Sulfation of Microcrystalline Cellulose Using Ultrasonic Activation in N,N-Dimethylformamide

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Abstract

A method is proposed for the sulfation of microcrystalline cellulose in the system N,N-dimethylformamide/ chlorosulphonic acid with preliminary treatment of cellulose with ultrasound in an organic solvent. It is demonstrated that the treatment with ultrasound results in an increase in the reactivity of cellulose in the sulfation reaction as well as in occurring the sulfation in homogeneous medium. The action of ultrasound on microcrystalline cellulose is accompanied by a decrease in the polymerization level of the cellulose material and does not affect its crystallinity index. Water-soluble cellulose sulphates with the substitution level up to 1.5 were obtained using the method proposed.

Key words: microcrystalline cellulose, cellulose sulphates, ultrasonic treatment

INTRODUCTION

Cellulose sulphate (SC) is one of the most relevant cellulose esters. It is readily available and can be obtained from different types of cellulose. There is a prospect of widespread introducing the SC instead of other polysaccharides used today. Owing to a greater availability and manufacturability of its obtaining, the SC could, to all appearance, partially replace natural sulphated polysaccharides in medical and food industries such as heparin and carrageenans.

In medicine, SC could be used for producing of special coatings and obtaining blood anticoagulants [1], antiviral [2], and anti-inflammatory agents [3].

The main method for SC producing consists in the treatment of cellulose with sulphuric acid in the presence of inert diluents or aliphatic alcohols [4]. Other methods for obtaining this substance are based on the use of either sulphuric acid anhydride or chloroanhydride, aminosulphonic acid, often in combination with tertiary amines [5, 6]. Another way to obtain SC consists in mod-ifying already existing cellulose esters. In such a way, for example, SC is obtained from cellulose nitrate after treatment by sulphur dioxide in the presence of a catalyst or *via* re-esterification or cellulose acetates and formates [7].

The disadvantages of the first method consist in a relatively low substitution level (SL) inherent in the product and a competitive strong degradation of cellulose. The application of the second method is limited due to the toxicity of tertiary amines as well as their high cost and low availability. In this context, it is promising to use an intermediate chemical modification of cellulose for the synthesis of SC. However, the products obtained to either extent contain some residues of unreacted groups, such as nitrate, which causes the physical and chemical properties to change and limits the scope of the SC application. This is especially important for the practical use of SC in the food and medical industries.

For these reasons, research work in the field of the development of novel synthetic methods for SC obtaining are undoubtedly important, being of both scientific and practical value.

In this paper, we propose a method for producing water-soluble SC basing on MSC, which includes a preliminary ultrasonic treatment of the starting material in a polar organic solvent. Such a treatment promotes the subsequent esterification reaction using N,N-dimethylformamide/ClSO$_3$H mixture in a homogeneous medium, as well as obtaining a product with a high homogeneity and substitution level.

EXPERIMENTAL

Materials

In this work we used cotton MCC produced at the Polyex JSC (Biysk, Russia). The samples of MCC from hardwood and softwood fibre cellulose were obtained by means of hydrolyzing the starting material with the use of sulphuric acid. Chlorosulphonic acid (ClSO$_3$H, Merc), chemical purity grade ethanol, analytical grade aminosulphonic acid (NH$_2$SO$_3$H, analytical grade NaOH, DMFA, N,N-dimethylacetamide (DMAA) was dried with BaO and distilled.

Methods of analysis

The IR spectra of the samples were registered using KBr pellets by means of a Prestige-21 IR spectrophotometer within the range of 700–4000 cm^{-1}. The NMR spectra were registered in D$_2$O using a Bruker DRX-300 spectrometer (300 MHz). The elemental analysis (the determination of sulphur) in the SC samples was performed using unit EA-1110 (CE Instruments) after the combustion of a sample in an oxygen flow with the chromatographic registration of products. The substitution level of sulphur (SL$_S$) in preparations SC–Na was determined from equation

$$SL_S = 162\omega_S/(3200 - 102\omega_S)$$

where ω_S is the mass fraction of sulphur, %; 102 and 3200 are the molecular mass value for the sulphate group and sulphur taking into account the coefficient (32 · 100), respectively [8].

The X-ray diffraction phase analysis (XRD) was carried out using DRON-3 X-ray diffractometer (initial angle of 5.00°, increment 0.05°, final angle of 40.00°). The crystallinity index (I_{cr}) was calculated from the ratio between re-

flex intensities at angles of 22 and 19° (the diffraction angle 2θ) according to the Segal method [9]. The samples were prepared for the XRD as it follows: after ultrasonic MCC treatment with power density equal to 260 W/cm^2 during preset time under argon, the flask was cooled, the MCC suspension and the solvent were separated using a glass filter. The preparation was washed with acetone and dried under vacuum at 60 °C. The molecular mass (MM) of SC samples was determined by means of high performance liquid chromatography (HPLC). For the analysis we used Shimadzu chromatographic system (Japan) with LC-20AD pump, CTO-10AS thermostat, RID-10A refractometer, Shodex OHpac SB804 HG column (8 mm × 30 cm). The elution was carried out with 0.15 M NaCl solution at 40 °C with a flow rate of 0.3 cm^3/min. In order to calibrate the column we used the samples of sulphated pullulans with MM ~ (1.3−800) · 10^3. The average polymerization level (APL) of MCC was determined by means of viscometric method [10]. The normalized viscosity (η_n) for the solutions was measured using an Ostwald viscometer with the capillary 0.56 mm in diameter at the temperature of (25±0.2) °C. The intrinsic viscosity (η) was calculated by means of extrapolating the η_n value to the polymer concentration $C \to 0$.

The ultrasonic (US) treatment was carried out using IL 10−0.1 laboratory unit at the specific power 170 and 260 W/cm^2, the frequency of the sound was equal to (22±0.5) kHz.

A routine synthesis of SC was carried out according to the scheme presented in Fig. 1. Cotton MSC (2 g, 0.0123 mol) was placed in a glass flask with 250 cm^3 capacity with further adding 35 cm^3 of anhydrous DMFA, to subject to ultrasonic treatment in a flow of argon. The duration time of sonication was equal to 20 min at a power of 170 W/cm^2 and 15 min at a power of 260 W/cm^2. The solvent temper-
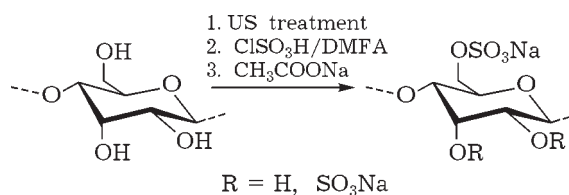

Fig. 1. Scheme of cellulose sulfation using ultrasonic pretreatment.

ature was maintained within the range of (80±5) °C. Further, the resulting MSC suspension was cooled down to 20 °C to add separately prepared $ClSO_3H$ solution in DMFA (dropwise while cooling and stirring the solvent, in an amount of 0.0617 mol, *i.e*, a fivefold excess of $ClSO_3H$ with respect to DMFA). The reaction was performed at 20 °C during 3 h with stirring. The reaction mixture exhibited homogenization during the first 15 min of the reaction.

In order to isolate the product, to 50 cm^3 of the reaction mixture was added 100 cm^3 of acetone. The precipitate was separated by means of centrifugation; it was washed with acetone and sodium acetate in ethanol and then with ethanol. The product was dissolved in water and neutralized with aqueous NaOH solution to obtain pH 7.8±0.5, followed by adding ethanol up to 70 % in volume. The SC sodium salt precipitate obtained was separated by means of centrifugation, and washed with 70 aqueous ethanol up to obtaining neutral washings and a negative qualitative reaction with respect to sulphate ions. It was then washed with acetone and dried under vacuum at 60 °C.

The yield of a powdery snow-white colour product in the form of the sodium salt (the substitution level SL= 1.47) amounted to 6.8, the product being completely soluble in water, the solution having a neutral pH value. IR spectra: 1240 cm^{-1} ν (S=0), 810 cm^{-1} ν (C−OS); 3400 cm^{-1}, ν (OH). ^{13}C NMR spectra (D$_2$O), δ, ppm (*I*, Hz): 100.8 (C$_1$), 79.2 (C$_2$ − OSO$_3^-$), 78.1, 75.1 and 73.3 (C$_3$−C$_5$), 66.7 (C$_6$ − OSO$_3^-$).

RESULTS AND DISCUSSION

The key stage of the sulfation method consists in MCC activation by ultrasound. It is known that the ultrasonic treatment results in the re-organization of the supramolecular structure of cellulose, in changing intra- and intermolecular bonds, in the disintegration of crystallites into aggregates [11, 12]. This facilitates the access of the solvent to the interior microcrystallites.

Table 1 demonstrates the average polymerization level (APL) and the crystallinity index (I_{cr}) for cotton MCC subjected to ultrasonic treatment in DMFA medium. It can be seen that the

TABLE 1

Changing the characteristics of MCC influenced by sonication in DMFA medium (power density of US treatment 260 W/cm^2)

Duration of treatment, min	APL	I_{cr}
0	220	0.88
5	200	0.88
10	180	0.86
15	180	0.86
20	180	0.86
25	160	0.87

treatment of MCC by ultrasound results in changes in the polymerization level of the material, but it does not affect the value of I_{cr}. Data presented in Table 1 indicate a partial degradation of cellulose macromolecules with the conservation of an ordered structure of fibrils. This results in increasing the surface of cellulose microcrystals accessible for reagents, as well as in the formation of a network of capillaries within the mentioned aggregates. As the result, the MCC reactivity exhibits an increase.

Table 2 demonstrates the results of studying the reaction of MCC sulfation in DMFA. The reaction of MCC esterification by N,N-DMFA/ClSO$_3$H mixture after preliminary ultrasonic treatment occurs in a homogeneous medium (the reaction mixture is homogenized during the first 15−20 min after the adding the esterifying mixture). In the case of MCC sulfation without ultrasonic treatment there were products obtained with a relatively low SL (see Table 2, No. 4). Increasing the reaction time up to 24 h in this case resulted in a marked increase in the substitution level (see Table. 2, samples Nos. 3 and 4). No homogenization of the reaction mixture was observed, too.

The sulfation of sonicated MCC by amino-sulphonic acid was carried out at 80 °C. The reaction proceeded under these conditions in a heterogeneous environment. A product with a low substitution level was obtained in this case (see Table. 2, No. 5). For comparison, we performed ultrasonic pre-treatment and subsequent MCC sulfation in DMAA. Using this solution resulted in a slower dissolution in the cellulosic material in the ClSO$_3$H/DMAA sys-

TABLE 2

Conditions and results of MCC sulfation in DMFA medium with ultrasonic treatment

Sample No.	Initial MCC	Sulphating agent/ Solvent	Reagent consumption, 1 M Agent/1 M MCC	Temperature, °C	Time, h	Substitution level
1	Cotton	$ClSO_3H$/DMFA	2.0	20	3	0.86
2	«	$ClSO_3H$/DMFA	3.0	20	3	1.20
3	«	$ClSO_3H$/DMFA	5.0	20	3	1.47
4*	«	$ClSO_3H$/DMFA	5.0	20	24	0.68
5	«	NH_2SO_4H/DMFA	5.0	80	3	0.15
6	«	$ClSO_3H$/DMFA	5.0	50	1	1.43
7	«	$ClSO_3H$/DMAA	5.0	20	3	1.26
8	From foliferous wood	$ClSO_3H$/DMFA	5.0	20	3	1.51
9	From coniferous wood	$ClSO_3H$/DMFA	5.0	20	3	1.42

* The sample was obtained without US treatment. The initial MCC was held in DMFA during 2 h at 100 °C with the further treatment by the sulphating mixture for 24 h at 20 °C (the reaction mixture was heterogeneous).

tem and a lower substitution level inherent in the SC obtained (see Table. 2, samples Nos. 3 and 7).

The homogenization of the reaction medium in the system DMFA/$ClSO_3H$ after the ultrasonic treatment of MCC could be explained by the modifying solvent effect [13]. On could assume that the ultrasonic treatment results in increasing the availability of cellulose reaction centers to promote thus a more even distribution of ester groups. Introducing a great amount of sulphate groups results in the formation of associates with the solvent, i.e., in dissolving the material (for the first minutes of the reaction). This homogenization of the reaction medium is similar to the dissolution of cellulose in other modifying solvents such as formic acid [13]. The sulfation of MCC in the DMFA/$ClSO_3H$ system without ultrasonic treatment results in a significant swelling the cellulosic material with no dissolution (see Table 2, No. 4),

including the case when the reaction temperature is raised up to 50 °C. In this case, the homogenization of the reaction mixture is impeded by a slow sulfation reaction rate, a heterogeneous distribution of sulphate groups and a restricted diffusion of the sulphating agent into microcrystallites.

With no preliminary US treatment, only outer areas of the microcrystals are, first of all, accessible for esterification. The inhomogeneity of sulphate group distribution in the SC preparations obtained without the use of ultrasound pre-treatment is confirmed by the low solubility in water. If sodium SC salts obtained via the ultrasonic treatment, are completely dissolved in water to form transparent solutions, the sodium salts obtained from the initial material with no pre-treatment, exhibit only swelling in water. In the case of SL > 0.5, less than 5−10 mass % of a sample is water-soluble,

TABLE 3

Molecular mass (M_n) and intrinsic viscosity (η) of SC samples

Sample No.	Substitution level	$M_n, 10^3$	M_w/M_n	η, in 1 M NaCl, dL/g
1	0.86	21	3.12	0.31
2	1.20	23	2.80	0.37
3	1.47	22	2.37	0.35
6	1.43	18	4.57	0.28

Note. M_w/M_n is the polydispersity level.

although it is known that soluble SC could be obtained already at SL ~ 0.3 [11].

Data those characterize the molecular mass of SC samples obtained using ultrasonic pretreatment, are presented in Table 3.

Relatively low molecular mass (MM) and the intrinsic viscosity values inherent in the SC samples could be connected both with a low MM of the initial MCC, and with the processes of polymer degradation occurring at the stage of US processing. The additional degradation of macromolecules due to the action of mineral acids can be observed also in the process of sulfation.

For the samples obtained at a higher reaction temperature, a more abrupt decrease of molecular mass is observed (see Table. 3, No. 6). The values of polydispersity criterion (M_w/M_n) determined *via* chromatographic investigation are higher than those for powder products obtained by means of acid cellulose hydrolysis, whereto the MSC belongs [11]. However, the methods used do not allow one to observe changing the polydispersity criterion of the cellulosic material separately at the stage of ultrasonic treatment and at the stage of sulfation.

CONCLUSION

Thus, using the method of cellulose sulfation after preliminary processing with ultrasound one could obtain soluble SC by means of homogeneous esterification by means of DMFA/ClSO$_3$H mixture. It is demonstrated that the preliminary MCC treatment by ultrasound in the organic solvent results in reducing the APL of cellulosic material, whereas its phase composition is not changed.

Owing to the simplicity of the method used and its efficiency it could find application as a preparative synthesis and as the basis for the developing the technologies of industrial SC synthesis.

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