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ORIGINAL PAPER

Esterification of cellulose with acyl-1*H*-benzotriazole

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Abstract For the first time, the acylation of cellulose was realized by activation of carboxylic acid with 1*H*-benzotriazole. The reaction could be carried out under mild conditions. The acyl-1*H*-benzotriazole reacts with cellulose leading to cellulose acetate, butyrate, caproate, benzoate, myristate, and stearate with DS values between 1.07 and 1.89. The reaction proceeds completely homogeneously in dimethyl sulfoxide (DMSO)/TBAF × $3H_2O$ (tetrabutylammonium fluoride trihydrate) using acyl-1*H*-benzotriazole as acylation agent. The cellulose esters were characterized by means of ^{1}H NMR, GPC measurements, and solubility tests.

Keywords Acyl-1H-benzotriazole · Cellulose ester · Activated carboxylic acid · DMSO/TBAF × 3H2O

Introduction

Cellulose is the most abundant natural polymer on earth and an important resource. Cellulose derivatives have found applications in various fields [1–3]. Esterification is one of the most important tools to modify the properties of the polymer. Cellulose esters are produced industrially under heterogeneous conditions. However, homogeneous derivatization possesses the enormous advantage of full availability of the hydroxyl groups. Thus, a better control of the degree of substitution (DS) and an uniform distribution of the functional groups along the polymer chain are possible.

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The mostly applied solvents in cellulose esterification are *N*,*N*-dimethylacetamide (DMAc) combined with LiCl [4] and a mixture of dimethyl sulfoxide (DMSO)/ tetrabutylammonium fluoride trihydrate (TBAF $\times$ $3H_2O$) [5]. Very recently, ionic liquids, in particular 1-butyl-3-methylimidazolium salts, have been studied as reaction medium for homogeneous esterification [6, 7].

DMSO/TBAF $\times$ $3H_2O$ dissolves cellulose without pre-treatment within minutes. It has been exploited for acylation using acid anhydrides and vinyl esters [5]. Another efficient synthesis path is the homogeneous one-pot esterification of cellulose with carboxylic acids by in situ activation. Reagents exploited for this functionalization are *p*-toluenesulfonyl chloride [8–10] and 1,3-dicyclohexylcabodiimide (DCC) in combination with 4-pyrrolidinopyridine (PP) [11, 12], although the reagents lead to degradation (*p*-toluenesulfonic acid and acid chloride are formed). Moreover, reagent toxicity must be taken into account. On the contrary, the activation of carboxylic acid with *N*,*N*′-carbonyldiimidazole (CDI) is a mild and efficient method [13, 14]. Homogeneous esterification of cellulose with (4-(4,6-dimethoxy-1,3,5-triazin-2-yl)-4-methyl-morpholinium chloride) and *N*-alkyl-2-halopyridinium salts as activating agents in DMSO/TBAF was carried out. It was found that CDI is most effective regarding the DS values [15]. Katritzky et al. reported a mild and efficient procedure for the activation of carboxylic acid using 1*H*-benzotriazole [16, 17] for subsequent esterification of hydroxyl groups of low molecular alcohols. Therefore, 1*H*-benzotriazole may be a valuable acylation agent for polysaccharides as well. Compared to acid chlorides, which are often used for polysaccharides esterification, no acidic by-products like HCl or the ammonium chloride are formed, which yield polymer degradation.

For the first time, the homogeneous esterification of cellulose in DMSO/TBAF applying acyl-1*H*-benzotriazole as acylation agent is realized. In order to study the potential of this new acylation method, carboxylic acids with different structure, i.e., different saturated and unsaturated/aromatic carboxylic acids, were used. The acyl-1*H*-benzotriazole agents and the cellulose esters were characterized by means of NMR- and IR spectroscopy, as well as by GPC.

Experimental

Materials

Cellulose Avicel® PH-101 (Fluka, degree of polymerization, DP = 260) was used. All other reagents were supplied by Fluka and used as received.

Measurements

^{1}H NMR spectra were measured in $CDCl_3$ (30 mg/mL) at 60 °C with a Bruker AVANCE 400 spectrometer running at 400 MHz. The accumulation number was 16. ^{13}C NMR spectra were acquired with a Bruker AVANCE 250 spectrometer, in $CDCl_3$ (80 mg/mL) at room temperature. The scan number was 1024.

The FTIR spectra were recorded on a BioRad FTS 25-spectrometer (ATR-technique) at room temperature. All spectra were recorded by accumulating 64 scans at a resolution of 4 cm^{-1} in the range of 4000 to 400 cm^{-1}.

For gel permeation chromatography (GPC), an Agilent 1200 series instrument was used including degasser, isocratic pump, and RI-detector. THF was applied as eluent (35 °C, 1 mL/min). The separation was carried out using PSS SDV lin M (Polymer Standards Service, Mainz) columns packed with styrene divinylbenzene copolymer network. Polystyrene standards were applied for calibration.

Synthesis

Synthesis of acyl-1H-benzotriazole (typical procedure)

14.3 g (120 mmol) 1*H*-benzotriazole was dissolved in 75 mL methylene chloride under stirring at room temperature within 30 min. Thionyl chloride (3.0 mL, 40 mmol) was added dropwise to the solution and allowed to react for 1 h under stirring. The solution was added dropwise to a solution of 3.8 mL (30 mmol) caproic acid in methylene chloride (75 mL) within 10 min. A white solid precipitate was formed within 5 min. The reaction mixture was stirred for 2.5 h at room temperature. The white precipitate was filtered off and washed with methylene chloride (2× 40 mL). The organic solution was washed with aqueous 2 M Na_2CO_3 solution (3× 50 mL) and dried over Na_2SO_4. The solvent of both organic solutions was removed under vacuum. A purification of the product was carried out by crystallization from chloroform.

Yield 6.0 g (92%).

^{1}H NMR ($CDCl_3$): $\delta = 8.0$ (d, CH), 8.1 (d, CH), 7.6 (t, CH), 7.4 (t, CH), 3.3 (t, CH_2), 1.8 (m, CH_2), 1.4 (m, CH_2) 0.9 (s, CH_3) ppm.

^{13}C NMR ($CDCl_3$): $\delta = 169$ (CO), 146 (CH), 131 (C), 130 (C), 126 (CH), 120 (CH), 114 (CH), 36 (CH_2), 31 (CH_2), 24 (CH_2), 22 (CH_2), 14 (CH_3) ppm.

Dissolution of cellulose in dimethyl sulfoxide (DMSO)/tetrabutylammonium fluoride trihydrate (TBAF)

1.0 g (6.2 mmol) dried cellulose (dried for 6 h at 110 °C under vacuum and KOH) suspended in 60 ml DMSO and 6.6 g TBAF × $3H_2O$ were stirred at room temperature for 30 min, yielding a clear cellulose solution.

Acylation of cellulose with acyl-1H-benzotriazole in DMSO/TBAF

For a typical conversion, 4.0 g (3 mol/mol anhydroglucose unit, AGU) caproyl-1*H*-benzotriazole was added to the cellulose solution and allowed to react for 3 h at 60 °C under stirring. The product was isolated by precipitation in 200 mL ethanol, washed three times with 100 mL ethanol, and finally dried under vacuum and KOH at 60 °C, sample **3**.

Yield: 0.78 g (50%).

DS = 0.96 determined by ^{1}H NMR spectroscopy after peracetylation.

FTIR (ATR): 3454 *v* (OH), 2961, 2871 *v* (CH), 1745 *v* (C=O), 1465, 1249 *v* (CH, CH_2), 1167, 1024 *v* (COC) cm^{-1}.

Peracylation of cellulose ester, typical example

In order to determine the DS of the cellulose ester by means of ^1H NMR spectroscopy, peracylation of the remaining hydroxyl groups was carried out. Cellulose acetate (0.30 g, sample **1**) was suspended in 7 mL pyridine and 7 mL propionic anhydride, and 0.2 g of DMAP as catalyst was added. After 24 h at 80 °C under stirring, the mixture was cooled to room temperature and precipitated in 200 mL ethanol, filtered off, washed with 100 mL ethanol three times and finally dried under vacuum and KOH at 60 °C.

FTIR (ATR): no *v* (OH), 1739 *v* (CO_{ester}) cm^{-1}.

^1H NMR ($CDCl_3$): $\delta = 5.2–3.5$ (H_{AGU}), 2.5–2.2 (CH_2-propyl), 2.2–1.9 (CH_3-acetyl), 1.3–1.0 (CH_3-propyl) ppm.

The peracylation of samples **2–6** was carried out with acetic anhydride.

DS values of the cellulose esters were calculated from the ^1H NMR spectra according to Eqs. 1–3:

For sample **1**:

$$DS_{acetate} = \frac{7I_{acetyl}}{3I_{AGU}}, \tag{1}$$

where I_{acetyl} peak integral of methyl protons of acetyl at 2.2–1.9 ppm and I_{AGU} peak integral of protons of anhydroglucose unit at 5.2–3.5 ppm.

For sample **4**:

$$DS_{benzoate} = \frac{7I_{benzoyl}}{5I_{AGU}}, \tag{2}$$

where $I_{benzoyl}$ peak integral of benzoyl protons at 8.1–6.9 ppm and I_{AGU} peak integral of protons of anhydroglucose unit at 5.2–3.5 ppm.

For samples **2**, **3**, **5**, and **6**:

$$DS_{ester} = \frac{7I_{methyl}}{3I_{AGU}}, \tag{3}$$

I_{ester} peak integral of methyl protons at 1.0–0.9 ppm and I_{AGU} peak integral of protons of anhydroglucose unit at 5.2–3.5 ppm.

Results and discussion

The solvent DMSO/TBAF × $3H_2O$ has been successfully applied for the homogeneous acylation of cellulose using reactive carboxylic acid derivatives, like anhydrides. The carboxylic acid itself, on the other hand, does not yield cellulose esters. An interesting alternative method for activation of the carboxylic acid is the formation of acyl-1*H*-benzotriazole with 1*H*-benzotriazole. Acyl-1*H*-benzotriazole could be synthesized according to Katritzky et al. [16]. The procedure involves

reaction of 1 equivalent of a carboxylic acid with 4 equivalents of 1*H*-benzotriazole and 1.3 equivalent of thionyl chloride in CH_2Cl_2 at room temperature for 2.5 h. This method represents a mild and efficient conversion of carboxylic acid into the corresponding activated ester (Fig. 1).

The structure of the acyl-1*H*-benzotriazole agents was proved by NMR spectroscopy. The proton and carbon signals could be well assigned in the spectra. Figure 2 shows typical ^{1}H- and ^{13}C NMR spectra of caproyl-1*H*-benzotriazole.

In order to prepare the cellulose ester, a solution containing 9.1% (w/w) TBAF in DMSO with 1.4% (w/w) cellulose was allowed to react with 3 mol acylation agent per mol AGU. Reaction conditions, DS values of the cellulose esters obtained and their solubilities are summarized in Table 1.

Peracylation of the products (**1**–**6**) provides cellulose esters soluble in $CDCl_3$ that could be characterized by means of ^{1}H NMR spectroscopy. Figure 3 shows representative ^{1}H NMR spectra (range from 0.5 to 3.0 ppm) of the peracylated cellulose esters (samples **1**, **3**, and **6**). The peaks were assigned according to the results published in references [5] and [18]. The CH_2 groups of the ester moiety adjacent to C=O were found for position 6 at $\delta = 2.4$ ppm, and for the positions 2 and 3 at $\delta = 2.3$ ppm. Thus, the chemical shift depends on the position within the modified AGU. The signal at $\delta = 2.1$ ppm is assigned to acetate methyl groups for position 6, at $\delta = 2.0$–1.9 ppm for positions 2 and 3. The signals of the CH_2 moiety of the alkyl chain are located between $\delta = 1.7$ and 1.3 ppm. The propionate methyl signals appear at $\delta = 1.2$ ppm for the position 6, and at $\delta = 1.1$ ppm for the positions 2 and 3. At $\delta = 0.9$ ppm, methyl groups of the alkyl chain (butyryl, caproyl, myristyl, and stearyl) are found. The signals for AGU are located at $\delta = 5.2$–3.5 ppm (not shown).

At a molar ratio of 3 mol acyl-1*H*-benzotriazole per mol AGU, a degree of substitution of ester moieties (DS_{ester}) of 1.07 was reached within a reaction time of

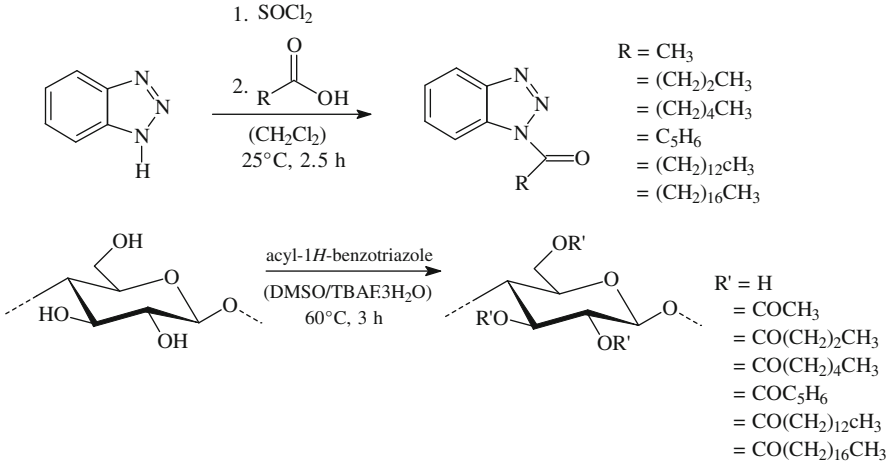

Fig. 1 Reaction scheme for the synthesis of acyl-1*H*-benzotriazole and the subsequent esterification of cellulose with the acylation agent in DMSO/TBAF × $3H_2O$

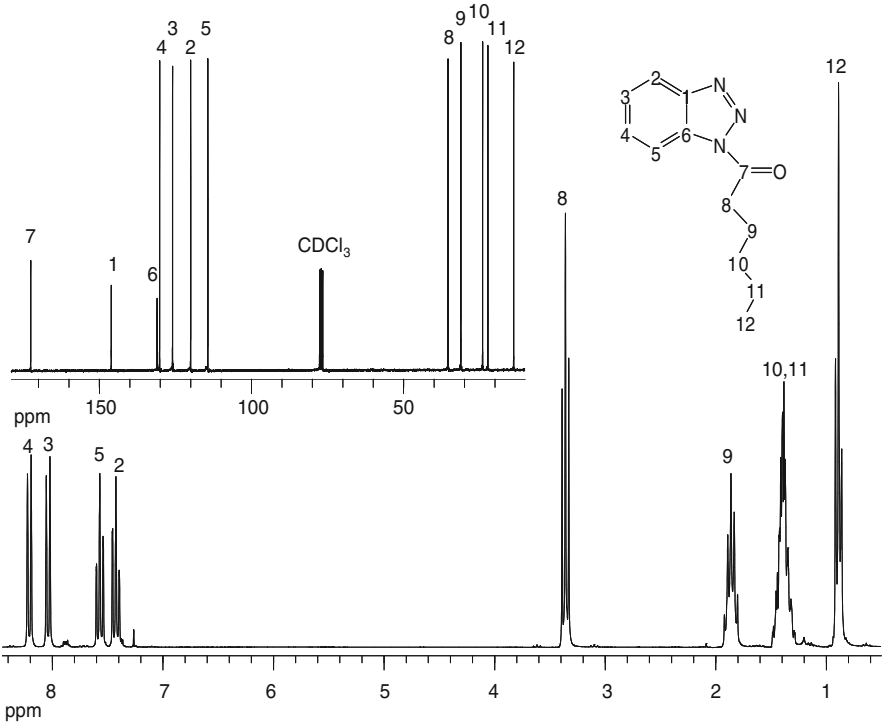

Fig. 2 ^{1}H- and ^{13}C NMR spectra of caproyl-1*H*-benzotriazole, measured at room temperature in $CDCl_3$

Table 1 Condition for and results of the homogeneous esterification of cellulose in dimethyl sulfoxide (DMSO)/tetrabutylammonium fluoride (TBAF) with 3.0 mol acylation agent per mol anhydroglucose unit at 60 °C for 3 h

Sample	Acyl-1*H*-benzotriazole	DS^{a}_{ester}			DP^{c}_{n}	Solubility[d]				
	Acyl group	Total	6	2.3		Py	DMSO	NMP	DMF	DMAc
1	Acetyl	1.07	0.31	0.76	100	+	+	+	+	+
2	Butyryl	0.79	0.30	0.49	202	−	+	−	−	−
3	Caproyl	0.96	0.36	0.60	164	+	+	+	+	+
4	Benzoyl	0.69	n.d.[b]	n.d.[b]	66	−	−	−	−	−
5	Myristyl	1.00	0.38	0.62	57	−	−	−	−	−
6	Stearyl	1.86	0.74	1.22	40	−	−	−	−	−

[a] Degree of substitution (DS) calculated from ^{1}H NMR spectra

[b] Not determined

[c] Calculated from GPC data

[d] DMSO = dimethyl sulfoxide, NMP = *N*-methylpyrrolidone, DMF = *N*,*N*-dimethylformide, DMAc = *N*,*N*-dimethylacetamide, soluble (+), insoluble (−)

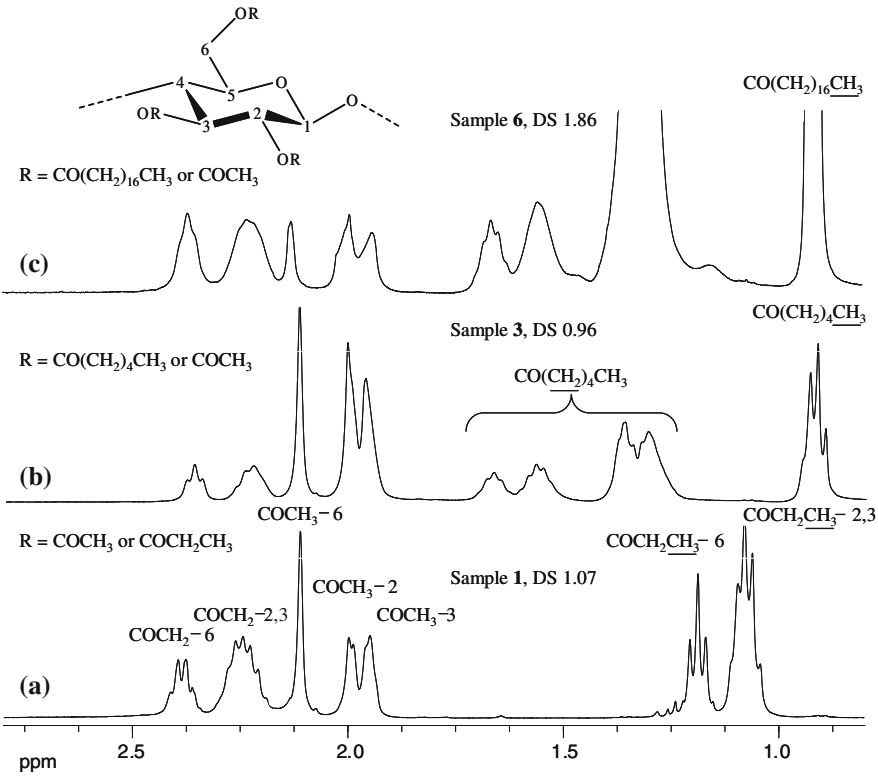

Fig. 3 ^{1}H NMR spectra (range between 3.0 and 0.5 ppm) of **a** perpropionylated cellulose acetate ($DS_{acetate} = 1.07$), **b** peracetylated cellulose caproate ($DS_{caproate} = 0.96$), and **c** peracetylated cellulose stearate ($DS_{stearate} = 1.86$)

3 h at 60 °C (sample **1**, Table 1). In the FTIR spectrum of sample **1**, the typical absorption bands for the cellulose backbone were found and additionally a signal at 1735 cm^{-1} ($C{=}O_{ester}$) indicating the presence of the ester moiety. Cellulose acetate prepared in this way is readily soluble in pyridine, dimethyl sulfoxide, *N*-methylpyrrolidone, *N*,*N*-dimethylformide, and *N*,*N*-dimethylacetamide.

With increasing alkyl chain length, the DS value decreases slightly from 1.07 (cellulose acetate, **1**) to 0.79 (cellulose butyrate, **2**), and then a slight increase to 0.96 was found (cellulose caproate, **3**). The cellulose benzoate showed lower DS value of 0.69. For long chain carboxylic acids like myristic, a DS of 1.00 was reached (**5**), and remarkably higher DS of 1.86 was found for cellulose stearate (**6**).

An explanation for the decrease of the DS value with increasing chain length or increasing bulkiness may be the higher hindrance of the substituents. The increasing hydrophobicity of the reagent as the chain length increases, and the necessity the hydrophilic cellulose molecule attack may be responsible for the decreasing DS value as well. Both effects are observed for the cellulose butyrate (DS = 0.79) and cellulose benzoate (DS = 0.69). However, the DS value of cellulose caproyl increases to 0.96, i.e., although the alkyl chain is longer and more hydrophobic, a

higher DS value was reached. Ciacco et al. have found comparable results that were explained by long hydrocarbon chain disturbing the intermolecular hydrogen bonds in solution, leading to dissociation of the chains, and therefore increasing the accessibility, i.e., the reactivity of the acylation agent is increased [19]. It may be assumed that comparable phenomena are true for the results discussed in the paper as well. It seems that a certain chain length is needed to disturb the interactions of the cellulose molecules in solution. Anyhow, there are further studies needed to proof these assumptions.

Carboxylic acid anhydrides and vinyl esters are compounds whose reactivity and water solubility decrease with increase of the alkyl chain length. In other words, the consumption of the acylation agent through hydrolysis due to the water present in DMSO/TBAF $\times$ $3H_2O$ mixture decreases with increase of the alkyl chain length. Therefore, this effect could also improve the efficiency of the acylation agent with increasing alkyl chain.

Regarding the selectivity between the esterification of the hydroxyl groups at the cellulose backbone, it was found that preferred derivatization at the primary hydroxyl groups occurred, as it is expected for homogeneous phase reactions.

Molar mass and molar mass distribution of the cellulose esters were determined by GPC analysis of the peracetylated esters (Table 1). An interesting finding is the fact that the degree of polymerization (DP_n) decreases with increasing alkyl chain length. However, this is of uncertain significance because of the poor interaction of the hydrophobic groups of the longer chain esters with the GPC column. Nevertheless, by comparing the obtained DP_n for peracylated cellulose esters with short alkyl chain (samples **1**, **2**, and **3**), it can be concluded that depolymerization between 30 and 60% occurred (starting cellulose material had a DP_n value of 260, and the cellulose ester a DP_n of 100, 202, and 164, respectively).

The solubilities of the cellulose esters were tested in pyridine, DMSO, NMP, DMF, and DMAc. In general, it was found that samples with DS values higher than 0.9, with comparably small ester functions groups (acetyl, butyryl, and hexanoyl) were soluble. The cellulose myristate and stearate samples were found to be insoluble, certainly due to the long alkyl chain, which is responsible for hydrophobic interactions.

Conclusions

For the first time, a new acylation agent was used in cellulose chemistry. The activation of carboxylic acid with 1*H*-benzotriazole was carried out under mild reaction condition. The acyl-1*H*-benzotriazole reacts with cellulose leading to cellulose acetate, butyrate, caproate, benzoate, myristate, and stearate with DS value between 1.07 and 1.89. The reaction proceeds completely homogeneous in DMSO/TBAF $\times$ $3H_2O$. With increasing the alkyl chain length, the DS value decreases from 1.07 (cellulose acetate) to 0.79 (cellulose butyrate). Cellulose caproate (0.96) and cellulose myristate (1.00) possess slightly higher DS values. For stearic acid with an even longer alkyl chain, the DS increase remarkable to 1.86. It was found that preferred derivatization at the primary hydroxyl groups occurred.

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