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The effect of quaternary ammonium base adsorbates on the molecular and morphological structure of microcrystalline cellulose

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Abstract

In order to obtain multicomponent polymer systems exhibiting biological activity, microcrystalline cellulose was used as a matrix for biologically active compounds, such as dimethylbenzylalkylammonium chloride, poly-*N*-vinylpyrrolidone, copolymer of *N*-vinylpyrrolidone and crotonic acid, and polymer complex of dimethylbenzylalkylammonium chloride with copolymer of *N*-vinylpyrrolidone and crotonic acid. Adsorption interaction of microcrystalline cellulose with these compounds was studied under various conditions. Adsorption isotherms of compounds of polymer nature are of similar character and are described by the Freundlich equation. The isotherms of the low molecular weight compound dimethylbenzylalkylammonium are described by the Langmuir equation. Characteristics of the resulting compounds were obtained using X-ray photoelectron and infrared Fourier spectroscopy, wide-angle X-ray diffractometry and scanning electron microscopy. Chemical interaction between microcrystalline cellulose and dimethylbenzylalkylammonium chloride takes place. This interaction leads to a new labile morphological cellulose structure accessible to penetration, which is confirmed at a morphological level by scanning electron microscopy.

Keywords: Quaternary ammonium; Microcrystalline cellulose; Biologically active compounds

1. Introduction

The use of cellulose, a natural polymer, as a matrix and as a carrier for biologically active compounds (BAC) is widely known (Kolokolkina et al., 1985; Okada et al., 1987; Rogovin and Virnik, 1974; Shishliannikova et al., 1988; Virnik, 1972). A large amount of literature dealing with the problem makes it possible to distinguish two main trends: (1) the development of biologically active cellulose materials by the synthesis of cellulose derivatives containing chemically-bound antimicrobial compounds (Rogovin and Virnik, 1974; Kolokolkina et al., 1985; Shishliannikova et al., 1988; Virnik, 1972) and (2) the preparation of cellulose adsorbates and BAC by their diffusion–adsorption interaction (Okada et al., 1987).

In the first case, the biological activity of the derived materials is due to the breaking of covalent bonds, formed during the synthesis and subsequent diffusion of BAC to the surrounding medium. In the second case, diffusion of BAC bound to cellulose by labile bonds during adsorption interaction by desorption mechanism takes place more readily, thus ensuring a rapid therapeutic effect.

Fibre cellulose materials, in the past, have been used mainly for these purposes. This was justified for the preparation of various antimicrobial dressings and objects of personal hygiene, etc. (Virnik, 1972). Powdered cellulose has principally been used as a filler for various drugs in the form of tablets and grains (Battista, 1975). Moreover, powdered cellulose with the ''limiting degree of polymerization'', microcrystalline cellulose (MCC), is used as a mild physiological regulator in peroral administration to patients with gastrointestinal diseases, atherosclerosis and some types of nervous system diseases (Rijenkov et al., 1986; Veinshtein et al., 1987). In many cases, it has been

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BAC = biologically active compounds; CVPCAD = polymer complex of dimethylbenzylalkylammonium chloride and copolymer of *N*-vinylpyrrolidone and crotonic acid; DMBAA = dimethylbenzylalkylammonium chloride; MCC = microcrystalline cellulose; PVP = poly-*N*-vinylpyrrolidone; QAB = quaternary ammonium base; VPCA = copolymer of *N*-vinylpyrrolidone and crotonic acid

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observed that although this filler is inert, the associated drugs exhibit prolonged activity. This is an important factor favouring MCC application. It is essential that MCC be used for these purposes in the pure form without additional modification, and its powder morphology and a unique ability to form gel-like dispersions in water and organic solvents (Kotelnikova et al., 1976) make it possible to apply it to formulations that are unsuitable for fibre cellulose.

One such application is the adsorption interaction between MCC and various drugs. Although many papers have been published on this subject, the adsorption mechanism is still obscure, mainly because a great variety of medicines require a specific approach in each case, which takes account of the chemical and structural features of adsorbates.

Antimicrobial drugs, widely used at present, which are bound to MCC, may be of practical interest. Among them is DMBAA, a salt of quaternary ammonium base (QAB). It is an organic ammonia derivative, which is a cationic surfactant and is applied for imparting antimicrobial properties to fibre materials including cellulose fibres. Other fields of application are grafting onto a polymer support or in the composition of polymer complexes.

DMBAA is known to be highly toxic, which restricts the fields of its application. One of the methods for decreasing its toxicity is to modify it by natural and synthetic polymers including complexation. This previously developed method for complexation of DMBAA with a water-soluble copolymer of *N*-vinylpyrrolidone and crotonic acid (VPCA) has led to the preparation of the medicine, CVPCAD, which exhibits biological activity, decreases the toxicity of the surfactant and prolongs its effect.

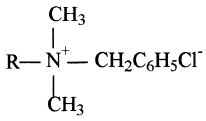
The main aim of the present study is to elucidate the mechanism of MCC adsorption interaction with DMBAA and its complex with the copolymer of *N*-vinylpyrrolidone and crotonic acid. Since VPCA itself is of polymeric nature, it was intended to study the adsorption interaction of MCC with each component of CVPCAD separately: DMBAA, PVP, VPCA and with DMBAA–VPCA complex (CVPCAD), (Afinogenov and Panarin, 1993).

It should be noted that combination of two compounds, greatly differing in their chemical nature and properties, cellulose, a natural water-insoluble polymer and CVPCAD, a synthetic water-soluble polymer, is of fundamental interest, whereas the preparation of antimicrobial compounds based on their combination can yield drugs with prolonged activity.

2. Experiment

2.1. Materials

DMBAA was used in aqueous solution form, the initial concentration of which was 52 wt%. DMBAA is a mixture of the individual homologous compounds of DMBAA with the following chemical structure:

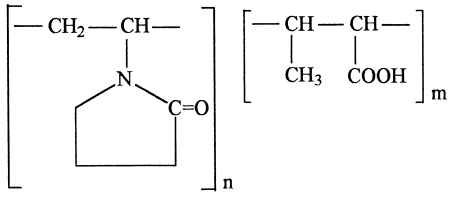


where $R–C_{12–16}H_{25–33}$.

Microcrystalline cellulose (MCC), obtained from cotton cellulose (Petropavlovsky et al., 1971), had the following characteristics: DP_v 170 and humidity 2% by weight. It was used in the form of a fraction with a particular size from 60 to 100 μm.

Poly-*N*-vinylpyrrolidone (PVP) was used in aqueous solution, the concentration of which (C_o), ranged from 0.09 to 0.90 mol/l. The polyvinylpyrrolidone:cellulose molar ratio ranged from 0.73 to 7.3. Samples of PVP with different molecular mass (M) ranging from 3.0×10^3 to 518.0×10^3 g/mol were studied. The molecular weight (M) was determined by gel-permeation chromatography (GPC).

The copolymer of *N*-vinylpyrrolidone and crotonic acid (VPCA) has the following chemical structure:



Samples of VPCA with M 19×10^3 and 33×10^3 were used in aqueous solutions, the concentration (C_o) of which ranged from 0.1 to 1.0 mol/l.

The polymer complex of DMBAA and VPCA, (CVPCAD) was used in the form of an aqueous salt solution containing 10% (by weight) of the principal substance (NaCl concentration 2.8% by weight).

2.2. Methods

Adsorption experiments of the above compounds on MCC and their desorption were carried out as described elsewhere (Kotelnikova et al., 1997, 1998; Panarin et al., 1995, 1996). The UV-spectroscopy control for compound concentration before and after adsorption and desorption was also applied where possible.

To investigate surface compositions and processes occurring at the surface, both X-ray photoelectron spectroscopy (XPS)—making it possible to carry out qualitative and quantitative analysis of the chemical state of elements in a layer up to 100 Å thick—and scanning electron microscopy (SEM) were widely used.

XPS spectra were recorded from an electron PHI 5400 (Perkin-Elmer) spectrometer with excitation by Mg^{2+} radiation. For these studies, the samples of MCC and of modified MCC were used in the form of powders. Solutions of

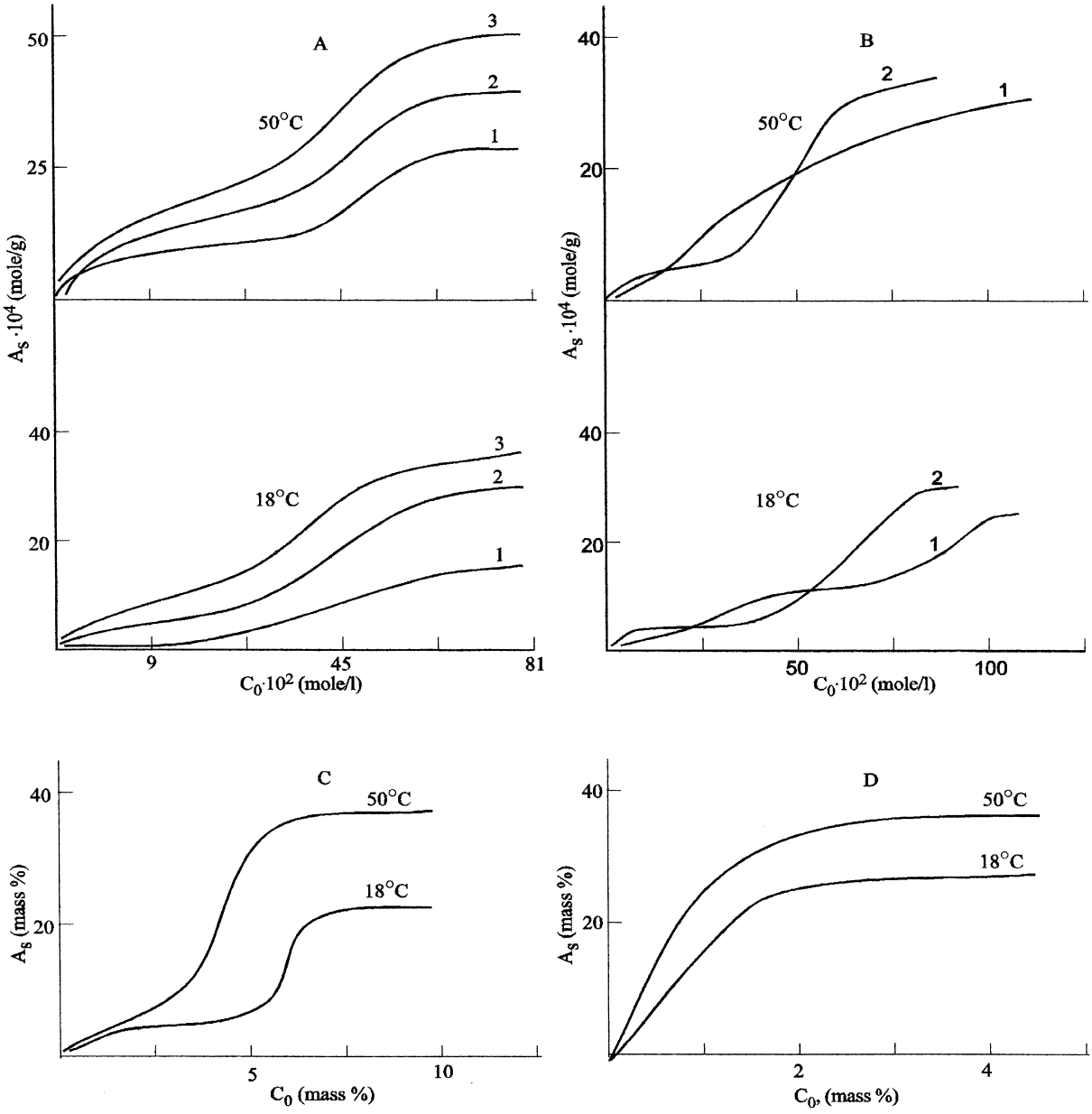


Fig. 1. Adsorption isotherms of (a) PVP with $10^{-3} \times M = 3.0$ g/mol (1), 53.9 g/mol (2), and 518.0 g/mol (3); (b) VPCA with $10^{-3} \times M = 19$ g/mol (1), 33 g/mol (2); (c) CVPCAD, and (d) DMBAA.

CVPCAD, PVP and DMBAA, before and after adsorption, were applied in condensed gel form, after vacuum drying on a glass support at 40°C to constant weight. The samples were fixed in a standard holder and after preliminary evacuation were placed on a manipulator previously cooled with liquid nitrogen. A working vacuum greater than 5×10^{-5} torr was maintained. The chemical composition of the surface was determined from the overall spectra. The analysis of the chemical state of elements and the calculation of relative atomic concentrations were carried out from the spectra of individual photoelectronic lines with the aid of standard programs. The precision of the bond energy (E_{bond}) determination was to $\pm$ 0.1 eV and that of quantitative analysis was to $\pm$ 10%. The spectra were calibrated by the carbon 1s line of hydrocarbon impurities (components) with $E_{bond} = 285.0$ eV.

A Bruker JFS 88 IR Fourier spectrometer was used for spectroscopic study in the IR range (from 400 to 3600 cm^{-1}) of modified MCC samples in the solid state which were prepared in the form of KBr pellets and condensed solution samples. For these purposes both initial solutions and those after desorption were vacuum-dried at 40°C on the KRS supports. These dried samples were thin films or concentrated gels. The transmission spectra were taken with a resolution of 4 cm^{-1}.

The wide-angle X-ray diffraction experiments were

Table 1
Freundlich's constants 1/*n* and K for PVP, VPCA, and CVPCAD and Langmuir's constants K_1 and K_2 for DMBAA adsorption on MCC

Adsorbate	$10^{-3} \times M$ (g/mol)	Adsorption temperature (°C)	Adsorption constants			
			Freundlich's constants		Langmuir's constants	
			1/*n*	$10^3 \times K$	K_1	K_2
PVP	3.0	18	1.62	1.77	–	–
		50	1.32	1.58	–	–
	518.0	18	0.79	3.55	–	–
		50	0.95	4.31	–	–
VPCA	19.0	18	1.85	2.04	–	–
		50	1.73	2.10	–	–
	33.0	18	1.10	4.87	–	–
		50	1.32	5.98	–	–
CVPCAD	–	18	1.95	8.5	–	–
	–	50	2.04	10.3	–	–
DMBAA	–	18	–	–	28.4	29.8
	–	50	–	–	62.5	75.4

performed using powder diffraction apparatus and monochromatized CuK_α radiation. The measurements were carried out in the $5° < 2\theta < 40°$ scattering angle range with an angle step of 0.25°. The samples in the form of a flat cake of thickness of about 1 mm were prepared by slight moulding of powdered samples in a special press mould. The samples were rotated during the experiments in an evacuated chamber.

Electron microscopic studies were performed with a scanning electron microscope (SEM) Leitz AMR 1200B.

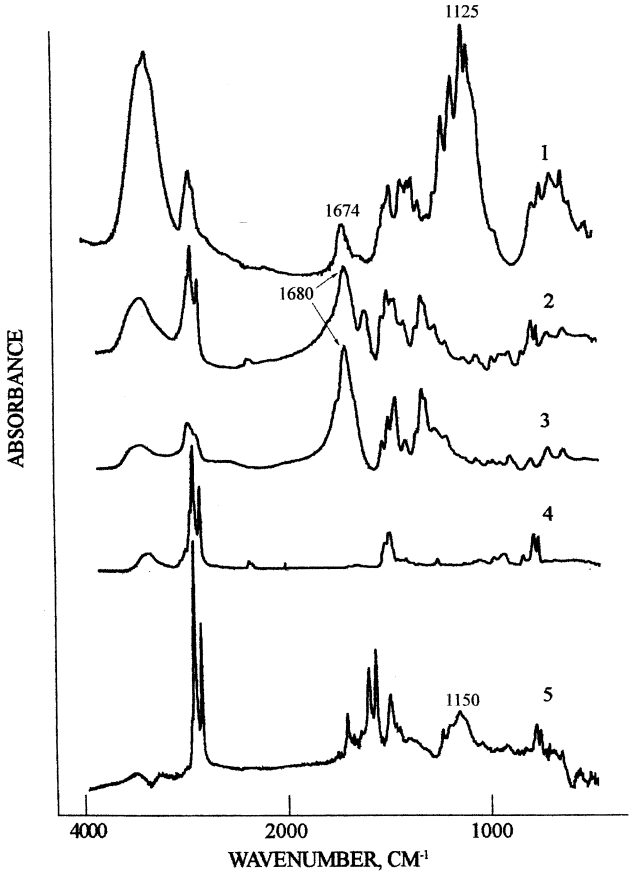


Fig. 2. IR spectra of (1) the MCC sample containing adsorbed CVPCAD (19.2 mass%), (2) CVPCAD, (3) VPCA, (4) DMBAA and (5) DMBAA solution after desorption in water at pH 6 of the MCC sample containing 4.1 mass% of DMBAA (release of DMBAA 58.1%).

3. Results and discussion

Fig. 1(a) shows adsorption isotherms for PVP solutions with different *M* at 18°C and 50°C (adsorption time 120 min) (Kotelnikova et al., 1997). The two-stage S-shaped isotherms in the adsorption of polyvinylpyrrolidone solutions over the entire *M* range shows that the adsorption mechanism is of the same character regardless of the *M* of the polymer. These stepwise isotherms belong to type IV and indicate that polymolecular adsorption takes place on the microcrystalline cellulose surface. It was established that adsorption isotherms cannot be described by the Langmuir equation. Taking into account the distinct adsorption dependence on *M* and the fact that adsorption seems to be complicated by interaction between the polymer molecules, we applied other equations for the calculations. Thus, it was found that the isotherms are adequately described by the Freundlich equation which is used for adsorption from solutions on non-homogeneous surfaces and takes into account the interaction between the adsorbed molecules: $A_s = K \times c^{1/n}$, where A_s is the quantity of the adsorbed compound in the surface layer of the adsorbent, *c* is the equilibrium solution concentration, and *K* and *n* are constants. The constant *K* represents the relative ability of a given adsorbent to sorb a given adsorbate, and 1/*n* is the adsorbate affinity for a given adsorbent. Freundlich's equation is expressed logarithmically as $\log A_s = \log K + (1/n)\log c$. The constants *K* and 1/*n* are expressed graphically as the ordinate intercept

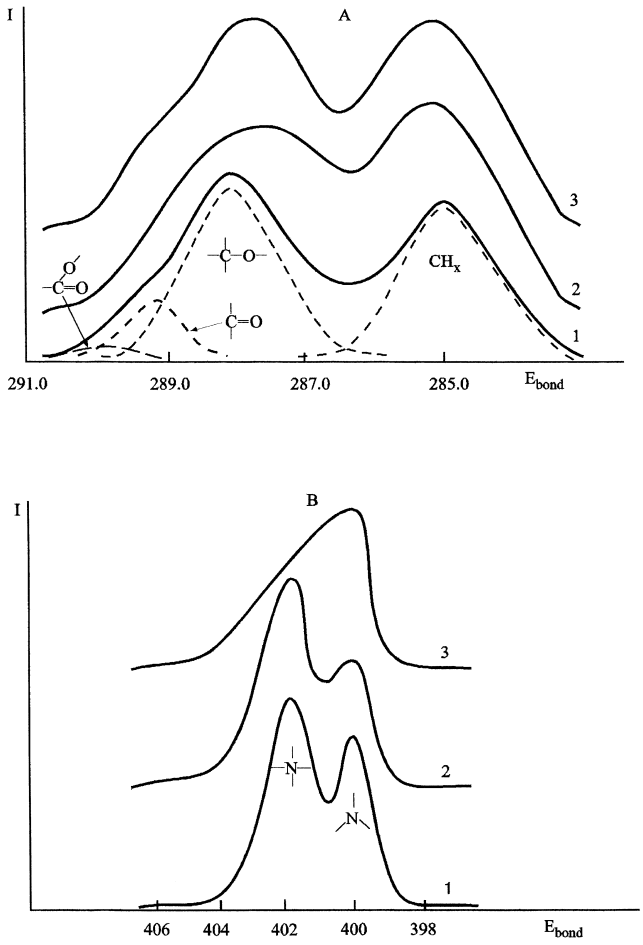


Fig. 3. (a) XPS spectra of carbon line 1s of (1) initial untreated MCC, (2) adsorbate of MCC and PVP (M of PVP = 53.9×10^{-3} g/mol, PVP content 15.4 mass%), and (3) adsorbate of MCC and DMBAA (DMBAA content 4.1 mass%); (b) XPS spectra of nitrogen line 1s of (1) CVPCAD, (2) DMBAA and (3) the MCC sample containing 1,7 mass% of DMBAA after DMBAA desorption in water at pH 6.

and the slope tangent, respectively. Freundlich's constants are listed in Table 1.

Fig. 1(b) shows adsorption isotherms of VPCA solutions ($M = 19 \times 10^3$ g/mol and 33×10^3 g/mol) at 18°C and 50°C (adsorption time 120 min). They can also be described by the Freundlich equation as in the case of PVP adsorption on MCC.

Fig. 1(c) shows adsorption isotherms of CVPCAD at 18°C and 50°C (adsorption time 120 min). All these isotherms can be assigned to type IV and can be characterised as a combination of physical adsorption and chemisorption (Greg and Sing, 1970; Panarin et al., 1995; Kotelnikova et al., 1997).

Fig. 1(d) shows adsorption isotherms for DMBAA solutions at 18°C and 50°C (adsorption time 300 min), which can be described by the Langmuir equation. The adsorption takes place until the monomolecular layer of DMBAA on the MCC surface is formed. Table 1 presents the Langmuir constants of this process.

It can be seen that the isotherms of compounds of polymer nature: PVP, VPCA and CVPCAD, are of similar character. This means that the polymer component of CVPCAD, VPCA, is responsible for its adsorption character on the cellulose matrix. The isotherms of DMBAA are quite different. Therefore, one can conclude that the effect of these adsorbed substances on the properties of modified MCC samples will also be different.

Fig. 2(1)–(5) show the IR spectra (1) of MCC samples containing adsorbed CVPCAD (19.2 mass%); (2) CVPCAD; (3) VPCA; (4) DMBAA and (5) that of DMBAA solution after desorption in water at pH 6 of the MCC sample containing 4.1 mass% of DMBAA (release of DMBAA 58.1%). The most characteristic and intense absorption in CVPCAD and VPCA spectra is observed in the region of 1680 cm^{-1}, assigned to stretching vibrations of the –C=O groups of the lactam ring (Gordon and Ford, 1976; Nakanishi, 1965). In the CVPCAD spectrum a new band at 1579 cm^{-1}, attributed to the stretching vibrations of COO^- groups (carboxylate ions), is formed in the complex as a result of the electrostatic interaction of VPCA ionogenic groups and DMBAA ammonium groups. The strongest absorption bands in the DMBAA spectrum are observed in the regions from 700 to 730 cm^{-1}, from 2850 to 2920 cm^{-1} (rocking and stretching vibrations of the CH_2

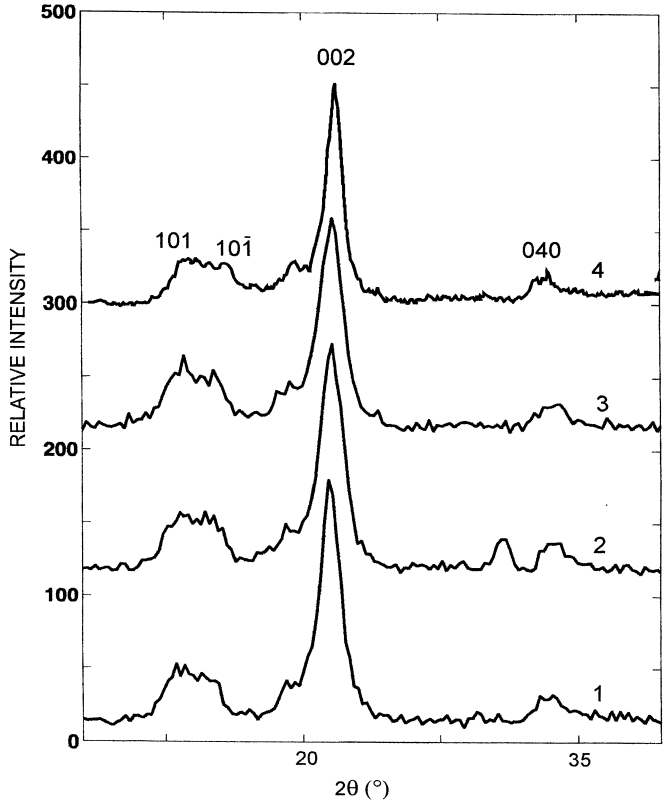


Fig. 4. The diffraction patterns of (1) initial untreated MCC, (2) adsorbate of MCC and CVPCAD (CVPCAD content 19.2 mass%), adsorbate of MCC and (3) VPCA (M of VPCA = 19.0×10^{-3} g/mol, VPCA content 23.2 mass%), (4) adsorbate of MCC and DMBAA (DMBAA content 4.1 mass%).

groups, respectively) and from 1460 to 1490 cm^{-1} (bending vibrations of CH_3 groups and scissor vibrations of CH_2 groups). The spectra of MCC containing adsorbed CVPCAD also exhibit an absorption band at 1650–1674 cm^{-1}, but this band is markedly displaced (to 1670 cm^{-1}). This shift is due to hydrogen bonding between the lactam carbonyl groups in PVP and the OH groups on the MCC surface. An interesting feature of the IR spectrum of DMBAA solution after desorption is the fact that it contains groups of the absorption band at 1000–1200 cm^{-1}, which can be assigned to the stretching vibrations of C–O and C–O–C groups in the glucopyranose ring. This result appears to indicate that DMBAA reacts with MCC and can partially dissolve it, as is confirmed by the literature data (Rogovin and Shorigina, 1953). Thus, it appears that QAB used for antimicrobial treatment of fibrous cellulose materials, under appropriate conditions can be strongly bound to cellulose, in some cases with the formation of molecular compounds. At high solution concentration they can even cause partial dissolution of cellulose.

XPS results are presented in Fig. 3(a,b). XPS spectra of the carbon 1s line (a) of (2) adsorbate complexes of MCC containing PVP (15.4 mass%) and (3) DMBAA (4.1 mass%), compared to the spectrum of initial untreated MCC (1), show that in all cases adsorption takes place on the MCC surface without any change in the electronic configuration of carbon atoms. This is indicated by the resolution of the XPS spectrum of C 1s into individual photoelectronic lines for all the samples. A similar conclusion can be drawn on the basis of the XPS spectra of the nitrogen 1s line (b). It can be seen that the spectra of (1) CVPCAD and (2) DMBAA contain nitrogen in two valence states: quaternary and ternary. The latter is possibly the admixture of ternary amine obtained during the preparation of DMBAA (Gershenovich et al., 1978). In the samples of adsorbates of these compounds on MCC, nitrogen is in the same two states. Taking as an example the adsorbate of MCC and DMBAA, it can be seen that, in contrast, after DMBAA desorption from the adsorbate, changes occur in the electronic state of carbon and nitrogen atoms in the MCC sample containing 1.7 mass% of DMBAA. This indicates that nitrogen is chemically bound in the ternary valence state and some of the alkyl groups belonging to DMBAA are also bound. Hence, the XPS method shows that DMBAA and MCC chemically interact on the surface, forming the adsorption complex on the MCC surface. Taking into account the fact that the adsorbate of MCC and DMBAA contains N, that the OH group is a relatively strong proton donor (i.e., an acid) and that the N atom is a proton acceptor (i.e., a base), it may be concluded that the OH…N bonds must be energetically more preferable than the OH…O bonds in MCC. Consequently, one can deduce

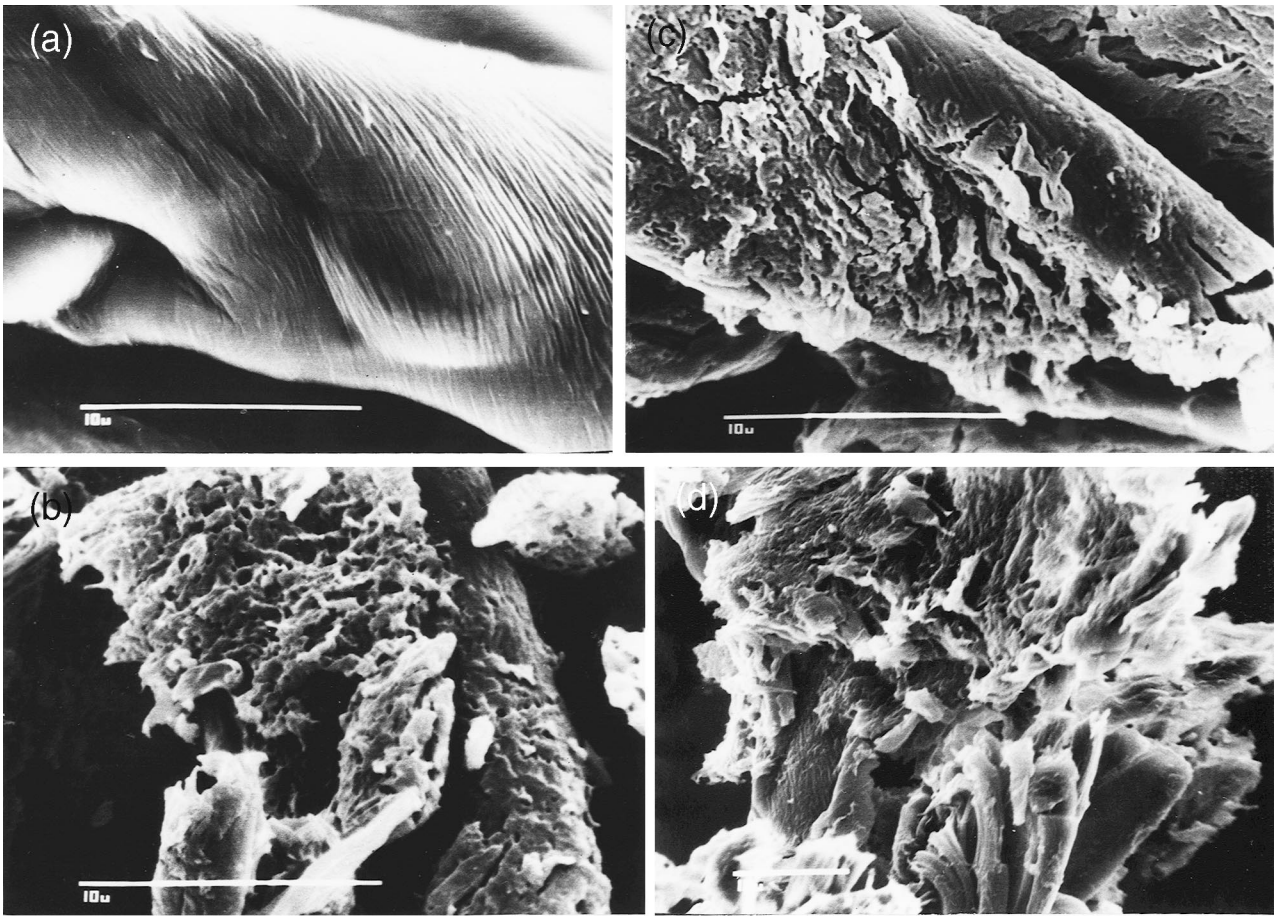


Fig. 5. SEM micrographs of the fibres of (a) initial untreated MCC; (b) the MCC sample containing adsorbed CVPCAD (19.2 mass%), and (c,d) the MCC sample containing 1,7 mass% of DMBAA after DMBAA desorption in water at pH 6.

that as a result of treatment with DMBAA, OH…N bonds are formed on the MCC surface.

Hence, it appears that by using IR spectroscopy and XPS, one of the CVPCAD components, namely DMBAA, chemically interacts with MCC. Moreover, although the IR Fourier spectroscopy characterises the interaction process in bulk whereas XPS characterises that on the surface, the interaction character is the same. Namely, the OH groups of MCC react with the quaternary nitrogen atom of DMBAA which leads to the formation of the OH…N bond. It is also evident that some of the short alkyl groups belonging to DMBAA are adsorbed on MCC.

The chemical interaction of DMBAA with MCC occurring not only on the surface but also in bulk, must lead to changes in the X-ray structure of modified MCC samples. Fig. 4(1)–(5) shows X-ray diffraction patterns (1) of initial MCC and of MCC samples containing (2) CVPCAD (19.2 mass%), (3) VPCA (23.2 mass%) and (4) DMBAA (4.1 mass%). The WAXS intensity curves of MCC samples containing VPCA (and PVP) are similar to those of pure MCC. The sample of MCC with adsorbed CVPCAD (2) exhibits an additional reflection at $2\theta = 32^\circ$ which can be attributed to crystalline NaCl belonging to CVPCAD. Perhaps additional concentration of NaCl occurs in the MCC matrix under conditions of adsorption and subsequent drying. It is important that all samples have the same structure of crystalline cellulose modification (CCM) I including the sample of MCC containing DMBAA (4). However, the latter is the only sample that exhibits some specific features. Thus, in spite of the fact that the WAXS intensity resembles that of the CCM I, there are differences in reflection intensities: MCC reflections 101, 101, 002 and 040 are smaller than those in pure MCC. These changes indicate that crystallites of MCC are partially destroyed. It is possible that they are rearranged from cube-like to sheet-like form.

Hence, the data obtained by the X-ray method confirm the fact that during DMBAA adsorption on MCC they undergo chemical interaction which leads to changes in the crystalline structure of MCC. At a morphological level these results were confirmed by the SEM method.

SEM results are shown in Fig. 5(a)–(d), i.e. the micrographs of the fibres of (a) an untreated MCC, of (b) an MCC containing adsorbed CVPCAD (19.2 mass%), and (c,d) a modified MCC sample containing DMBAA (DMBAA content 4.1 mass%), subjected to desorption in water at pH 6. It can be seen that DMBAA adsorption takes place

not just on the surface. Profound changes in the morphological structure of the initial MCC can be seen. The micrographs show that DMBAA is inserted into the cellulose fibre structure, MCC is partially dissolved and a new morphological design of the fibre with a porous and loose structure is formed. The size of pores is 0.1–0.3 μm. It is evident that porosity will favour the penetration of reagents inside the cellulose fibre. Hence, the chemical interaction of DMBAA with MCC forms a new labile morphological cellulose structure accessible to reagents. It is noteworthy that the MCC sample containing adsorbed CVPCAD to a level of 19.2 mass% also exhibits a very loose structure. Since CVPCAD is a labile complex of VPCA and DMBAA, it is apparent that during the treatment of MCC with CVPCAD the chemisorption of DMBAA on MCC takes place first and leads to the above changes in the MCC morphological structure. Subsequently, the interaction between VPCA and MCC, with the porous structure already formed takes place. Hence, the adsorption of CVPCAD, which is of polymeric nature in contrast to DMBAA, proceeds readily and the amount of adsorbed CVPCAD is relatively large (CVPCAD content up to 50 mg/g MCC). Note that the polymeric nature and the large size of this polymer complex do not prevent this considerable adsorption.

Hence, during the adsorption process the functions of the CVPCAD components appear to be distributed as follows. The first stage is determined by DMBAA chemisorption on MCC and leads to the formation of a new morphological and structural design of the cellulose fibre. The second stage is the physical adsorption of VPCA on the prepared modified surface of this fibre. The features of this stage are determined by the mechanism of polymer component adsorption on MCC. It is for this reason that adsorption isotherms for PVP, VPCA and CVPCAD appear similar.

Consequently, the adsorbates of MCC and the above compounds are compatible complexes, the structure of which depends on the chemical structure of the compounds adsorbed.

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