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Moisture sorption by cellulose powders of varying crystallinity

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Abstract

Moisture in microcrystalline cellulose may cause stability problems for moisture sensitive drugs. The aim of this study was to investigate the influence of crystallinity and surface area on the uptake of moisture in cellulose powders. Powders of varying crystallinity were manufactured, and the uptake of moisture was investigated at different relative humidities. The structure of the cellulose powders was characterized by X-ray diffraction, BET surface area analysis, and scanning electron microscopy. Moisture uptake was directly related to the cellulose crystallinity and pore volume: Cellulose powders with higher crystallinity showed lower moisture uptake at relative humidities below 75%, while at higher humidities the moisture uptake could be associated with filling of the large pore volume of the cellulose powder of highest crystallinity. In conclusion, the structure of cellulose should be thoroughly considered when manufacturing low moisture grades of MCC.

Keywords: Microcrystalline cellulose; Algae cellulose; Moisture sorption; Cellulose structure

1. Introduction

Microcrystalline cellulose (MCC) is one of the most commonly used tabletting excipients (Bolhuis and Chowhan, 1995) and many of its properties depend on its moisture content (Ahlneck and Alderborn, 1988; Ahlneck and Zografi, 1990; Amidon and Houghton, 1995). However, moisture sorption by MCC has also been reported to cause stability problems for moisture sensitive drugs (Carstensen et al., 1969; Genton and Kesselelring, 1977; Carstensen and Lothari, 1983). Ordinary MCC is manufactured with 4–5% (w/w) moisture content (European Pharmacopoeia, 2002). For moisture sensitive drugs, low moisture grades of MCC are available (1.5%, w/w, moisture in Avicel PH 112 and 3%, w/w, moisture in Avicel PH 103, FMC Corp.); however, these appear hygroscopic (Doelker et al., 1995).

In general, vapor sorption can occur either on the surfaces or in the bulk of a material. Moisture uptake by cellulose powder is recognized as predominantly occurring in the bulk of disordered regions (Howsman, 1949). Absorption of moisture in the bulk of disordered regions of cellulose particles has been widely accepted as the reason for manifold differences between BET N_2 and BET H_2O surface area values

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(Zografi et al., 1984; Zografi and Kontny, 1986). One complication in understanding the mechanisms of moisture sorption and its dependence on the material's structure is the complexity of the cellulose structure. Therefore, the applicability of the term amorphous (or "liquid-like") in its original meaning is sometimes questionable. Whilst X-ray diffraction analysis clearly indicates various degrees of order in cellulose, many parameters (e.g. Tg, "glassy-rubbery" state transitions, etc.) directly associated with the amorphous state cannot be reliably reproduced (Stubberud et al., 1996). Verlhac et al. (1990) suggested that what appears to be "amorphous" cellulose consists mainly of surface chains. A clear relationship between availability of surface hydroxyl groups and cellulose crystallinity was established.

Varying the crystallinity of cellulose powder is expected to cause changes in the moisture content. In order to investigate the influence of the structural properties of cellulose on moisture sorption, it is necessary to select cellulose powders over a broad range of crystallinities. The crystallinity may be altered by various methods: The disordered state in cellulose can be induced either by addition of swelling agents (Patil et al., 1965) or by grinding (Suzuki and Nakagami, 1999), whereas extraction of cellulose from cell walls of certain algae is reported to produce highly crystalline cellulose (Ek et al., 1998).

The aim of this study is to, for the first time, show how structural properties, such as surface area, pore volume, and crystallinity, are interconnected when influencing the cellulose powder's ability to interact with moisture. The study is performed over a broad range of cellulose crystallinities and surface areas including, a.o., cellulose powders of algal origin. As a consequence of this, unique SEM pictures together with physical characteristics of the algal celluloses will also be presented.

2. Materials and methods

2.1. Materials

Five different types of cellulose were used: microcrystalline cellulose (MCC, Avicel PH 102, FMC, Ireland), agglomerated micronized cellulose (AMC), low crystallinity cellulose (LCC), Algiflor brown algae cellulose (Algiflor, Danisco, France), and Cladophora green algae cellulose (*Cladophora glomerata* harvested from the Baltic Sea). The Algiflor brown algae were a blend of five species: *Laminaria digitata*, *Lessonia nigrescens*, *Macrocystis pyrifera*, *Ascophyllum nodosum*, and *Fucus serratus*.

2.1.1. Agglomerated micronized cellulose (AMC)

To produce AMC, MCC was ground in a mortar mill (Retsch KM 1, Germany) for 2 h with water (1 ml of water per 2 g of powder). A 10% suspension of the resultant powder (w/v) was then spray-dried (Minor Type 53, Niro Atomizer A.S., Denmark) at $T_{in} = 205–210\,^{\circ}C$ and $T_{out} = 95–100\,^{\circ}C$ with a feed-rate of 1.7 l/h.

2.1.2. Low crystallinity cellulose (LCC)

To produce LCC, 50 g of MCC was dispersed in 1 l of 70% $ZnCl_2$ solution and vigorously stirred. After allowing it to swell for 1 h, the cellulose was precipitated with additional water. The resultant powder was washed repeatedly until the conductivity of the washed water approximated that of deionised water (i.e. 10^{-6} S/cm) and, thereafter, spray-dried as described above.

2.1.3. Cladophora and Algiflor algae cellulose

Five hundred grams of algae (i.e. Cladophora green algae and Algiflor brown algae) were bleached with 180 g of $NaClO_2$ in 0.5 l acetic buffer. The mixture was diluted to 5 l, poured into a plastic bag and stored in a water-bath for 3 h at 60 °C. The product was washed until neutrality (pH ∼7) as indicated by coloration of a paper indicator (Universalindikator, Merck, Sweden) and filtered. Three liters of 0.5 M NaOH was added to the remainder, and the resultant product was stored at 60 °C in a water-bath overnight. The resultant pulp was washed till neutrality, filtered, and dried at room temperature. Dry, purified algae were ground prior to acidic hydrolysis (Fitz Mill type D6, Manesty Machines, UK). To 50 g of the product 1 l of 5% HCl was added, and the suspension was heated till boiling. Once boiling, it was removed from the heat, and the slurry was allowed to stand overnight. The remainder was washed till neutrality, filtered and spray-dried as described above.

2.2. Methods

2.2.1. Scanning electron microscopy

Micrographs of each sample were taken (Leo Gemini 1550 FEG SEM, UK) at a 100,000 magnification. The samples of each powder were mounted onto double-sided sticky tape over aluminium stubs and coated with gold under vacuum prior to the studies.

2.2.2. X-ray diffraction

An X-ray diffractometer with Bragg-Brentano geometry was used (Diffraktometer D5000, Siemens, Germany). The Cu Kα radiation was utilized ($\lambda = 1.54\,\text{Å}$) and the angle 2θ was set between 10 and 45°. The crystallinity index was calculated as

$$\text{CrI} = \frac{I_{002} - I_{\text{am}}}{I_{002}} \qquad (1)$$

where I_{002} is the overall intensity of the peak at 2θ about 22° and I_{am} is the intensity of the baseline at 2θ about 18° (Segal et al., 1959).

2.2.3. Moisture sorption

The moisture content was measured gravimetrically after samples had been stored at 25 °C over saturated salt solutions of LiCl, CH_3COOK, K_2CO_3, NaBr, NaCl, and KNO_3 corresponding to 11, 25, 40, 63, 75, and 96% relative humidity (RH), respectively (Nyqvist, 1983) for at least 48 h. Prior to the measurements, the samples were stored over P_2O_5 (0% RH) for 10 days.

2.2.4. Surface area and porosity

The specific surface area of the powders was obtained from a BET (Brunauer et al., 1938) analysis of N_2 adsorption isotherms (ASAP 2010, Micrometrics, USA). The total pore volume of the powders was obtained as the volume of adsorbed nitrogen at relative pressure approximating unity. The weight of the samples in these measurements was chosen so as to produce a total surface of 5–10 m^2. The surface area available for water adsorption was calculated based on the principles described by Brunauer et al. (1938) and the assumption that each water molecule occupies a surface area of 12.3 Å^2 (Wefers, 1964). The method is applicable for relative humidities below 40%.

3. Results

3.1. Scanning electron microscopy

Fig. 1 illustrates the texture of the cellulose samples as obtained by SEM. The surface of the LCC particles was smooth: a similar texture was visible in the MCC particles. The surface of the AMC particles was irregular, whereas the Algiflor cellulose particles appeared deeply grooved. In the Cladophora cellulose sample, a web-like structure composed of numerous filaments was visible.

3.2. X-ray diffraction

The X-ray diffraction patterns of the samples are presented in Fig. 2. As a result of the chemical treatment, a smeared out diffractogram was observed in LCC indicating a high degree of disorder. From the AMC panel, we observe that grinding MCC was less efficient in reducing crystallinity than was the chemical treatment. The MCC diffractogram revealed a relatively ordered structure with a narrow peak at 22° and a diffuse peak between 13 and 18°. Two peaks of low intensity at 14 and 16° were identified in the Algiflor cellulose sample; however, these were diffused in pattern, indicating lower degree of order than seen in Cladophora cellulose powder. Sharp, distinct peaks at around 14, 16, and 22° as well as a small peak at 20° featured the Cladophora cellulose sample, characterizing this material as highly crystalline. The corresponding crystallinity indices are summarized in Table 1.

3.3. Moisture sorption

The moisture sorption isotherms are presented in Fig. 3. Below 75% RH, the moisture sorption was higher for materials with a lower crystallinity index. At very high relative humidities, the moisture content of the Cladophora cellulose powder increased sharply. The level of hysteresis between the sorption and desorption curves was broader for materials with a lower crystallinity index. In Fig. 4, the moisture content of the samples is plotted as a function of their crystallinity index at different relative humidities. The moisture content of the materials decreased steadily at RHs between 11 and 75%. At higher RHs, the

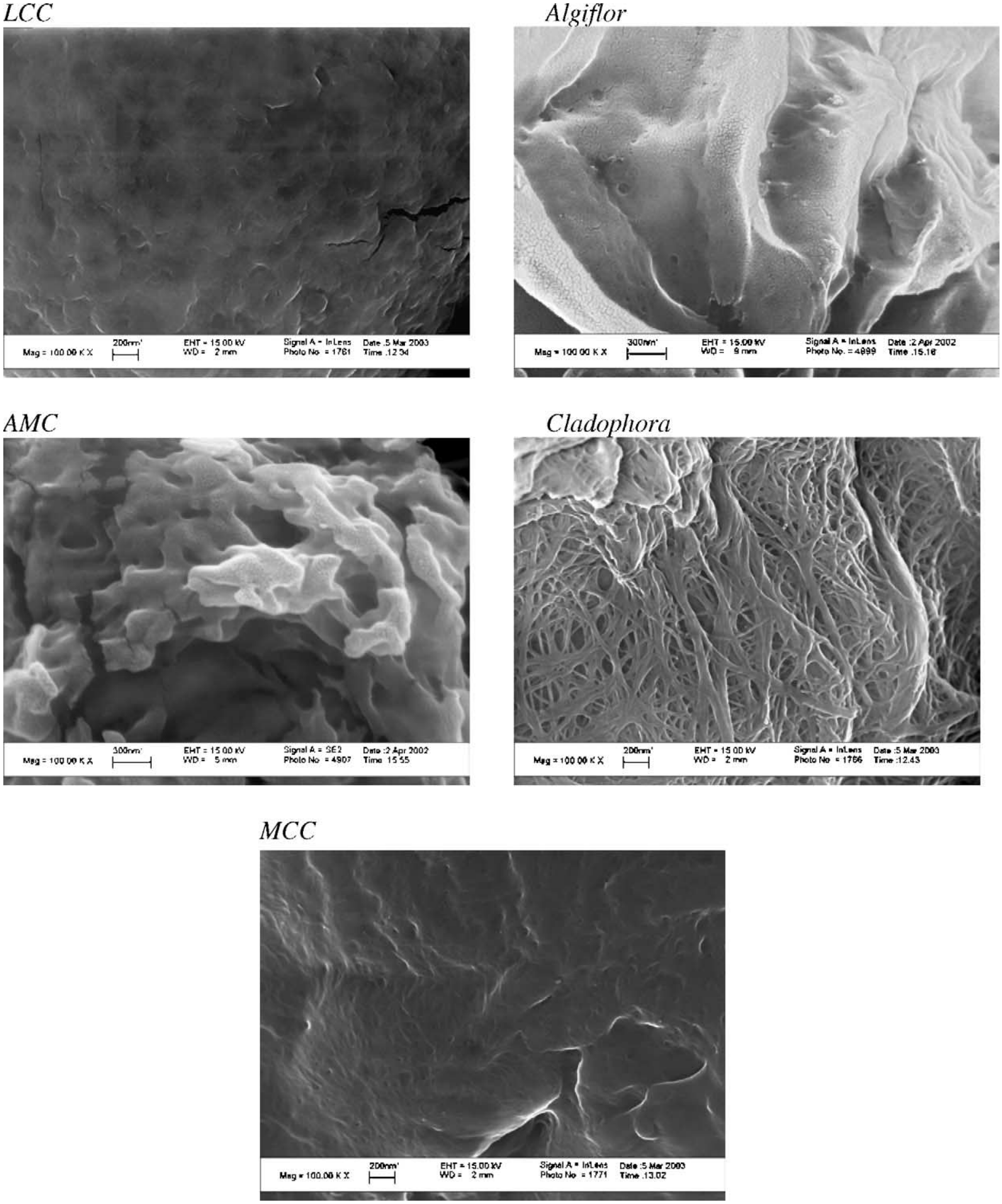

Fig. 1. SEM micrographs of cellulose powders at 100,000× magnification.

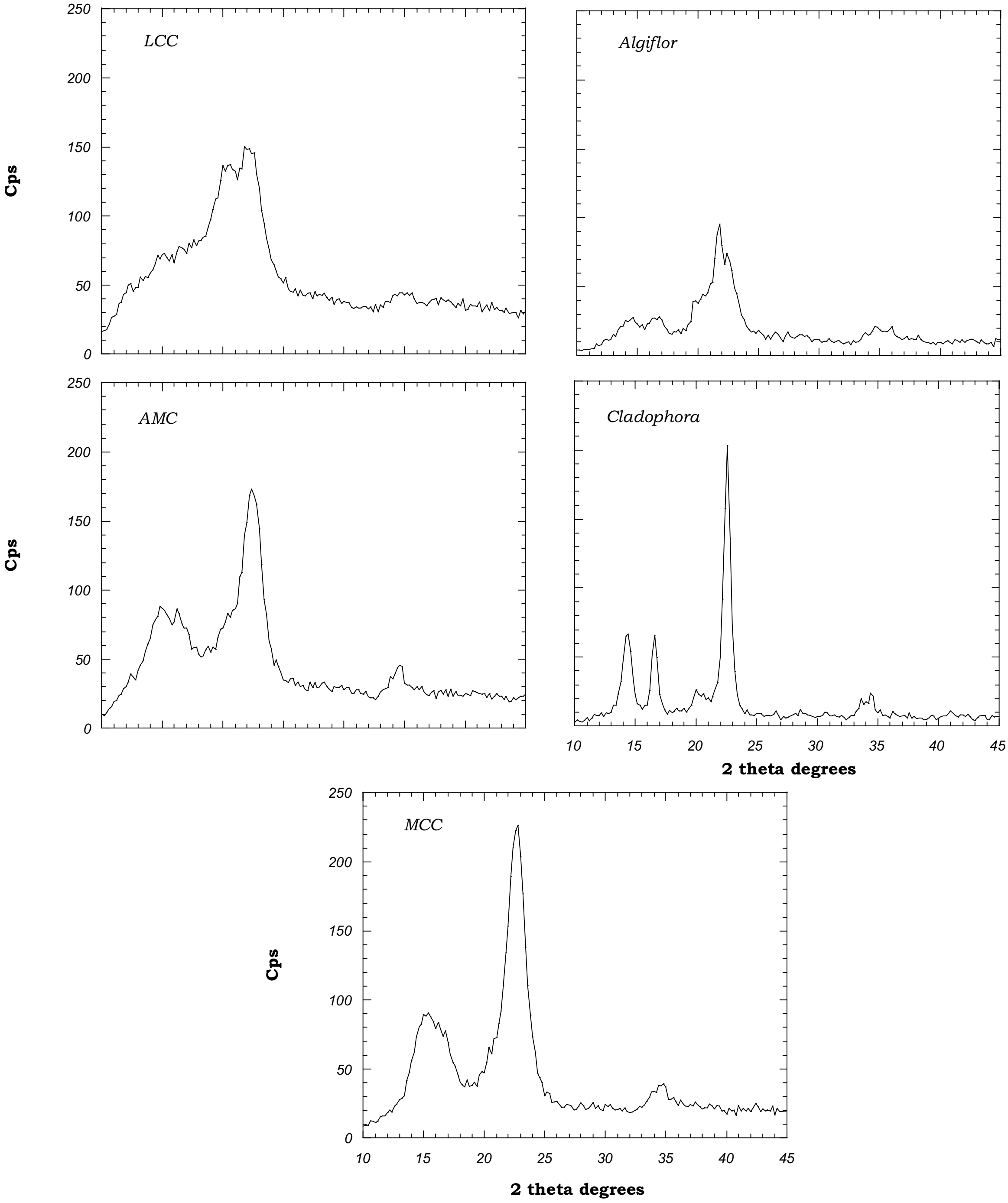

Fig. 2. X-ray diffraction patterns of cellulose powders of varying crystallinity.

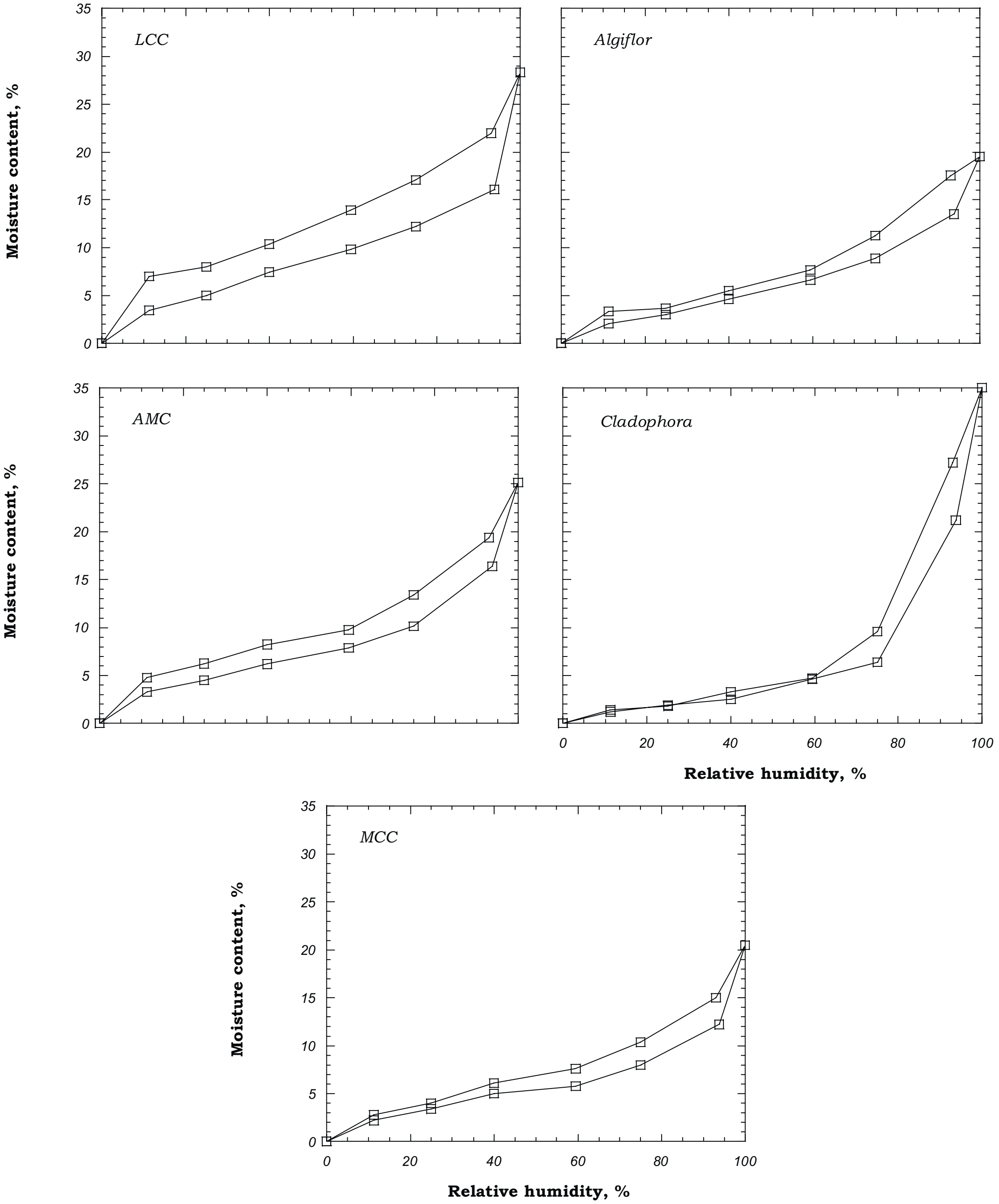

Fig. 3. Moisture sorption isotherms for cellulose powders of varying crystallinity. The lower curve represents adsorption and the upper curve desorption.

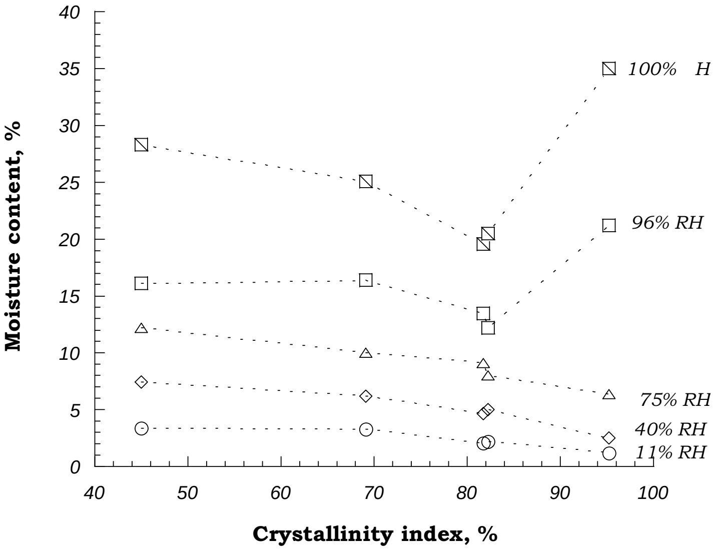

Fig. 4. Moisture content vs. crystallinity of cellulose powders. Lines are drawn as guides for the eye. Note that, for clarity, RH 25 and 63% are omitted.

monotonic decrease with increased crystallinity was no longer observed.

3.4. Surface area and porosity

The surface area values and the pore volumes are presented in Table 1. The BET N_2 surface area of the Cladophora cellulose powder exceeded the corresponding values of the other samples manifold. Also the pore volume of Cladophora cellulose powder was found to be significantly larger than for the other cellulose samples. For all cellulose powders except from the Cladophora cellulose sample, the BET H_2O surface was much larger than that obtained using N_2.

Table 1
Primary characteristics of cellulose powders

	Crystallinity index (%)	Surface area		Pore volume (cm^3/g)
		N_2 (m^2/g)	H_2O (m^2/g)	
LCC	45.0	0.48	204.2	0.00163[a]
AMC	69.1	1.13	168.3	0.00441[b]
MCC	82.2	0.96	117.3	0.0030[c]
Algiflor	81.7	5.76	130.6	0.0250[d]
Cladophora	95.2	94.7	52.80	0.5540[e]

[a] Total volume of pores filled with nitrogen at a relative partial pressure of 0.9861.

[b] Total volume of pores filled with nitrogen at a relative partial pressure of 0.9857.

[c] Total volume of pores filled with nitrogen at a relative partial pressure of 0.9862.

[d] Total volume of pores filled with nitrogen at a relative partial pressure of 0.9858.

[e] Total volume of pores filled with nitrogen at a relative partial pressure of 0.9799.

4. Discussion

Various methods, such as grinding, swelling, and extraction, were used to induce crystallinity changes. The chemical treatment was found to be the most efficient way to obtain low crystallinity cellulose. Extraction of cellulose from green algae produced a higher crystallinity material than extraction from brown algae. Not only were materials different in their crystallinity but also in their surface texture. Interestingly, the Cladophora cellulose sample was composed of numerous intertwined strings, which produced an aggregate web-like structure of high porosity and large surface area. It should be noted that SEM micrographs of the Cladophora cellulose particles taken previously (Strømme et al., 2002) were of lower magnification (10,000×); hence, fine texture of the Cladophora cellulose particles was not clearly visible.

A unique combination of high porosity, surface area, and crystallinity distinguishes Cladophora cellulose powder from any other cellulose hitherto reported.

The main task of this paper was to investigate how the material's structure affected the moisture sorption process. The results of this study revealed direct relationship between crystallinity and extent of moisture sorption at RHs below 75%: the lower crystallinity of the powder, the higher moisture content. At higher RHs, a sudden increase in the moisture sorption of the Cladophora cellulose sample was observed. A similar increase has been observed earlier in very porous celluloses and was then ascribed to capillary condensation in the pore network (Matsumoto et al., 1998). A comparison between the pore volume obtained by the BET N_2 adsorption analysis of the Cladophora cellulose powder ($0.554\,cm^3/g$) and the amount of water adsorbed at 100% RH ($0.350\,cm^3/g$) shows that the observed increase is related to pore network filling.

It could also be noticed that, even though present in all samples, the hysteresis loop may have different origins for the different samples. The hysteresis loops *at high relative pressures* are often identified in highly porous materials (Sing et al., 1985). They usually arise due to differences in condensation and evaporation occurring in pores with narrow necks and wide bodies, i.e. "ink bottle" pores, or due to differences of menisci during adsorption and desorption in cylindrical pores (Cohan, 1938). The presence of hysteresis *at low relative pressures* is associated with swelling or some other kind of interaction between the sorbate and sorbent in the bulk (Sing et al., 1985). Thus, the hysteresis loop observed in the moisture sorption isotherm of the Cladophora cellulose sample is likely to arise due to the porous texture of this material, whereas in the rest of materials the hysteresis arises mainly due to absorption in the bulk of cellulose particles. Furthermore, the lower the degree of cellulose order, the broader is the hysteresis.

Fig. 5 illustrates the surface area available for moisture sorption as a function of crystallinity. According to contemporary understanding of the cellulose structure, cellulose particles are aggregates composed of coaxial fibrils with abundant fibril-to-fibril contact surfaces (Wickholm et al., 1998). When adsorbed on the fibrilar contact surfaces, water molecules cause swelling and thus further exposure of the bulk (Fig. 6). The ability of water to penetrate the structure and

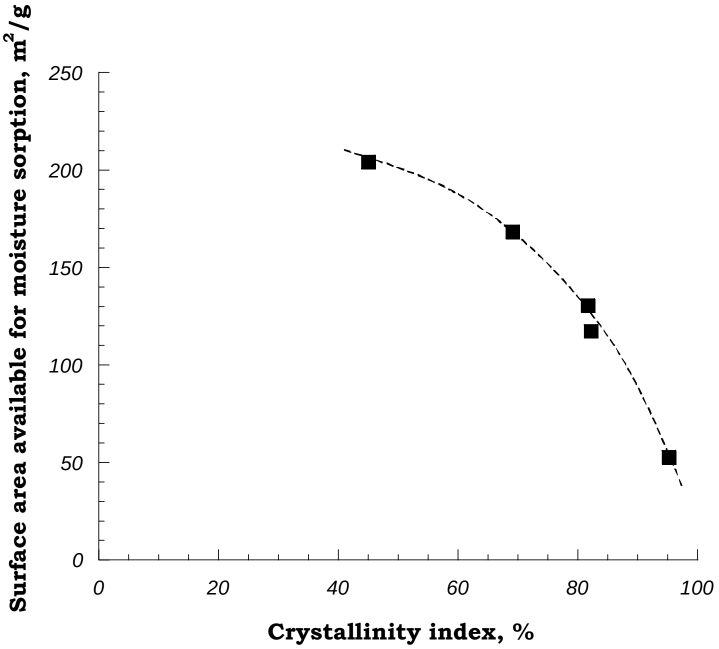

Fig. 5. Surface area vs. crystallinity of cellulose powders. The line is drawn as a guide for the eye.

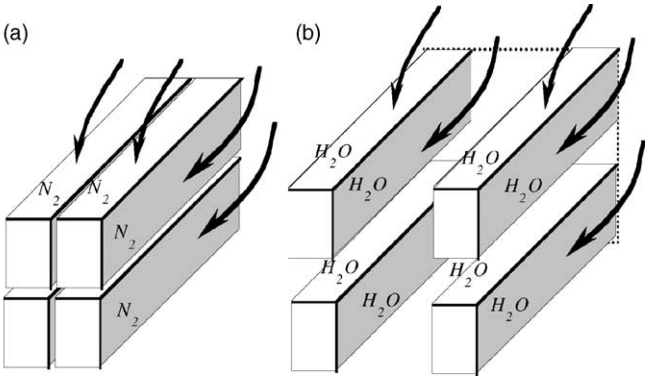

Fig. 6. Schematic representation of vapor sorption by cellulose.

cause swelling will depend on the number of available hydroxyl groups or, in other words, degree of crystallinity (Verlhac et al., 1990). Since gases such as N_2, Kr, or Ar, which are commonly used for BET gas adsorption, do not specifically interact with cellulose, the surface area available for their sorption will be limited to the outer surface of the aggregates only. This is why the surface area values obtained with BET H_2O are orders of magnitude larger than those obtained with N_2 for all the cellulose powders in this study except from the highly crystalline Cladophora cellulose.

5. Conclusions

This study showed that moisture sorption in cellulose is a complex process directly associated with, and controlled by, the structural properties of cellulose, such as surface area, pore volume, and crystallinity. The extent of moisture sorption was shown to decrease with increasing crystallinity of the samples at relative humidities below 75%. At higher relative humidities, filling of the large pore volume of the Cladophora cellulose accounted for the observed increase in moisture content. In conclusion, the structure of cellulose should be thoroughly considered when manufacturing low moisture grades of MCC.

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