ELSEVIER
Carbohydrate Research 268 (1995) 319–323
CARBOHYDRATE RESEARCH

Note

Homogeneous alkylation of cellulose in lithium chloride/dimethyl sulfoxide solvent with dimsyl sodium activation. A proposal for the mechanism of cellulose dissolution in LiCl/Me_2SO

Ladislav Petruš [a], Derek G. Gray [b], James N. BeMiller [c,*]

[a] *Institute of Chemistry, Slovak Academy of Sciences, SK-84238 Bratislava, Slovak Republic*
[b] *Pulp and Paper Research Institute of Canada and Department of Chemistry, McGill University, Montreal, PQ H3A 2A7, Canada*
[c] *The Whistler Center for Carbohydrate Research, Purdue University, West Lafayette, IN 47907, USA*

Received 7 June 1994; accepted in revised form 23 September 1994

Keywords: Homogeneous alkylation of cellulose; Dimsyl sodium activation; Mechanism of cellulose dissolution; Cellulose dissolution

1. Introduction

Several more or less efficient cellulose solvents have been reported [1], but only some are true solvents that do not form derivatives. For complete alkylation, only true solvents can be used because any blocking effect on hydroxyl groups must be avoided. In addition, a homogeneous solution is required.

To achieve complete methylation of oligosaccharides and polysaccharides, the Hakomori procedure, which exploits highly reactive dimsyl sodium (sodium methylsulfinylmethylide) or corresponding salts of other alkali metals, is used almost universally [2]. In addition to their powerful alkoxidation ability, dimsyl salts react with carbonyl compounds [3] and are sensitive to higher temperatures [4]. Hence, cellulose solvents containing water or carbonyl groups are not convenient media for alkali cellulose generation with the dimsyl anion. Often methylation of cellulose must be repeated three or more times to achieve complete methylation in dimethyl sulfoxide (Me_2SO) as the solvating medium. Me_2SO by itself is able to dissolve only cellulose oligomers [5].

---

[*] Corresponding author.

SSDI 0008-6215(94)00330-0

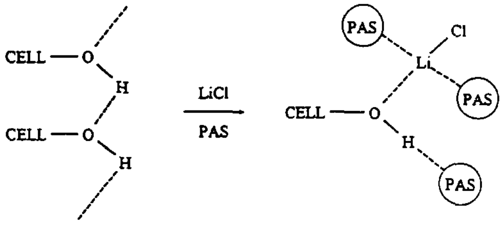
The fact that addition of lithium chloride increases the solubility of poly(4-benzhydrazidoterephthalamide) in Me_2SO [6] led us to try lithium chloride in Me_2SO as a cellulose solvent compatible with efficient alkylation procedures.

2. Results and discussion

Cellulose was dissolved in Me_2SO containing 5 to 10 wt% LiCl as follows. Anhydrous regenerated cellulose, dried by solvent exchange, was added to a $LiCl/Me_2SO$ solution, and solvent was removed from the stirred mixture at ambient temperature by placing it under vacuum under moisture-excluding conditions. Dissolution of this regenerated cellulose was complete within 1 h at ambient temperature. Dissolution of a dry, solvent-free cellulose (even in the case of amorphous, regenerated cellulose) was much slower and incomplete, even after several hours. Under optimal conditions (as described), solutions of regenerated cellulose (dp 174) containing up to 3 wt% of cellulose in Me_2SO containing 5–10% LiCl could be prepared. More concentrated solutions were very viscous and gel-like, but did not contain any undissolved or anisotropic material.

The ^{13}C NMR spectrum of a 2% solution of cellulose in Me_2SO containing 10% LiCl (w/w/w) obtained at 90°C shows four signals at 102.3, 79.0, 73.5, and 59.9 ppm, and two, poorly resolved signals at 75.1 and 74.8 ppm. The spectrum is almost identical to that of cellulose oligomers in Me_2SO [5], which contains signals at 102.8, 80.0, 75.0, 74.9, 73.2, and 60.5 ppm. These results suggest that $LiCl/Me_2SO$ is a true cellulose solvent, since it does not effect significant changes in chemical shifts of the six carbon atoms, indicating that no derivatives or complexes are formed.

The new solvent resembles LiCl/DMAc [7–9] and LiCl/NMP [8]. The extensive investigations and discussions devoted to the mechanism of cellulose dissolution in polar aprotic solvents containing lithium chloride have been summarized [10]. Both El-Kafrawy [8] and McCormick et al. [9] emphasized a unique role for LiCl and proved a strong interaction between LiCl and DMAc in the LiCl/DMAc solvent system. Dissolution of cellulose was considered to result from chloride ion association with hydroxyl protons via hydrogen bonding and a simultaneous association of the chloride anion with the $Li^+(DMAc)_x$ macrocation. El-Kafrawy [8] also considered a simultaneous interaction of carbonyl carbon atoms and lithium atoms of macrocations with oxygen atoms of hydroxyl groups. According to Turbak [13], Li cations are extensively complexed with the oxygen and nitrogen atoms of DMAc molecules, as well as with oxygen atoms of cellulose hydroxyl groups. Based on a more detailed ^1H NMR study of LiCl/DMAc solutions of chitin and its monomer and dimer, which revealed an equimolar interaction of LiCl with each labile saccharide proton [12], other schemes suggesting an important role of the lithium moiety of the LiCl ion pair in the dissolution mechanism were proposed [12,13]. Direct interaction of lithium ions with hydroxyl oxygen atoms, which is strongly supported by ^7Li NMR [14,15], is incorporated into another interpretation of cellulose dissolution in LiCl/DMAc [15]. A common feature of all these explanations is the formation of a solvated macrocation (or a macro-ion pair) with simultaneous



PAS = polar aprotic solvent

Scheme 1.

hydrogen bonding of the chloride anion (or the chloride moiety) to a hydroxyl group proton of cellulose.

Another view, which might lead to a better understanding of the interactions in LiCl/polar aprotic solvent/cellulose systems, comes from analyses of lithium salt systems not containing labile protons. Complex formation between LiBr (and LiCl, but not halogenides of other alkali metals) and polyacrylonitrile (PAN) was observed [16]. Other interesting interactions of lithium atoms with oxygen atoms are observed in the $LiAlH_4$ reduction of carbonyl componds in tetrahydrofuran [17]; similar complexes with lithium halogenides also exist [17]. In these cases of lithium salts in aprotic solvents, interactions of non-dissociated ion-pairs of the lithium salt with a strongly electronegative atom was proven. Moreover, evidence has been presented that the LiCl molecule is undissociated in both DMAc and NMP [14,18].

These observations, together with finding experimental conditions for dissolution of cellulose in LiCl/Me_2SO (and LiCl/DMF [19]), suggest that the unique ability of a solution of LiCl in a polar aprotic solvent to dissolve cellulose can be attributed to the interaction of the lithium moieties of solvated, undissociated ion-pairs of the lithium chloride molecule with the hydroxyl group oxygen atoms of cellulose. At a sufficient concentration, these interacting species disrupt interchain hydrogen bonds of cellulose (Scheme 1). Cooperative action of a polar aprotic solvent is apparently only incremental, i.e., the main dissolution activity is due to dissolved, but undissociated, LiCl. Solvents (e.g., DMAc and NMP) that complex more strongly with LiCl than Me_2SO or DMF, in combination with lithium chloride, dissolve cellulose without a special pretreatment and afford solutions with much higher cellulose concentrations. The unique properties of the chloride moiety of the undissociated LiCl ion-pair with regards to the dissolution of cellulose are probably related to its more electropositive lithium cation (as compared with that of undissociated lithium bromide) because of the hard-base nature of the chloride anion (as compared with the soft-basic nature of the polarizable bromide anion). Simultaneous existence of a weak chloride-hydrogen bond, as proposed in all previous mechanisms [8,9,11–13,15], would be less probable, because chlorine atom hydrogen bonding in an oxygen-containing, strongly-polar, aprotic solvent is unlikely.

In summary, we propose that the lithium atoms of undissociated lithium chloride molecules in a polar aprotic solvent interact with the oxygen atoms of hydroxyl groups in a manner analogous to the hydrogen bonding that occurs between the protons of water molecules and the oxygen atoms of hydroxyl groups. However, the lithium chloride bonding is able to disrupt and prevent reformation of cellulose interchain hydrogen bonds, while the hydrogen bonds formed by water are not able to disrupt such bonding and solubilize cellulose.

Solutions of the regenerated cellulose in LiCl/Me_2SO were used for alkylations using a modified Hakomori procedure. To achieve complete *O*-methylation of the dissolved cellulose, as evidenced by the disappearance of the OH peak in the IR spectrum, it was sufficient to use a 10 molar excess (based on the cellulose repeating unit) of dimsyl sodium, followed by a 15–20 molar excess of methyl iodide. *O*-Ethyl, *O*-propyl, and *O*-butyl-cellulose were prepared similarly. The IR spectra of these *O*-alkylcelluloses showed decreasing OH substitution with increasing length of the alkyl substituent as a result of a single alkylation reaction. This result might be caused by a lower reactivity of higher alkyl halogenides under otherwise identical alkylation conditions. The complete *O*-methylation of cellulose in the LiCl/Me_2SO solvent provides additional evidence that LiCl/Me_2SO is a true, underivatizing solvent of cellulose.

3. Experimental

General methods.—Regenerated cellulose (dp 174, determined by the scan testing method [20]) was prepared [21] from cellulose acetate (Eastman, Rochester, NY, acetyl content 39.4%, ASTM viscosity 45). ^{13}C NMR spectra were recorded with a Varian XL-200 spectrometer in LiCl/dimethyl sulfoxide-d_6 at 90°C (pulse width 9.0 μs, repetition time 1.0 s, internal standard tetramethylsilane). IR spectra (KBr pellets) were obtained using a Mattson Instruments Cygnus 25 FTIR spectrometer equipped with a TGS detector by averaging 32 scans to give 4 cm^{-1} resolution and were baseline corrected and smoothed with the Savitsky–Golay algorithm.

Preparation of cellulose solutions.—Regenerated cellulose, prepared from cellulose acetate (1 g), was washed by centrifugation and decantation, first with water until the washings were neutral, then with MeOH, anhyd acetone, and petroleum ether (each 5×50 mL). The cellulose from the last solvent-exchange was added to a solution of lithium chloride (2–10 g) in Me_2SO (20–100 mL). The flask was evacuated (for the removal of petroleum ether) under moisture-excluding conditions while offsetting the cooling effected by evaporation of the petroleum ether with external heating to maintain the temperature at 23–25°C. Dry nitrogen was then introduced. The entire process was repeated twice more. The mixture was stirred under nitrogen at ambient temperature for 24 h [1], then alkylated. A solution of cellulose in dimethyl sulfoxide-d_6 was prepared similarly.

Alkylation of cellulose.—To the cellulose solution (prepared by the above procedure from 0.6 g of regenerated cellulose obtained from 1 g of cellulose acetate, 5 g of lithium chloride, and 70 mL Me_2SO) under nitrogen, a dimsyl sodium solution (22 mL; prepared [4] from 1.2 g of sodium hydride and 30 mL of Me_2SO) was added, using a

---

[1] When dried cellulose was used, the solution was filtered through a sintered glass filter to remove undissolved particles before alkylation.

syringe, and the mixture was thoroughly stirred at ambient temperature for 15 min. After cooling to 0°C, iodomethane (5 mL), iodoethane (6 mL), bromoethane (6 mL), 1-bromopropane (7 mL), or 1-iodobutane (8 mL), respectively, was added in 3 parts, again using a syringe, and the mixture was stirred vigorously. The mixture was stirred 16 h at room temperature. The atmosphere of nitrogen was maintained throughout the entire process. *O*-Alkylcellulose was isolated by pouring the mixture into water (750 mL). The powdery material was recovered by filtration, washed (in order) with water until neutral, then with aq sodium thiosulfate, water, MeOH, and petroleum ether (each 5 × 20 mL), and dried. Colorless, chloroform-soluble samples of *O*-methyl-, *O*-ethyl-, *O*-propyl-, and *O*-butyl-cellulose were isolated in yields of ca. 0.6 g.

References

[1] D.C. Johnson, in T.P. Nevell, and S.H. Zeronian (Eds.), *Cellulose Chemistry and Its Applications*, Ellis Horwood, Chichester, 1985, pp. 181–201.

[2] N.C. Carpita and E.M. Shea, in C.J. Biermann and G.D. McGinnis (Eds.) *Analysis of Carbohydrates by GLC and MS*, CRC Press, Boca Raton, FL, 1989, pp. 157–216.

[3] E.J. Corey and M. Chaykovsky, *J. Am. Chem. Soc.*, 87 (1965) 1345–1353.

[4] A.B. Blakeney and B.A. Stone, *Carbohydr. Res.*, 140 (1985) 319–324.

[5] D. Gagnaire, D. Mancier, and M. Vincendon, *J. Polym. Sci., Polym. Chem. Ed.*, 18 (1980) 13–25.

[6] A. Ciferri, *Polym. Eng. Sci.*, 15 (1975) 191–198.

[7] C.L. McCormick and T.S. Shen, in R.B. Seymour and G.A. Stahl (Eds.), *Macromolecular Solutions: Solvent–Property Relationship in Polymers*, Pergamon, New York, 1982, pp. 101–107.

[8] A. El-Kafrawy, *J. Appl. Polym. Sci.*, 27 (1982) 2435–2443.

[9] C.L. McCormick, P.A. Callais, and B.H. Hutchinson, Jr., *Macromolecules*, 18 (1985) 2394–2401.

[10] T.R. Dawsey and C.L. McCormick, *J. Macromol. Sci., Rev. Macromol. Chem. Phys. Sect. C*, 30 (1990) 405–440.

[11] A.F. Turbak, *Tappi J.*, 67 (1984) 94–96.

[12] M. Vincendon, *Makromol. Chem.*, 186 (1985) 1787–1795.

[13] H. Herlinger and P. Hirt, *Chemiefasern / Textilind.*, 37 (1987) 788–792.

[14] J. Saint Germain and M. Vincendon, *Org. Magn. Reson.*, 21 (1983) 371–375.

[15] B. Morgenstern, H.W. Kammer, W. Berger, and P. Skrabal, *Acta Polym.*, 43 (1992) 356–357.

[16] M.R. Padhye and A.V. Karandikar, *J. Appl. Polym. Sci.*, 30 (1985) 667–673.

[17] E.C. Ashby, F.R. Dobbs, and H.P. Hopkins, Jr., *J. Am. Chem. Soc.*, 95 (1973) 2823–2829.

[18] A. Aust, K. Klockgeter, A. Steffen, and M. Stockhausen, *J. Mol. Liq.*, 52 (1992) 41–65.

[19] L. Petruš, M. Petrušová, and J.N. BeMiller, unpublished results.

[20] Scan Testing Method Cl:62, *Svensk Papperstidn.*, 65 (1962) 921–925.

[21] J.W. Green, *Methods Carbohydr. Chem.*, 3 (1963) 95–103.