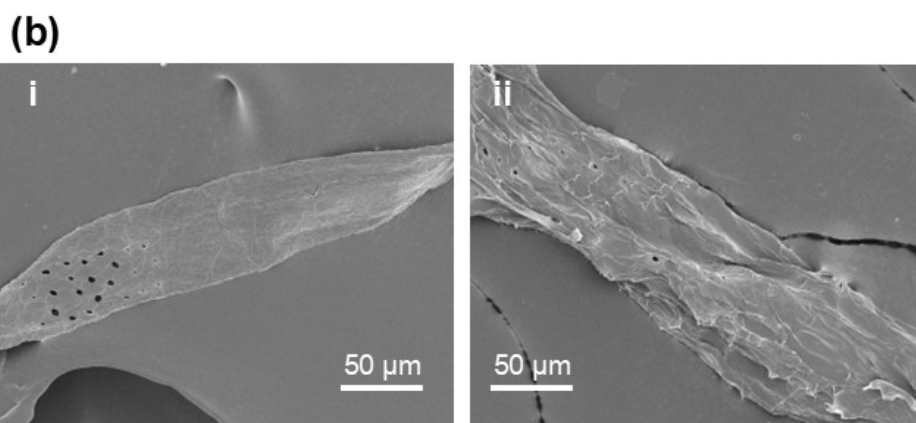
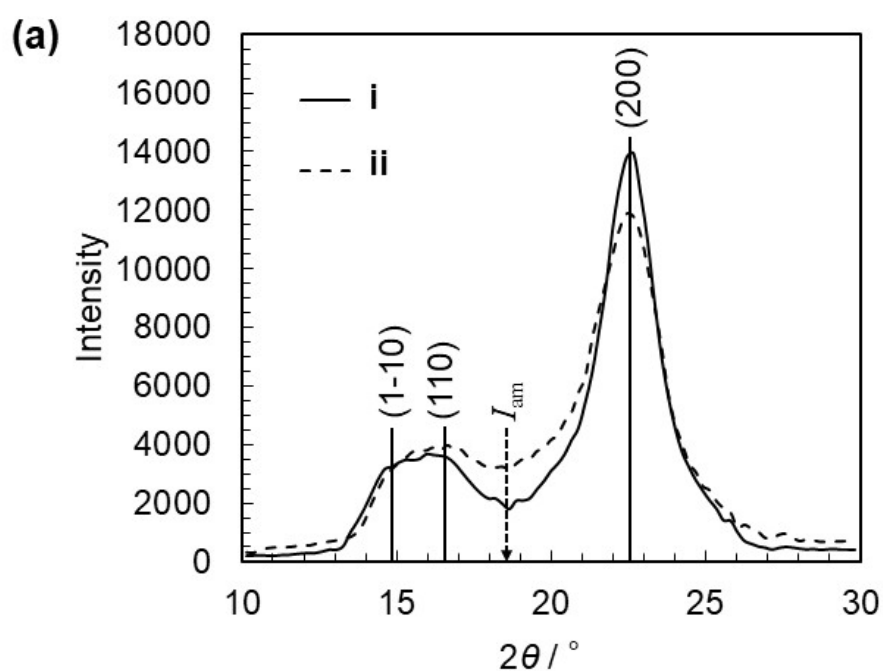
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209 **Fig. 2** Water retention value (WRV) of sulfated cellulose pulp (SCP) with different R values

210

211 The crystallinity of SCP was investigated by XRD, and the fiber morphology was
 212 examined using FE-SEM to elucidate the cause of this hydration phenomenon.
 213 Figure 3(a) shows the XRD pattern of CP and SCP, denoted as i and ii, respectively.
 214 After the sulfation of CP, the peak corresponding to the (200) plane decreased
 215 slightly, and the line shape broadened slightly. However, the typical cellulose I
 216 peaks 1-10, 110, and 200 were observed at 2θ angles of 14.8° , 16.6° , and 22.6°
 217 (with the 1-10 and 110 peaks overlapping), respectively, indicating that the crystal
 218 structure was almost maintained (French 2014). The CI of CP and SCP was
 219 estimated using the Segal equation, based on unprocessed raw XRD profiles.
 220 Although the absolute values may be affected by the baseline contribution, the CI
 221 of SCP decreased slightly from approximately 85% for CP to approximately 73%,
 222 indicating a relative trend of reduced crystallinity following sulfation. No baseline
 223 correction or smoothing was applied to the XRD profiles used for this calculation.
 224 FE-SEM was used to investigate the micromorphology of SCP to understand this
 225 decrease in crystallinity. Figure 3(b) shows the FE-SEM images of CP and SCP
 226 with $R = 4.19$, denoted as i and ii, respectively. The widths of both fibers are
 227 approximately the same, at around $100\ \mu\text{m}$. In contrast, SCP exhibited different

228 surface morphologies than CP, whose fiber surface was ragged. These morphology
 229 results clarified that despite the intense reaction with strong acid and heat, SCP
 230 maintained almost the same fiber morphology as CP before the reaction, and the
 231 fiber surface was rough. It is considered that the increase in the amorphous region
 232 on the fiber surface made it easier for water to access in fiber. In addition to these
 233 results of surface observations, SCP was assessed at the molecular level to clarify
 234 the mechanism of WRV increase further.

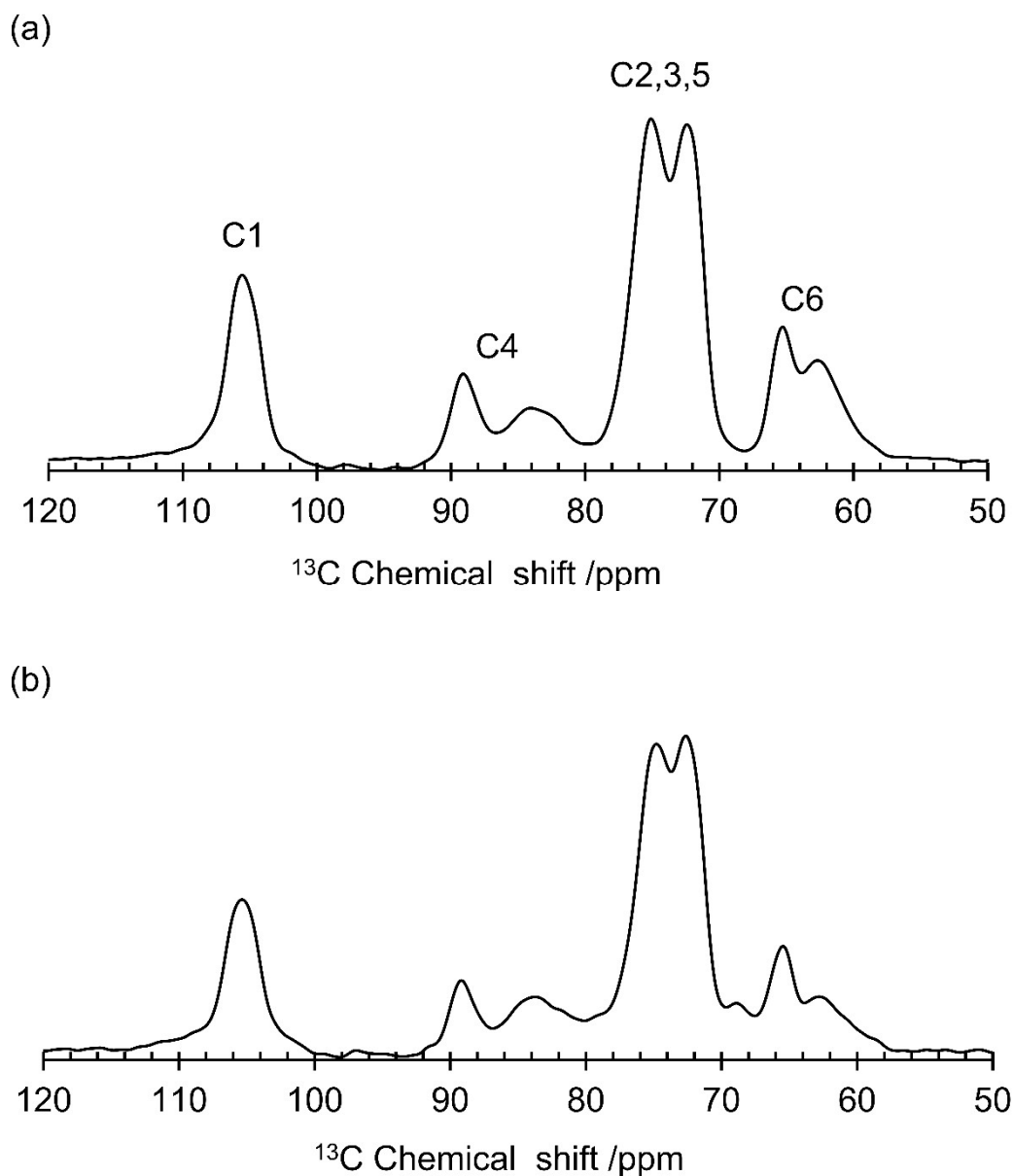


235

Fig. 3 (a) X-ray diffraction patterns of CP and SCP with R values of 4.19, **(b)** SEM images of CP and SCP with R values of 4.19. Labels i and ii correspond to CP and SCP, respectively

The molecular structure of SCP was investigated by solid-state ^{13}C NMR spectroscopy to elucidate the reason for the significant increase in WRV. Figure 4(a) shows the further ^{13}C CPMAS NMR spectrum of CP with the spectral assignment based on the literature (Atalla and VanderHart 1999; El Hariri and El Nokab 2022; Foston 2014; Solum 1996). C6_{cry} and C6_{am} denote the crystalline and non-crystalline C6 signals, respectively. The C6_{am} peak was observed at 62 ppm, the C6_{cry} peak was at 65 ppm, the C2, C3, and C5 carbon peaks were located between 70 and 78 ppm, the C4_{am} peak was at 84 ppm, the C4_{cry} carbon peak was at 89 ppm, and the C1 peak was at 105 ppm. Figure 4(b) shows the ^{13}C CPMAS NMR spectrum of SCP at $R = 4.19$. A new peak was observed in the spectrum of SCP at 69 ppm, which was attributed to the sulfated C6 carbon (Zhang et al. 2011). The intensities of the C6_{am} peak changed, and a new peak appeared, suggesting that C6_{am} was involved in the reaction. In addition, the intensities related to C2, C3, and C5 were also changed. However, these peaks overlapped and it was not easy to distinguish between them. Therefore, this study focused on the peak associated with C6 which

254 is clearly distinguishable.



255

256 **Fig. 4** ^{13}C CPMAS NMR spectra of (a) CP and (b) SCP with an R value of 4.19

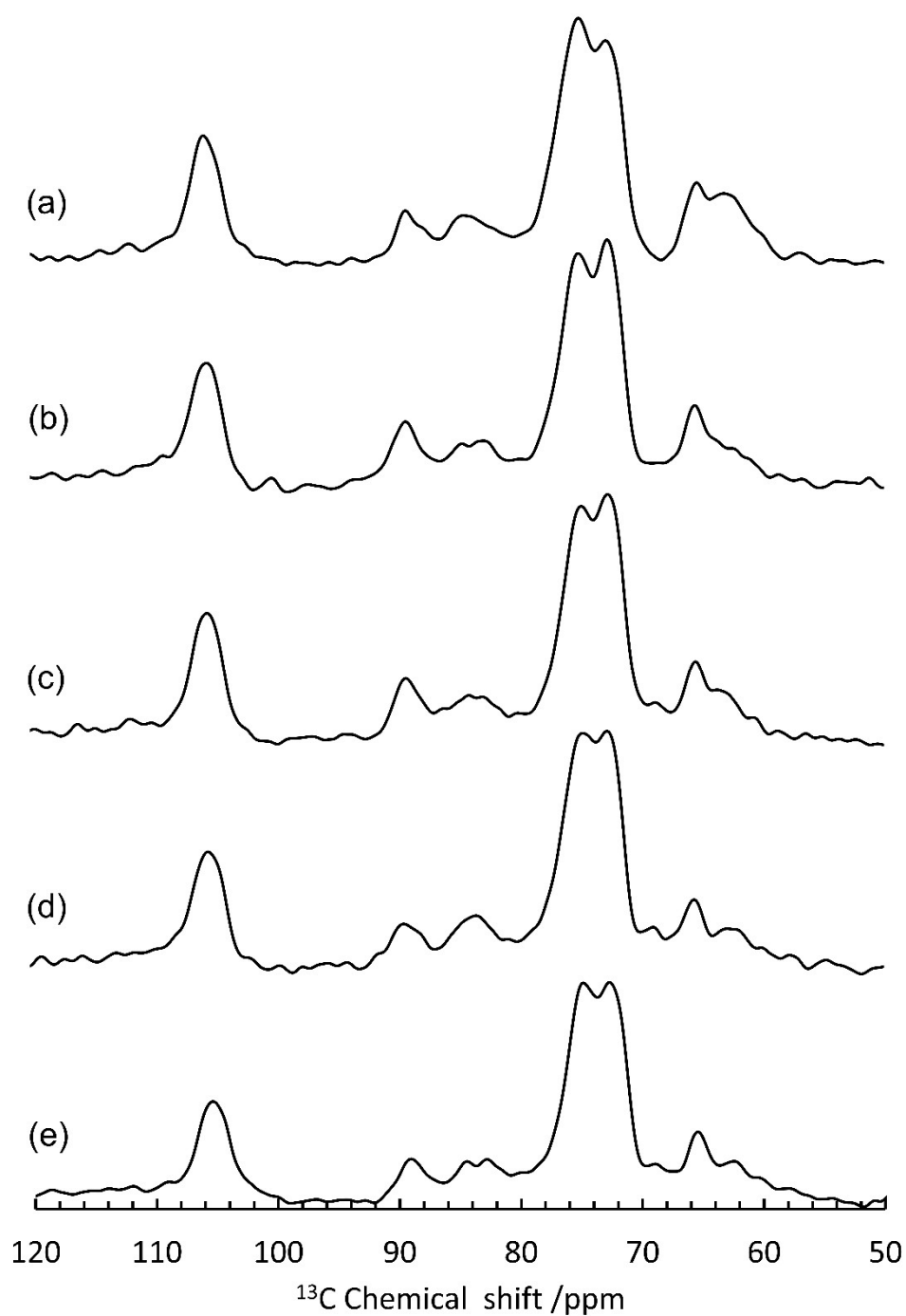
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258 As was mentioned, the DDMAS method is valid for quantitative measurements of
259 the above structural changes if RD is set to more than five times that of T_1 . The
260 longest T_1 in CP, which is believed to be the same as that in SCP, was 163 s for
261 C4_{cry} . Under these experimental conditions, RD was set at 1200 s so that the
262 intensity of each signal was guaranteed to be quantitative. Figure 5 shows the solid-

state ^{13}C DDMAS NMR spectra of the SCP with R values ranging from 0 to 4.19. Although the trend was not strictly linear, the peak intensity derived from the sulfate groups of SCP at 69 ppm appeared to increase as the R value increased from 0 to 4.19. Furthermore, the C6_{am} peak at 62 ppm decreased as R increased from 1.05 to 4.19, whereas the C6_{cry} peak at 65 ppm did not exhibit any significant change. Previous studies reported that CP consists of alternating crystalline and non-crystalline regions (Wickholm et al. 1998). The crystalline region of CP was hardly accessible in the sulfated reaction because of its regularly lined and high-density composition. Moreover, the non-crystalline sections of CP are irregular and flexible, which enhances the reactivity of the chemicals (Yu and Wu 2010). The hydroxy groups of C6 exposed on the surface of microfibrils in the amorphous regions may be sulfated first.

This interpretation is further supported by NMR analysis. Horii et al. (1983) first reported the relationship between solid-state ^{13}C NMR chemical shifts and the conformation of the hydroxymethyl group at C6, and Yoneda et al. (2008) demonstrated that the *gt* conformation is the most abundant of the three conformations (*tg*, *gg* and *gt*) in a simpler, more readily crystallisable cellulose-like model compound. According to Horii et al., the *tg* conformation is characteristic of the crystalline regions of cellulose I. In contrast, the *gg* and *gt* conformations are typically observed at 60–62.6 ppm and 62.5–64.5 ppm, respectively, and are predominant in amorphous regions. Furthermore, the *gt* and *gg* conformations are also predominant in some disordered surface chains of native cellulose I, whereas the *tg* conformation is largely absent (Viřtor et al., 2002). Therefore, the decrease in the signal at 60–64.5 ppm and the appearance of a new peak at 69 ppm suggest that hydroxy groups originally in the *gt* and *gg* conformations, which are typically present in amorphous and some cellulose surface regions, were selectively sulfated. The 69 ppm signal reflects the presence of newly introduced sulfate groups. This is considered to result from both conformational changes and alterations in the

291 electronic environment introduced through sulfation.



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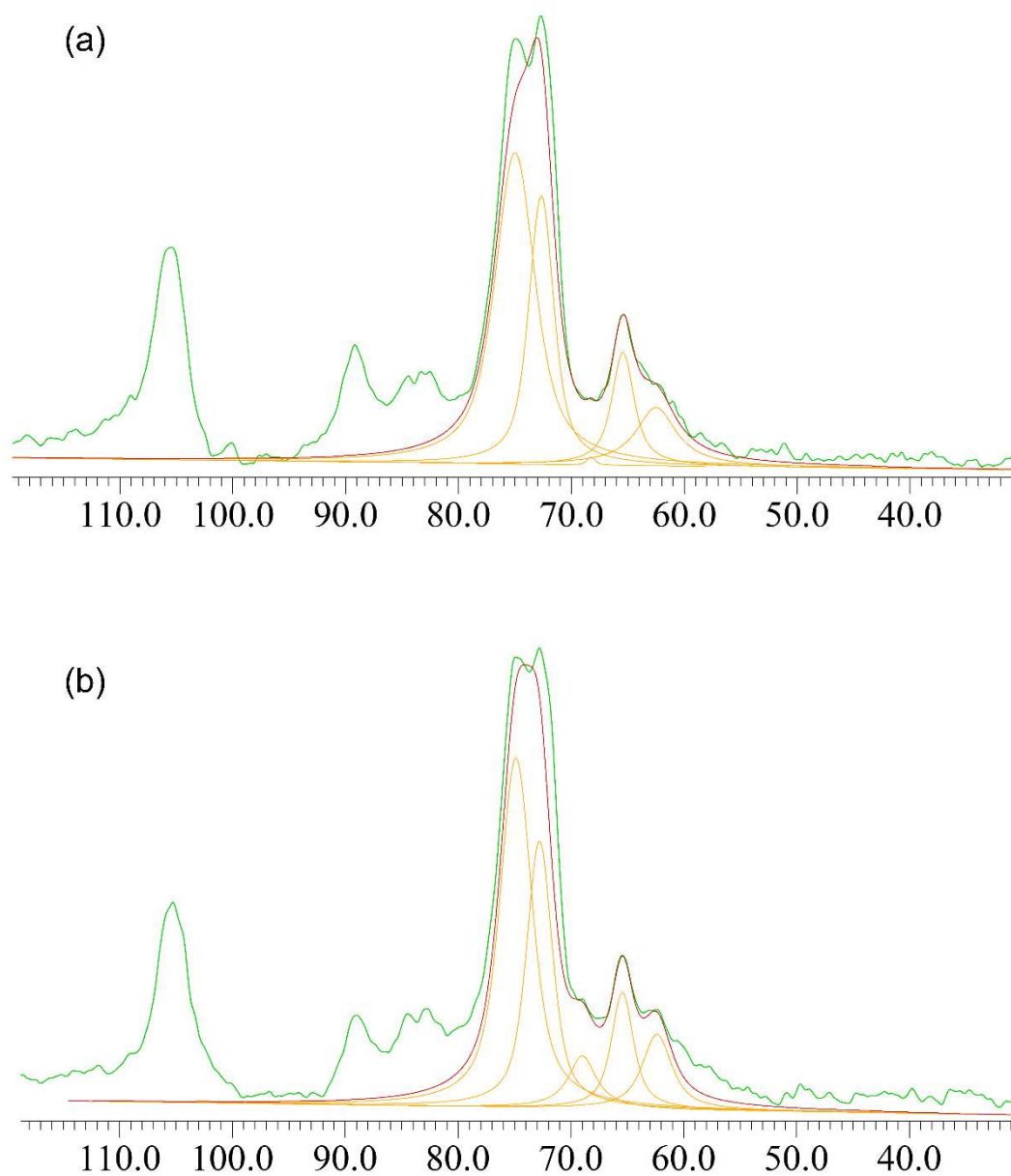
293 **Fig. 5** ^{13}C DDMAS NMR spectra of SCP with R values of (a) 0, (b) 1.05, (c) 2.09, (d) 3.14, and (e)
294 4.19

295

296 Quantitative measurements of SCP focused on the peaks between 57 and 70 ppm
297 regarding C6. Figure 6 shows the deconvolution of sulfated C6 in the ^{13}C DDMAS
298 NMR spectra of SCP with (a) R = 1.05 and (b) R = 4.19. Deconvolution of the
299 signals was performed using Voigt functions. The percentage of C6 converted to

300 sulfated C6 in CP was calculated by comparing the intensities of each peak. Figure
301 7 shows the correlation between the amount of sulfate groups at C6 in SCP and the
302 R values. The amount of sulfate groups increased as the R value increased from
303 1.05 to 2.09 and continued to increase slightly as the R value increased from 2.09
304 to 4.19. Sulfated C6 was almost absent when $R = 1.05$. The maximum value of
305 sulfated C6 was approximately 18% when $R = 4.19$. The results shown in Figures
306 2 and 7 indicate that WRV increased as the amount of sulfated C6 increased.
307 Some hydroxy groups extend outward onto the surface of microfibrils. Regarding
308 CP, some microfibrils are closely packed together via hydrogen bonds between the
309 exposed hydroxy groups. However, replacing the hydroxy groups with polar sulfate
310 groups results in electron repulsion and steric hindrance. Such findings suggest that
311 WRV increased because the space between the microfibrils expanded by sulfation
312 reaction, creating space for water to enter. Additionally, the hydroxy groups of C6
313 are located farther from the surface of microfibrils than those of C2 and C3,

314 suggesting that the quantity of sulfated C6 significantly impacts WRV.



315

316 **Fig. 6** Deconvolution of sulfated C6 in the ^{13}C DDMAS NMR spectra of SCP with R values of (a)

317 1.05 and (b) 4.19

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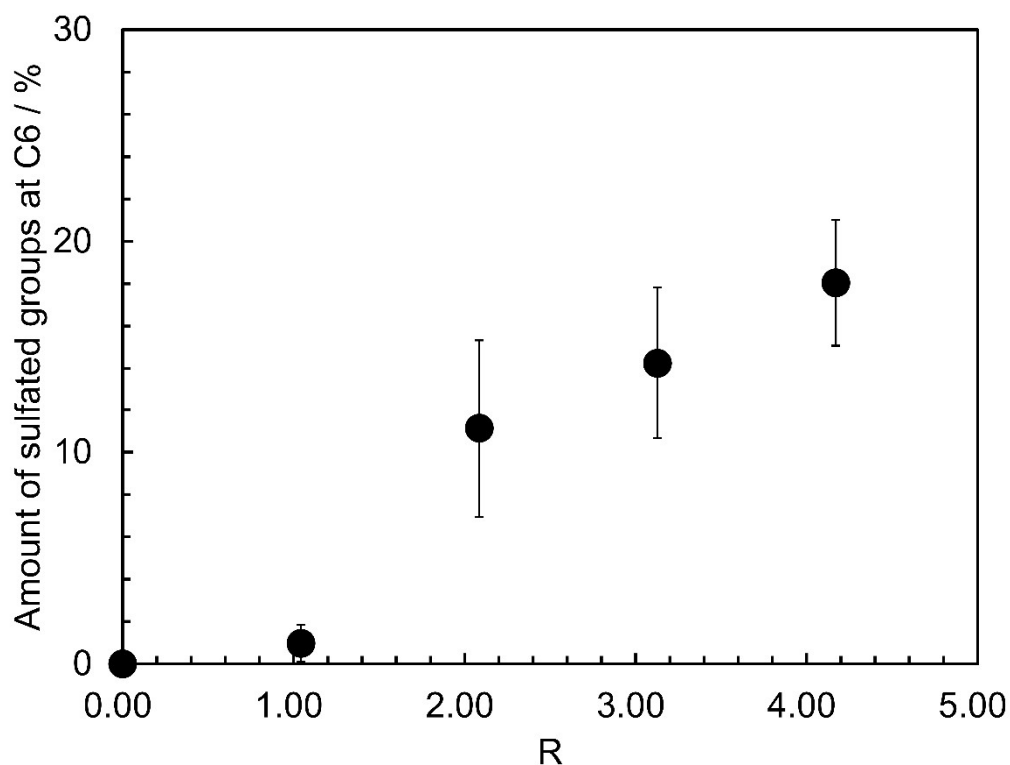
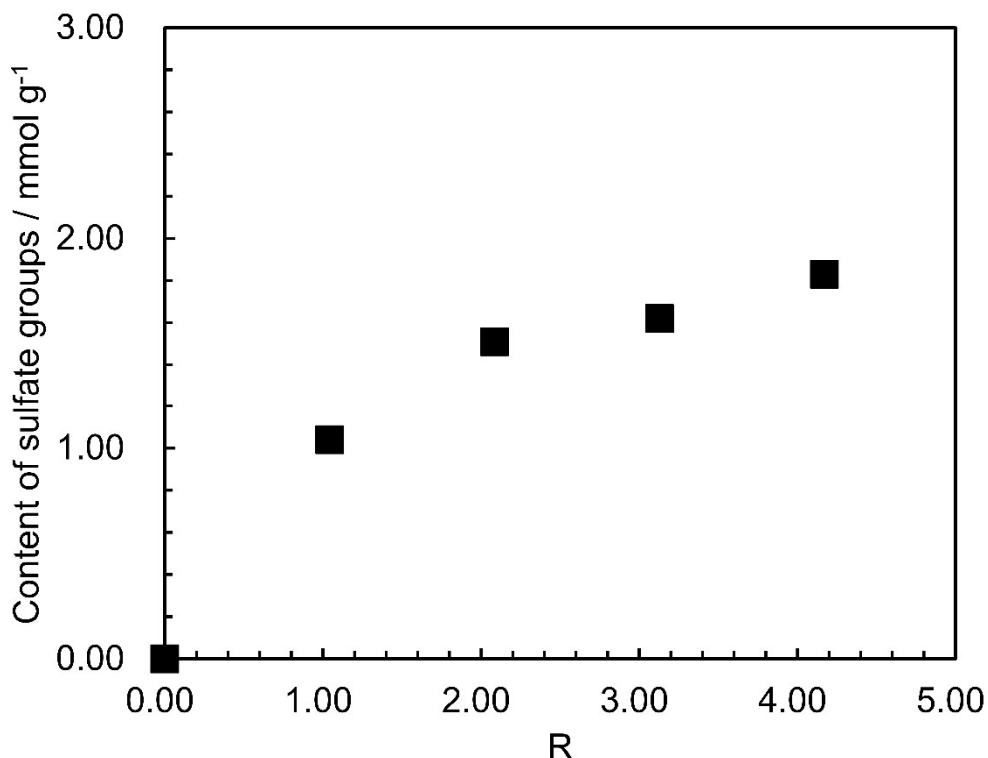


Fig. 7 Relationship between the amount of sulfate groups at C6 and the R value

To further consider the relationship between the amount of sulfated C6 and WRV, the total amount of sulfate groups in SCP was measured. Figure 8 shows the correlation between the total content of the SCP sulfate groups determined by the elemental analysis method and the R values. The total amount of sulfate groups increased from 0 to 1.04 mmol/g as the R value increased from 0 to 1.05, and continues to increase slightly from 1.51 to 1.83 mmol/g as the R value increased from 2.09 to 4.19. The maximum total amount of sulfate groups reaches 1.83 mmol/g when $R = 4.19$, suggesting that it is nearly equivalent to that of the amount of modifiable hydroxy groups of C6 present on the surface of microfibrils (Isogai 2018). These results indicate that sulfate groups are mainly introduced to the hydroxy groups at the C2 and C3 positions of CP via the sulfation reaction when the amount of sulfamic acid reacting with cellulose pulp is small. In contrast, the proportion of sulfated C6 relative to the total sulfate groups increases, with more sulfamic acid reacting with cellulose pulp. Interestingly, at $R = 1.05$, although sulfated C6 is almost absent (Figure 7), the total amount of sulfate groups is 1.04 mmol/g (Figure 8). This suggests that most of 1.04 mmol/g is sulfated C2 and C3. In addition, Figure 2 shows that WRV is hardly enhanced at $R = 1.05$. In other words, the sulfated C2 and C3 do not significantly enhance the water retention

340 capacity. This indicates that the amount of sulfated C6 is essential for improving
 341 the WRV of CP materials.



342
 343 **Fig. 8** Association between the amount of sulfate groups and the R value

344
 345 FTIR spectroscopy was used to verify the sulfation of the hydroxy groups in CP.
 346 Figure 9 shows the infrared spectra of (a) CP and SCP with R values of (b) 0, (c)
 347 1.05, (d) 2.09, (e) 3.14, and (f) 4.19. The intensity of the peaks at 810 and 1230
 348 cm⁻¹ gradually increased as the R value increased. The peak at 810 cm⁻¹ was
 349 attributed to S=O vibrations and that at 1230 cm⁻¹ was attributed to C-O-S
 350 vibrations. However, S=O and C-O-S vibrations were almost nonexistent in the
 351 spectra of CP and SCP with R = 0. Therefore, urea is not directly involved in the
 352 sulfate reaction of CP, supporting the preferential sulfation of hydroxy groups.

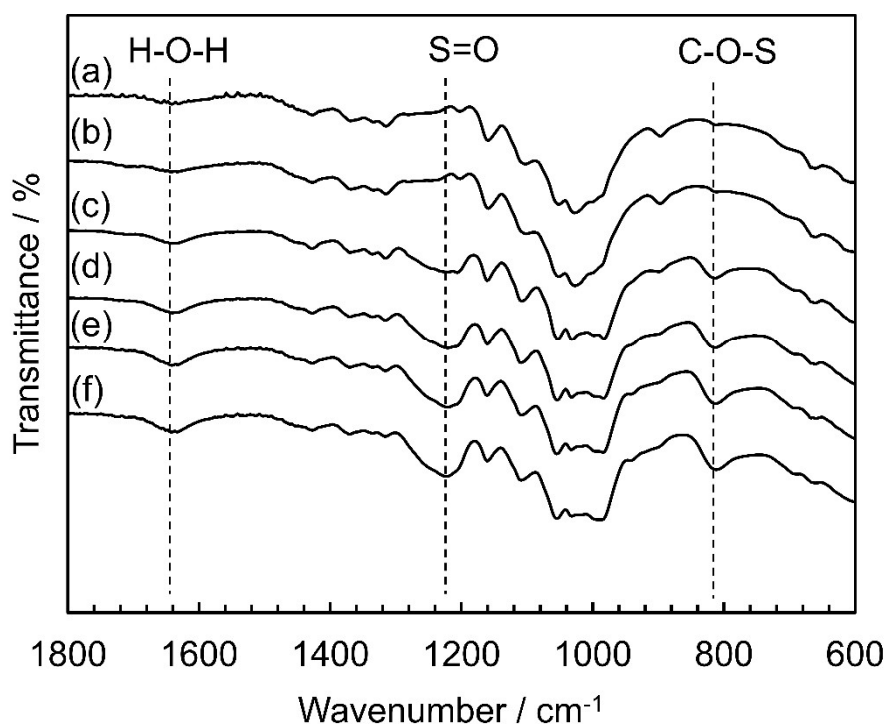


Fig. 9 Fourier-transform infrared spectra of (a) CP and SCP with R values of (b) 0, (c) 1.05, (d) 2.09, (e) 3.14, and (f) 4.19

Conclusions

A novel SCP was developed using a sulfate reaction with CP, exhibiting a WRV of 16000% for $R = 4.19$. Solid-state ^{13}C NMR was used to investigate and quantify the molecular structure of SCP. After sulfation, the intensity of the C6_{am} peak at 62 ppm decreased, whereas the new peak at 69 ppm increased. The other peaks remained almost unchanged. The amount of sulfate at C6 increased with an increase in R value. Under the presence of sulfamic acid in low quantities during the sulfate reaction, sulfate groups are preferentially introduced into the hydroxy groups at C2 and C3 of CP. The sulfate reactions occur at C2, C3, and C6 for high quantities of sulfamic acid. FT-IR spectroscopy confirmed that the hydroxy groups were mainly sulfated. This study demonstrates the importance of the substitution rate of the sulfated C6 in SCP to achieve ultra-high water retention in cellulose pulps.

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