

Pyridine-Catalyzed Depolymerization of Cellulose during Carbanilation with Phenylisocyanate in Dimethylsulfoxide

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SYNOPSIS

Carbanilation reactions of cellulose samples (bleached cotton linters and Avicel) with phenylisocyanate in dimethylsulfoxide (DMSO) were carried out at 60°C in the presence of various pyridine derivatives. The molecular weight distributions of the resulting cellulose tricarbanilates (CTCs) were measured by high-performance size exclusion chromatography. When pyridine or its derivatives were included in the reactions, the CTCs had reduced degree of polymerization (DP) values compared to those of CTCs prepared without the additives. The cellulose depolymerization was promoted by pyridines with electron-donating substituents and was not favored by pyridines with electron-withdrawing substituents nor with groups at positions *ortho* to the pyridine ring nitrogen atom. For the 3-, 4-, and 3,4-substituted pyridines, there was a linear relationship between log (weight-average CTC DP) and the pK_a (in water) of the pyridine derivative. For 2- and 2,6-substituted pyridines, the DP- pK_a relationships were different, probably because of steric effects of the different substituents *ortho* to the pyridine nitrogen atom. The optimum DMSO : pyridine solvent ratio for cellulose depolymerization during carbanilation in DMSO : pyridine mixtures was 3 : 1. All three components, phenylisocyanate, pyridine or its derivatives, and DMSO, are required for the depolymerization reaction. It is suggested that the depolymerization may be a consequence of cellulose oxidation by DMSO and/or cleavage of glucosidic bonds of partially carbanilated celluloses by reactions promoted by an enhanced solvent effect of DMSO.

INTRODUCTION

Cellulose tricarbanilate (CTC) is an increasingly important derivative for determining the molecular weight distribution (MWD) of cellulose by high-performance size exclusion chromatography (HPSEC).¹⁻¹⁰ In an effort to improve the preparation of CTCs, the effect of amine additives on the carbanilation reaction of cellulose with phenylisocyanate was examined.¹¹ Some amines accelerated the reactions, while with other amines the reactions were actually retarded. Carbanilation of high degree of polymerization (DP) cellulose samples (e.g., cotton linters) in dimethylsulfoxide (DMSO) gave CTCs with reduced DPs, although no DP reduction was observed in the lower DP samples (e.g., Avi-

cel).^{10,11} It was suggested that the DP reduction could be due to partial oxidation of the cellulose by DMSO during the carbanilation reaction,¹¹ as DMSO is well known for its ability to act as an oxidant,¹² and the oxidation could render the cellulose more susceptible to depolymerization. When N-methylimidazole was included in the carbanilation reaction of bleached cotton linters in DMSO, a severe reduction in cellulose DP was noted; the weight-average DP (\bar{P}_w) obtained was only 13% of the value obtained in the reaction without added amine.¹¹ Pyridine and its derivatives are known to catalyze carbanilation reactions of alcohols with phenylisocyanate,^{13,14} and from rate studies on the reaction with methanol in carbon tetrachloride, a base-catalysis mechanism was proposed.¹⁴ To further examine the depolymerization of cellulose during carbanilation in DMSO, the effect of pyridine and its derivatives on the reaction was assessed.

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EXPERIMENTAL

Analytical Methods

Nitrogen contents of the CTC samples were obtained by the Dumas method and were performed by the Australian Microanalytical Service, Melbourne.

Fourier transform infrared (FT-IR) spectra were obtained for KBr discs (1% sample, 64 scans, 4 cm⁻¹ resolution) on an Alpha Centauri FT-IR spectrometer (Mattson Instruments Inc).

HPSEC of the CTC samples was carried out on columns containing crosslinked polystyrene, tetrahydrofuran was the eluant, and MWDs were calculated according to a published method.¹⁰

Chemicals and Cellulose Samples

All chemicals used were commercial products of analytical grade. The DMSO and pyridine solvents were dried with molecular sieves. The cellulose samples used were bleached cotton linters (99.3% α -cellulose) and Avicel (FMC Aust Ltd., Melbourne).

Reaction of Cellulose Samples with Phenylisocyanate in the Presence of Amines

Dry cellulose (50 mg) was treated with phenylisocyanate (1.0 mL) in dry solvent (DMSO, pyridine, or DMSO-pyridine mixtures) (10 mL) at 60 or 80°C in a 15 mL reaction bottle capped with a PTFE-

Table I Effect of Pyridine and its Derivatives on the Carbanilation of Cellulose Samples With Phenylisocyanate in DMSO^a

Sample	Amine Additive	pK _a of Amine		Time (h)	MWD of CTCs		
		Water ^b	DMSO ^c		\bar{P}_w	\bar{P}_n	\bar{P}_w/\bar{P}_n
Bleached cotton linters	—			46	3970	1420	2.8
	pyridine	5.17	3.45	24	764	275	2.8
	2-methylpyridine	5.96	4.01	48	998	376	2.7
	3-methylpyridine	5.68		45	432	129	3.3
	4-methylpyridine	6.00		45	404	127	3.2
	2-ethylpyridine	5.89		70	1510	641	2.4
	4- <i>t</i> -butylpyridine	5.99		28	355	103	3.5
	2-acetylpyridine	2.64		96	^d		
	3-acetylpyridine	3.26		94	3520	1160	3.0
	2-bromopyridine	0.71		94	3640	1270	2.9
	3-bromopyridine	2.85		94	4060	1310	3.1
	4-phenylpyridine	5.55 ^e		96	^d		
	4-benzylpyridine	5.65 ^e		73	839	261	3.2
	2,3-dimethylpyridine	6.56 ^f		69	925	367	2.5
	2,4-dimethylpyridine	6.74		32	648	237	2.4
	2,5-dimethylpyridine	6.43		50	826	325	2.6
	2,6-dimethylpyridine	6.71	4.46	69	3710	1330	2.8
	3,4-dimethylpyridine	6.47		29	254	91	2.8
	3,5-dimethylpyridine	6.09		29	272	86	3.2
	2,6-di- <i>t</i> -butylpyridine	4.95 ^g	0.81	93	4040	1570	2.6
2,6-dimethoxy-pyridine			94	4350	1780	2.4	
2,4,6-trimethylpyridine	7.43		53	1650	620	2.7	
2,6-di- <i>t</i> -butyl-4-methylpyridine			93	4260	1680	2.5	
Avicel ^h	pyridine			22	171	63	2.7
	pyridine ⁱ			18	136	44	3.1
	4- <i>t</i> -butylpyridine			22	123	50	2.4
	3,4-dimethylpyridine			20	107	49	2.2
	3,4-dimethylpyridine ⁱ			21	92	46	2.0
CTC ^j	pyridine			24	4230	2320	1.9

^a 50 mg cellulose, 1.0 mL phenylisocyanate, 2.0 mmol amine, 10 mL solvent; ^bRef. 15; ^cRef. 16; ^dincomplete reaction; ^eRef. 17; ^fRef. 18; ^gRef. 19; ^h $\bar{P}_w = 242$; ⁱDMSO : amine 80 : 20 (v/v); and ^j $\bar{P}_w = 4470$.

Table II Effect of Solvent Composition on Carbanilation of Bleached Cotton Linters in DMSO—Pyridine Mixtures With Phenylisocyanate

Solvent				MWD of CTCs		
Vol. % DMSO	Vol. % Pyridine	Temp. (°C)	Time (h)	\bar{P}_w	\bar{P}_n	\bar{P}_w/\bar{P}_n
100	0	60	46	3970	1420	2.8
98 ^b	2 ^b	60	31	682	231	3.0
98 ^c	2 ^c	60	28	723	246	2.9
90	10	60	19	378	142	2.7
90 ^d	10 ^d	60	19	3710	1420	2.6
80	20	60	20	275	90	3.0
70	30	60	20	273	93	2.9
60	40	60	20	284	103	2.8
50	50	60	25	335	129	2.6
40	60	60	25	539	165	3.3
30	70	60	52	941	294	3.2
20	80	60	71	1460	426	3.4
10	90	60	71	2300	679	3.4
2	98	80	50	3870	1160	3.3
0	100	80	32	4450	1420	3.1
0 ^e	100 ^e	80	52	4230	1430	3.0

^a 50 mg cellulose, 1.0 mL phenylisocyanate, 10 mL solvent; ^b nitrogen atmosphere; ^c oxygen atmosphere; ^d 2.0 mmol DMAP added; ^e pretreated with DMSO : pyridine 98 : 2; and 24 h at 60°C.

coated septum. In most of the reactions in DMSO, pyridine, or a pyridine derivative (2.0 mmol) was included (Tables I and II). In one case, a cotton linters sample (50 mg) was pretreated with DMSO : pyridine 98 : 2 for 24 h at 60°C before solvent exchanging with pyridine, and carbanilating in pyridine solution as above. The contents of the bottle were periodically swirled, to aid the reaction. After dissolution of the cellulose, dry methanol (1 mL) was added, and the CTC was recovered by precipitation from the reaction solution in 100 mL aqueous methanol, prepared by mixing 7 volumes water with 3 volumes methanol. In some cases, a drop of saturated aqueous sodium sulphate was added and the mixture was swirled vigorously to break the colloidal dispersion which formed. The derivative was collected by centrifugation, washed successively with aqueous methanol, twice with water, and dried. The CTCs had nitrogen contents of $8.1 \pm 0.2\%$ (calcd. for CTC: 8.09%).

Treatment of Cellulose Tricarbanilate with Phenylisocyanate in DMSO–Pyridine

Cellulose tricarbanilate ($\bar{P}_w = 4470$, 150 mg) was treated with phenylisocyanate (1.0 mL) in dry DMSO (10 mL) containing pyridine (2.0 mmol) in

a 15 mL reaction bottle for 24 h at 60°C. The reaction product was isolated as above.

RESULTS AND DISCUSSION

Cellulose samples were carbanilated with phenylisocyanate in DMSO in the presence of pyridine or one of its derivatives at 60°C, and DP data on the resulting CTCs were obtained by HPSEC (Table I). Pyridine, as an additive to the carbanilation reaction of bleached cotton linters in DMSO, had a similar effect to that noted earlier for N-methylimidazole¹¹; the CTC product had a considerably lower weight-average and number-average DP (\bar{P}_w and \bar{P}_n respectively) than the original cellulose sample (Fig. 1). Although pyridine alone is a preferred medium for carbanilation of cellulose without degradation,² its presence in the carbanilation reaction of cellulose in DMSO effects the depolymerization of cellulose. For the carbanilation of cotton linters in DMSO, the 3- and 4-methyl and 4-*t*-butyl derivatives of pyridine had a greater detrimental effect on DP than pyridine itself. The effect was even greater than that previously obtained by the addition of N-methylimidazole.¹¹ When the 2-methyl- and 2-ethylpyridines were added to the reactions, depo-

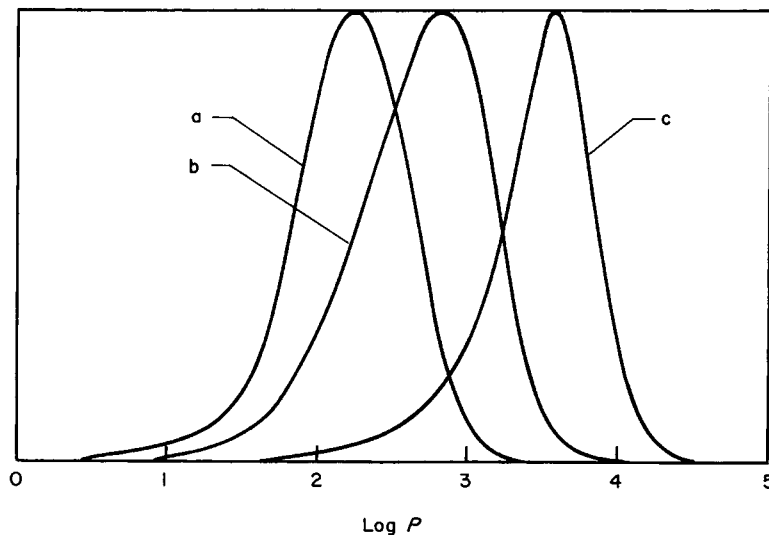


Figure 1 Differential mass distributions for CTCs prepared by reaction of bleached cotton linters with phenylisocyanate in DMSO at 60°C in the presence of: (a) 3,4-dimethylpyridine; (b) pyridine; and (c) no additive.

lymerization did not occur to the same extent as for the 3- and 4-alkyl derivatives. The acetylpyridines and bromopyridines added to the carbanilation reactions retarded the dissolution of the cotton linters, and the resulting CTCs did not suffer large DP losses (Table I). The reactions containing 4-bromo- and 4-phenylpyridine were not complete after 96 h at 60°C, although with 4-benzylpyridine, dissolution was complete after 73 h, and there was a considerable reduction in DP.

For the series of reactions of cotton linters to which dimethylpyridines (lutidines) had been added, those which gave rise to depolymerized products had shorter reaction times (Table I, Fig. 2). The reaction time was shortest and the depolymerization was greatest for the 3,4-isomer (Figs. 1 and 2), whereas with the 2,6-isomer the least depolymerization and longest dissolution time were recorded. However, the 2,4,6-trimethyl derivative (*sym*-collidine) gave a product which was significantly depolymerized. When the 2,6-di-*t*-butylpyridines and 2,6-dimethoxy-pyridine were the additives, the dissolution times were longer than that for the reaction with no additive, and the DPs of the CTCs were higher. All CTC products tested had nitrogen contents and FT-IR spectra which were consistent with authentic samples.

Carbanilation reactions of a microcrystalline cellulose sample (Avicel, $\bar{P}_w = 242$) in DMSO were carried out to test whether pyridine or its derivatives depolymerize lower DP cellulose samples (Table I). Pyridine or its 4-*t*-butyl or 3,4-dimethyl derivative added to the reaction mixtures did effect the depo-

lymerization of Avicel, and higher amounts of amine gave CTCs with lower DPs. The lowest DP obtained ($\bar{P}_w = 92$) was for the CTC obtained from reaction in a DMSO : 3,4-dimethylpyridine 80 : 20 (v/v) medium. Thus the depolymerization of cellulose during carbanilation in DMSO catalyzed by pyridine or its derivatives is not a phenomenon peculiar to the high DP cotton linters sample.

Several trends emerge from the data in Table I. Cellulose depolymerization during carbanilation in DMSO is promoted by pyridine derivatives with electron-donating substituents (e.g., alkyl groups), whereas depolymerization is less favored when the

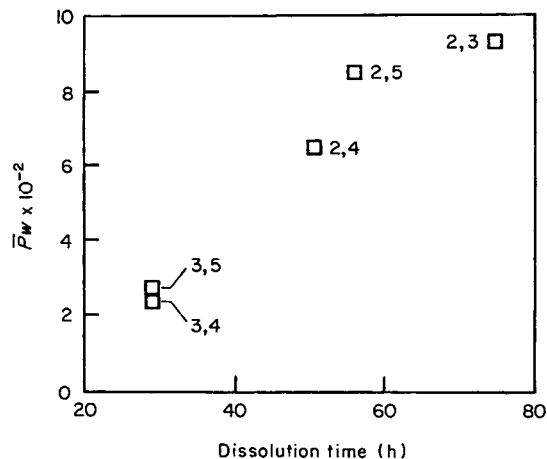


Figure 2 Relationship between dissolution time and \bar{P}_w of CTCs prepared from carbanilation of bleached cotton linters in DMSO in the presence of lutidine (dimethylpyridine) isomers.

pyridine derivatives have electron-withdrawing groups (e.g., acetyl or bromo substituents) and when the substituents are located at the 2 and 6 positions in the pyridine ring, *ortho* to the ring nitrogen atom. In addition, carbanilation reactions of cellulose which proceed with depolymerization are generally faster.

Moodie and Sansom¹⁴ have shown that the catalytic rate constants for the reaction of phenylisocyanate with methanol in carbon tetrachloride catalyzed by pyridine and its 3- and 4-substituted derivatives correlate with the pK_a of the pyridine derivatives in water. However, 2,4,6-trimethylpyridine had a lower catalytic effect than was expected from its pK_a value. This was attributed to a steric effect of the two methyl groups *ortho* to the ring nitrogen atom of the pyridine, and has been used to support a mechanism of base catalysis for the carbanilation reaction of methanol.

The pK_a values for most of the pyridine catalysts in water are listed in Table I. Also shown are some values measured in DMSO, which are typically lower than those measured in aqueous media. A plot of

$\log \bar{P}_w$ of the CTCs vs. pK_a of the pyridines in water is given in Figure 3. For pyridine and its 3- and 4-substituted derivatives, there is a linear relationship between $\log \bar{P}_w$ and pK_a , with pyridines with higher basicities giving greater cellulose depolymerization. For 2- and 2,6-substituted pyridines, the cellulose depolymerization was less than that expected on the basis of pK_a , with the exception of 2-bromopyridine, which has a very low pK_a value. The data points for the 2,6-disubstituted pyridines are further removed from the $\log \bar{P}_w$ - pK_a line than those for the 2-substituted pyridines (Fig. 3). For the 2- and 2,6-substituted pyridines, steric factors in addition to the basicities of the pyridines would govern the extent of cellulose depolymerization during carbanilation.

The cotton linters sample was carbanilated with phenylisocyanate in DMSO-pyridine mixtures covering the entire range of composition (Table II). Dissolution time at 60°C was fastest for the composition range DMSO : pyridine 9 : 1-6 : 4, and slowest with higher proportions of pyridine. The \bar{P}_w values for the CTC products were drastically lowered by small additions of pyridine to the DMSO solvent,

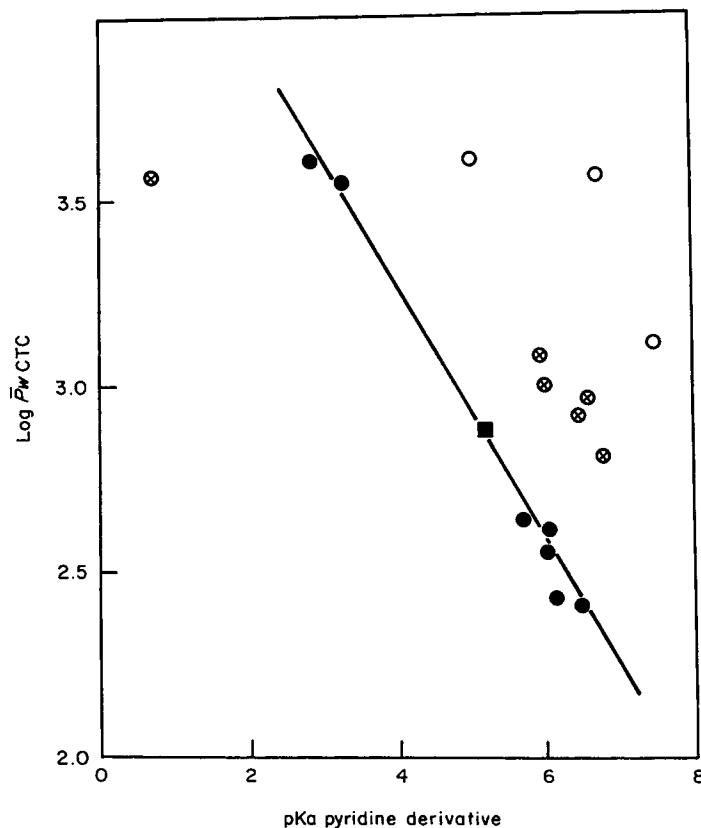


Figure 3 Plot of $\log \bar{P}_w$ of CTCs prepared from carbanilation of bleached cotton linters in DMSO in the presence of pyridine derivatives vs. pK_a in water of pyridine derivatives: ■ pyridine; ● 3-, 4- and 3,4-substituted pyridines; ⊗ 2-, 2,3-, 2,4- and 2,5-substituted pyridines; and ○ 2,6- and 2,4,6-substituted pyridines. The line is fitted to the filled points only.

and then passed through a shallow minimum at about 3 : 1 DMSO : pyridine before rising not as steeply toward 100% pyridine (Table II, Fig. 4). Because small amounts of pyridine in DMSO have a much greater effect on the \bar{P}_w of the CTC than small amounts of DMSO in pyridine, it is evident that pyridine is the catalyst for the depolymerization in the DMSO medium rather than the reverse.

The pyridine derivative 4-*N,N*-dimethylamino-pyridine (DMAP) catalyzed the carbanilation of cotton linters in DMSO, giving a shorter dissolution time and a CTC product which was not significantly depolymerized.¹¹ When the reaction was carried out in 9 : 1 DMSO : pyridine solution in the presence of DMAP, the DP reduction was small (Table II) which shows that the stronger base had the controlling influence on the depolymerization despite the higher concentration of pyridine in the reaction solution.

A high DP CTC sample ($\bar{P}_w = 4470$) when subjected to carbanilation conditions in DMSO-pyridine for 24 h at 60°C was not significantly depolymerized (Table I), and a cotton linters sample when pretreated with DMSO-pyridine for 24 h at 60°C before carbanilation in pyridine did not suffer depolymerization (Table II). This indicates that the depolymerization occurred *during* the carbanilation reaction. Depolymerization of cellulose is a consequence of cleavage of glucosidic bonds between anhydroglucose units in the cellulose chain, and in the present case cleavage would occur on either the unsubstituted or partially substituted cellulose chains. Partial substitution of cellulose at different positions can have varying effects on subsequent glucosidic cleavage reactions. Rowland and Howley²⁰ have found that the rates of acid hydrolysis of cellulose substituted at very low levels with 2-diethylamino-

ethyl groups were faster than that of unsubstituted cellulose and were dependent on the location of the substituent. In the present case, partially carbanilated cellulose could render the glucosidic bonds more labile to cleavage.

From the results above, it is clear that all three components, phenylisocyanate, DMSO, and pyridine, are necessary for the depolymerization reaction. Of all the amines tested as additives for the carbanilation reaction of cotton linters in DMSO,¹¹ only *N*-methylimidazole and pyridine and its derivatives have caused a severe depolymerization of the cellulose. As we have shown that the extent of depolymerization during carbanilation is related to the pK_a of the pyridine derivative, the basicity of the amine is a key factor in the reaction. It could be significant that these amines have unsaturated nitrogen atoms, whereas the remaining amines tested were saturated aliphatic compounds.¹¹ Earlier, we suggested that oxidation of cellulose by DMSO during carbanilation might be a factor in the cellulose depolymerization,¹¹ although there was no supporting evidence for the proposal. Pfitzner and Moffatt²¹ found that DMSO in the presence of anhydrous orthophosphoric acid and dicyclohexylcarbodiimide (DCC) oxidized various alcohols to carbonyl groups at ambient temperatures, and the reaction was extended to include carbohydrates.²² Thus it is possible that the pyridines promote oxidation of cellulose hydroxyl groups even though FT-IR spectra of the CTC products showed no additional carbonyl absorptions; no odor of dimethylsulfide, the reduction product of DMSO, was detected in the reaction products. When DCC itself was an additive in the carbanilation reaction of cotton linters in DMSO, no cellulose depolymerization was noted. In spite of these observations, the possible involvement of

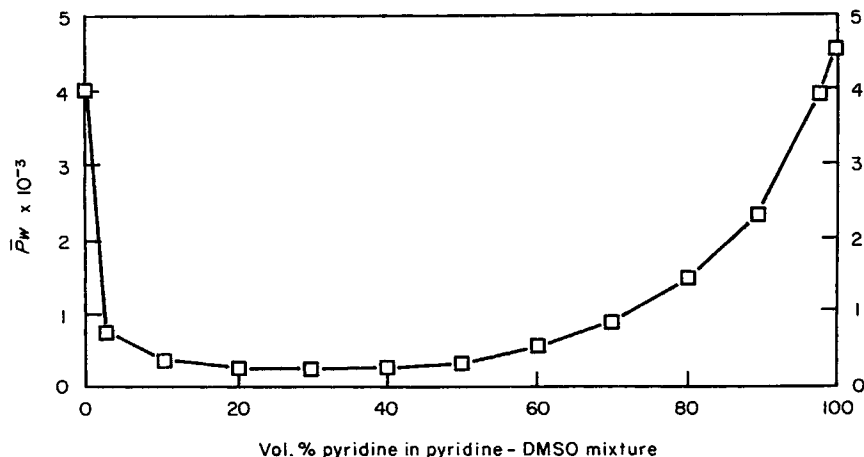


Figure 4 Effect of solvent composition on the \bar{P}_w of CTCs prepared from bleached cotton linters in DMSO-pyridine mixtures.

DMSO as an oxidant during the carbanilation reaction cannot be ruled out, because cleavage of a few glucosidic linkages in cellulose can have a large effect on DP reduction.

Traynelis and Hergenrother²³ have shown that molecular oxygen promoted the oxidation of benzyl alcohol to benzaldehyde by DMSO. The cotton linters sample when carbanilated in DMSO containing pyridine, both under nitrogen and in an oxygen atmosphere, gave CTC products with DP values that were not significantly different (Table II). Thus the presence of molecular oxygen does not influence the cellulose depolymerization.

DMSO as a dipolar aprotic solvent exerts remarkable solvent effects such as greatly enhancing the rates of nucleophilic displacements¹² and it could aid the nucleophilic reactions of the pyridines in the carbanilation reaction. It is also known for its ability to facilitate the dehydration of some aliphatic alcohols,¹² and dehydration or decarbanilation of cellulose or partially carbanilated cellulose could be an intermediate process in the depolymerization. We thus suggest that the depolymerization may be a consequence of cellulose oxidation by DMSO and/or cleavage of glucosidic bonds of partially carbanilated celluloses in reactions which are facilitated by special solvent effects of DMSO. Further elucidation of the chemistry of the depolymerization reaction would require studies of the reactions of cellulose models.

CONCLUSIONS

1. The presence of pyridine or its derivatives in carbanilation reactions of cellulose with phenylisocyanate in DMSO causes depolymerization of the cellulose. Pyridines should thus be avoided when preparing CTCs in DMSO for MWD studies.
2. The extent of the depolymerization is dependent on the nature and position of the substituent in the pyridine ring; depolymerization is promoted by pyridines with electron-donating substituents and was not favored by pyridines with electron-withdrawing substituents, nor with groups at positions *ortho* to the pyridine ring nitrogen atom.
3. The three components, phenylisocyanate, pyridine or its derivatives, and DMSO, are required for the depolymerization reaction to take place. The depolymerization may be a result of cellulose oxidation by DMSO rendering the glucosidic bonds more labile, and/

or cleavage of glucosidic bonds of partially carbanilated cellulose.

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REFERENCES

1. L. Valtasaari and K. Saarela, *Pap. Puu*, **57**, 5 (1975).
2. L. R. Schroeder and F. C. Haigh, *Tappi*, **62**(10), 103 (1970).
3. J. J. Cael, D. J. Cietek, and F. Kolpak, *J. Appl. Polym. Sci. Appl. Polym. Symp.*, **37**, 509 (1983).
4. H. U. Körner, D. Gottschalk, and J. Puls, *Papier (Darmstadt)*, **38**, 255 (1984).
5. B. F. Wood, A. H. Conner, and C. G. Hill, *J. Appl. Polym. Sci.*, **31**, 3703 (1986).
6. T. Rantanen, P. Färm, and J. Sundquist, *Pap. Puu*, **68**, 634 (1986).
7. J.-M. Lauriol, P. Froment, F. Pla, and A. Robert, *Holzforchung*, **41**, 109 (1987).
8. L. L. Lloyd, C. A. White, A. P. Brookes, J. F. Kennedy, and F. P. Warner, *Brit. Polym. J.*, **19**, 313 (1987).
9. T. Rantanen and J. Sundquist, *Tappi J.*, **70**, 109 (1987).
10. R. Evans, R. H. Wearne, and A. F. A. Wallis, *J. Appl. Polym. Sci.*, **37**, 3291 (1989).
11. R. Evans, R. H. Wearne, and A. F. A. Wallis, *J. Appl. Polym. Sci.*, **41**, 813 (1991).
12. L. F. Fieser and M. Fieser, *Reagents for Organic Synthesis*, Wiley, New York, 1967, p. 296.
13. V. S. Pshezetsky, I. Massouh, and V. A. Kabanov, *J. Polym. Sci. (Part C)*, **22**, 309 (1967).
14. R. B. Moodie and P. J. Sansom, *J. Chem. Soc. (Perkin Trans.)*, **2**, 664 (1981).
15. J. A. Dean, *Lange's Handbook of Chemistry*, 13th ed., McGraw-Hill, New York, 1985, p. 18.
16. R. L. Benoit, M. Fréchet, and D. Lefebvre, *Can. J. Chem.*, **66**, 1159 (1988).
17. P. Tomasik and R. Zalewski, *Chem. Zvesti*, **31**, 246 (1977).
18. R. P. Thummel and D. K. Kohli, *J. Org. Chem.*, **42**, 2742 (1977).
19. H. P. Hopkins, D. V. Jahagirdar, P. S. Moulik, D. H. Aue, H. M. Webb, W. R. Davidson, and M. D. Pedley, *J. Am. Chem. Soc.*, **106**, 4341 (1984).
20. S. P. Rowland and P. S. Howley, *Carbohydr. Res.*, **165**, 69 (1987).
21. K. E. Pfitzner and J. G. Moffatt, *J. Am. Chem. Soc.*, **85**, 3027 (1963).
22. B. R. Baker and D. H. Buss, *J. Org. Chem.*, **30**, 2304 (1965).
23. V. J. Traynelis and W. L. Hergenrother, *J. Am. Chem. Soc.*, **86**, 298 (1964).

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