The Effect of Moisture on the Mechanical and Powder Flow Properties of Microcrystalline Cellulose

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Purpose. This study determined the effects of moisture on the mechanical and powder flow properties of microcrystalline cellulose. ***Methods.*** A variety of mechanical properties were determined as a function of solid fraction at moisture levels ranging from 0 to 12.2% and included: compaction pressure required to form a compact, dynamic indentation hardness, quasi-static indentation hardness, tensile strength, best case and worst case Bonding Index, Brittle Fracture Index, Strain Index, Compressibility Index and shear cell index. ***Results.*** Significant changes were observed as the moisture level of microcrystalline cellulose increased. The compaction pressure required to produce a compact at a solid fraction of 0.6 decreased with increasing moisture content. The permanent deformation pressure and tensile strength of compacts were observed to be relatively independent of moisture content below about 5% moisture and then decrease as the moisture content increased further. The "best case" Bonding Index was also observed to be independent of moisture content below 5% and then increase with increasing moisture. The Brittle Fracture Index and "worst case" Bonding Index, however, did not appear to be affected by changes in moisture content. Powder flow was shown to decrease with increasing moisture content. ***Conclusions.*** These mechanical property data are consistent with the hypothesis that water acts as a plasticizer and influences the mechanical properties of microcrystalline cellulose. At moisture levels above about 5%, the material exhibits significant changes consistent with a transition from the glassy state to the rubbery state.

KEY WORDS: microcrystalline cellulose; moisture; mechanical properties; flow; tableting indices; compression; hardness; tensile strength; brittleness.

INTRODUCTION

Microcrystalline cellulose is a common tableting excipient used in the pharmaceutical industry. It consists of purified, partially depolymerized cellulose prepared by treating α-cellulose with mineral acids. It exists as a partially amorphous material with microcrystalline regions and serves a number of functions in solid dosage formulations. The moisture content of a typical lot of microcrystalline cellulose is about 3 to 4% while USP monograph specifications limit moisture content to not more than 5%. A number of studies have, in fact, confirmed that the moisture content of microcrystalline cellulose influences such physico-mechanical properties as compaction properties (1), tensile strength (1,2) and viscoelastic properties (3).

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Upon hydration, it has been proposed that the amorphous regions of the material absorb water (4) and that the total amount of sorbed water is proportional to the fraction of amorphous material present in the solid and independent of the surface area (5). Recent work with PVP and other polymeric materials containing amorphous regions suggests that moisture affects the solid properties by acting as a plasticizer as it is absorbed into the amorphous regions, lowering the glass transition temperature (T_g) of the material (4). This change in T_g would be expected to affect the molecular mobility of the solid and produce significant changes in its viscoelastic and mechanical properties. The effects of hydration have, in fact, been seen to change the viscoelastic properties of this excipient over the range of relevant moisture levels (3). These changes would also be expected to have an influence on the mechanical, flow, and tableting properties of the solid. The purpose of this study was to determine the effects of moisture on the mechanical and powder flow properties of microcrystalline cellulose.

MATERIALS AND METHODS

Materials

A single lot of microcrystalline cellulose NF—medium powder (Avicel PH101, Lot 6043, FMC Corporation, Philadelphia, PA) was used in this study. The material was screened prior to use to eliminate any large agglomerates which might be present. The particle size distribution was determined by sonic sifter to be log normally distributed with a geometric mean diameter of 50 μm and a geometric standard deviation of 1.9.

Hydration and Storage

Equilibration of microcrystalline cellulose at various moisture levels was accomplished by placing a thin layer (usually less than 1 cm) of the material into a shallow dish and placing the uncovered dish in a constant humidity atmosphere. Material was periodically mixed to facilitate homogeneity of moisture sorption. Humidity was controlled by one of several methods including: (1) glass chambers containing saturated salt solutions, (2) controlled humidity room, or (3) controlled humidity chamber (ETS Model 512 Automatic Humidity Controller, Cole-Parmer Air Cadet Pressure/Vacuum Pump). Dry microcrystalline cellulose (i.e. 0% moisture) was obtained by drying microcrystalline cellulose for 3 hours at 105°C. The moisture level of the material was determined by loss on drying at regular intervals until a constant level of moisture was achieved. Once equilibration had been reached, the material was double bagged in polyethylene and promptly tested. Exposure of the bagged material outside the constant humidity atmosphere was minimized so that the equilibrium moisture level of the microcrystalline cellulose would be maintained. The moisture content is reported on a % (w/w) basis.

Moisture Determination

The moisture level of the microcrystalline cellulose was

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determined by loss on drying at 105°C as described in USP (6).

True Density Determination

The true density of dried microcrystalline cellulose was determined using a helium-air pycnometer (Micromeritics Model 1305 Multivolume Helium-Air Pycnometer).

Moisture Sorption

The moisture sorption characteristics of microcrystalline cellulose were examined using an automated, controlled atmosphere microbalance. About 10 mg of material was used. The sample was equilibrated on the balance at a low relative humidity (1–2%) until a stable weight was obtained (nominally 1 hour). The moisture uptake was then measured in a sequence of sorption steps, and the moisture loss was subsequently measured in a sequence of desorption steps.

Compact Formation

A specially designed triaxial tablet press (7) was used to prepare compacts of pure microcrystalline cellulose which were free of macroscopic defects such as cracks, laminations, etc. Briefly, 19 mm square compacts were formed by adding an appropriate amount of material to the specially designed split die (7,8,9). The material was compressed and the punch pressure maintained by computer control for 1 minute. By computer control, decompression was then initiated and both the punch and die-wall pressures were released simultaneously in a linear fashion over a 1.5 minute period. Computer control permitted the punch and die-wall pressures to be maintained approximately equal during a majority of the decompression process. This process minimizes the internal stresses within the compact during decompression. Compacts prepared in this way have been shown to be essentially free of macroscopic defects which could influence mechanical property characterization (8,10). By varying the amount of material added to the die, the solid fraction of the compact was varied between approximately 0.5 and 0.7. Compact solid fraction was calculated: (1) by assuming the tablet was homogeneous, (2) by measuring the dimensions of the square compact formed immediately upon removal from the die and (3) on the basis of the weight of microcrystalline cellulose present in each compact by subtracting the weight of the moisture present.

Dynamic Indentation Hardness

A pendulum impact arrangement was used to determine the dynamic hardness of compacts (8,11,12). A pendulum arrangement was formed by suspending a 2.54 cm diameter stainless steel ball from a thin wire 92 cm in length. The stainless steel ball was released from a height corresponding to an angle of 30° and was allowed to strike a compact of microcrystalline cellulose which was held firmly in place on all sides but the front. The diameter of the indentation was subsequently determined using a surface analyzer (9) and the energy consumed in the formation of the indentation was calculated from the rebound height of the stainless steel ball. The dynamic hardness (worst case hardness) was then calculated as previously described (11).

Quasi-static Indentation Hardness

A specially designed multi-function tablet tester (13,14) was used to determine compact hardness under "quasi-static" conditions (15). Briefly, a 2.54 cm diameter stainless steel ball was pressed into a compact of microcrystalline cellulose at a velocity of 0.025 mm/sec a total distance of 0.25 mm and held in place for 15 minutes. During the test, the force applied to the indenter was monitored by computer. On removal of the indenter, the diameter of the indentation was determined as described above and the quasi-static hardness (best-case hardness) of the compact was calculated according to the following equation:

$$H_b = \frac{F_r}{\pi r^2} \quad (1)$$

where F_r is the indentor force at completion of the test and r is the chordal radius of the indentation.

Tensile Strength

The tensile strength of square compacts was determined using the multi-function tablet tester described above. The tensile strength of solid compacts was determined by transverse compression (8). Because variations in the viscoelasticity of the different samples can influence the tensile strength, the rate at which stress was applied to the square compacts was varied such that the time constant (1/e) was maintained in the range of 3 to 5 seconds (15). Platens 0.4 times the width of the square compacts were used to determine the force necessary to cause the tablet to fail in tension. To determine the brittleness of microcrystalline cellulose, the tensile strength of compacts with a hole in the center of the tablet (to serve as a stress concentrator) was also determined and the Brittle Fracture Index calculated (10).

Bonding Indices

Several indices of tableting performance have been developed by Hiestand and coworkers (8,9,10,11,16). These indices provide relative measures of properties which are considered important and which reflect the performance of materials during processing. These include the Bonding Index, Strain Index and the Brittle Fracture Index (8,10). These indices of tableting performance are useful tools in understanding and interpreting the events and processes which are occurring during material compaction. A high Bonding Index, for example, indicates that, relatively speaking, a significant portion of the compact strength (a maximum at the maximum compaction pressure) has survived decompression. Conversely, a low Bonding Index indicates that less of the strength remains. The term Bonding Index, then, is a good description since it, in effect, characterizes the tendency of the material to remain a strong compact after it has been decompressed. Tablets made of materials with poor bonding characteristics may be quite friable. Compacts made of materials with a good Bonding Index may, conversely, make strong tablets.

Hiestand has further refined the concept of Bonding Index to include both a worst case and a best case Bonding Index (8). The Bonding Index is determined under different

experimental conditions such that the viscoelastic properties of the material are assessed. If a material is very viscoelastic, there is substantial stress relaxation with time. The Worst Case Bonding Index is measured using the dynamic indentation method described above where indentor contact with the compact is less than 1 msec. The Best Case Bonding Index is measured using the quasi-static method described above: the indentation was made for a period of 15 minutes.

Strain Index

The Strain Index is an indicator of the relative strain (change in size) during decompression assuming that plastic deformation has occurred (10). Some materials require large stresses to cause a given dimensional change, other materials require relatively less stress to give the same change in dimension. The latter have a low modulus of elasticity and therefore, for a given stress, are going to show a larger change in dimension. The Strain Index is determined from data obtained using the pendulum impact device (8).

Brittle Fracture Index

The Brittle Fracture Index is a measure of the brittleness of a material. It is a measure of the ability of a compact of material to relieve stress by plastic deformation. The Brittle Fracture Index (BFI) is determined (10,8) by comparing the tensile strength of a compact to that of a compact with a small hole (stress concentrator) in it. The hole in the center of the compact generally weakens the tablet. If the material is very brittle, theoretical considerations show that the tensile strength of the tablet will be about 1/3 that of a "solid" tablet. However, if the material can relieve stress by plastic deformation, then the strength of the compact with the hole in it will approach that of a compact with no hole. The Brittle Fracture Index is defined such that very brittle compacts have a BFI of 1 and very non-brittle materials have a BFI close to 0.

Powder Flow

The compressibility index (17) was calculated from the volume occupied by 60.0 g of material in a 250 ml graduated cylinder before and after tapping 2400 times. Simplified shear cell measurements utilizing equipment based on the design of Nash (18) and modified by Hiestand et al. (19,20) were also determined. In general, a yield locus is obtained which relates the shear strength of the powder bed to the consolidation load and reduced load. The yield locus has been found to take the following form (21):

$$\frac{\tau}{\tau_p} = \left(\frac{\sigma + s}{\sigma_p + s}\right)^{1/n} \qquad (2)$$

where τ_p is the shear strength of the powder bed when the consolidation load, σ_p, is applied; τ is the shear strength of the powder bed at the reduced load, σ. The value of S corresponds to the tensile strength of the powder (the negative load at which the shear strength is zero) and n is commonly termed the shear index (related to the curvature of the yield locus) which ranges from a value of 1 for very free flowing materials to approximately 2 for very poor flowing materials.

Tablet Machine Compaction

Tablets of pure microcrystalline cellulose varying in moisture level were compressed on a Manesty B3B 16 station rotary tablet press with standard 1/2" flat beveled B-type tooling in one station. Tablets were compressed to a solid fraction of approximately 0.6 (range 0.58 to 0.60). The solid fraction of the tablets was calculated in the same way as those prepared in the triaxial tablet machine taking into consideration the shape of the beveled tooling. The dimensions of five tablets were determined after completion of compressing. The compression force required to make a tablet of a given solid fraction was determined by manually rolling the punch under the compression cam and recording the maximum compression force.

RESULTS

The true density of dry microcrystalline cellulose was determined to be 1.540 g/cm^3. For these studies, the relative density of compacts was computed using the density of dry microcrystalline cellulose and correcting for the moisture content.

The moisture sorption isotherm determined using an automated, controlled atmosphere microbalance is shown in Figure 1. It is generally accepted that microcrystalline cellulose is adequately described by the GAB equation (22). This equation is similar to the well-known BET sorption equation but includes a third state of sorbed species in addition to the tightly bound and condensed states. The constants determined for the adsorption phase of this lot of microcrystalline cellulose are consistent with those reported in the literature. W_m is equal to 3.62% and corresponds to what is interpreted as monomolecular coverage. The other two constants estimated by nonlinear least squares regression are: C = 9.40 and k = 0.769.

The mechanical properties of microcrystalline cellulose at a variety of moisture contents are reported in Table I. The numerical values are reported and standard errors of the estimated values are reported in parentheses. In general, the standard error in the estimates is less than 5%. The values in Table I were obtained by determining the mechanical prop-

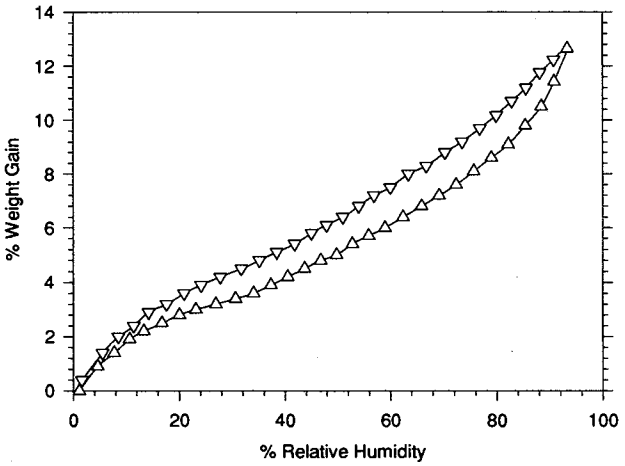

Fig. 1. Moisture sorption isotherm of microcrystalline cellulose for adsorption (△) and desorption phase (▽).

Table I. Mechanical Properties of Microcrystalline Cellulose as a Function of Moisture Content at a Solid Fraction of 0.6[a]

Moisture content, % (w/w)	Mechanical properties (kN/cm²)				Tableting indices				
	σ_t	σ_{to}	H_w	H_b	BFI	BI_w	BI_b	SI	σ_c (kN/cm²)
0.0	.1692	.1574	5.74	1.336	.0375	.0295	.1266	0.025	2.977
	(.0069)	(.0055)	(.14)	(.022)	(.0020)	(.0014)	(.0056)	(0.00004)	(.050)
1.5	.1678	—	8.31	1.331	—	.0202	.126	0.020	2.513
	(.0076)		(.34)	(.075)		(.0012)	(.075)	(0.0014)	(.036)
3.9	.2010	.1698	8.09	1.479	.0919	.0248	.1359	0.019	2.004
	(—)	(—)	(—)	(.022)	(—)	(—)	(.0020)	(—)	(—)
6.9	.1408	.1223	5.24	0.934	.0758	.0269	.1507	0.017	1.497
	(.0063)	(.0011)	(.01)	(.048)	(.0035)	(.0012)	(.0103)	(0.001)	(.043)
7.0	.1536	.1325	8.34	0.974	.0796	.0184	.1577	0.015	1.413
	(.0002)	(—)	(.56)	(.066)	(.0001)	(.0012)	(.0107)	(0.001)	(.010)
9.9	.1224	.1090	4.60	0.688	.0616	.0266	.1779	0.014	1.150
	(.0001)	(.0086)	(.13)	(.007)	(.0048)	(.0007)	(.0017)	(0.0001)	(.021)
12.2	.1013	.0956	3.09	0.526	.0299	.0328	.1927	0.016	0.935
	(.0024)	(.0058)	(.15)	(.013)	(.0019)	(.0018)	(.0065)	(0.0002)	(.015)

[a] The values in parentheses are the standard error of the estimate.

erties of compacts with solid fractions in the range of approximately 0.5 to 0.7. Since the mechanical properties of a compact are dependent on the solid fraction, it is necessary to select a reference solid fraction at which comparisons can be made. Semi-log linear regression analysis has been shown to yield linear relationships for the parameters measured in this study over the range of solid fractions used (8). It was performed on the measured parameters and the value and standard error of the mechanical property were estimated at a solid fraction of 0.6.

The compaction pressure, σ_c, necessary to make square compacts for characterization with a solid fraction of 0.6 was seen to decrease log-linearly with increasing moisture content over the range studied and is shown in Figure 2. The observed changes are significant: a three fold change in compaction pressure was observed as moisture varied from 0% to 12%. Even in the range of moisture content consistent with the USP monograph for microcrystalline cellulose which specifies not more than 5% moisture, there is a significant change in the compaction pressure required to form a tablet of a given solid fraction. These changes are expected to be significant during tableting operations and have been observed when compressing pure microcrystalline cellulose on a rotary tablet machine as seen in Figure 2. The differences in the compaction pressures in Figure 2 could be attributed, at least in part, to different dwell times.

The permanent deformation pressure values (both best case, H_b and worst case, H_w) and tensile strength, σ_t, of compacts at a solid fraction of 0.6 are shown in Figure 3 as a function of moisture content. All three parameters appear to be relatively independent of moisture content up to about 5% moisture. Above this level, there is a noticeable decrease in both deformation pressure values and tensile strength values. In Figure 4, the Best Case Bonding Index, BI_b, is also

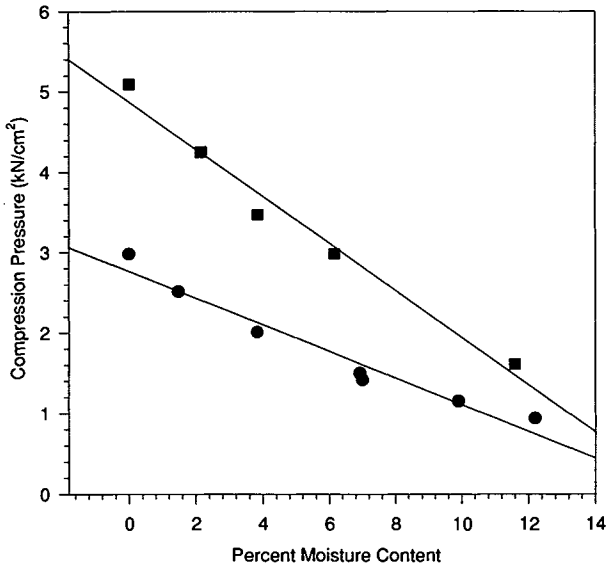

Fig. 2. Compression pressure required to form compacts of microcrystalline cellulose in the triaxial tablet press (●) and on a rotary tablet machine (■) as a function of moisture content. Solid fraction = 0.6.

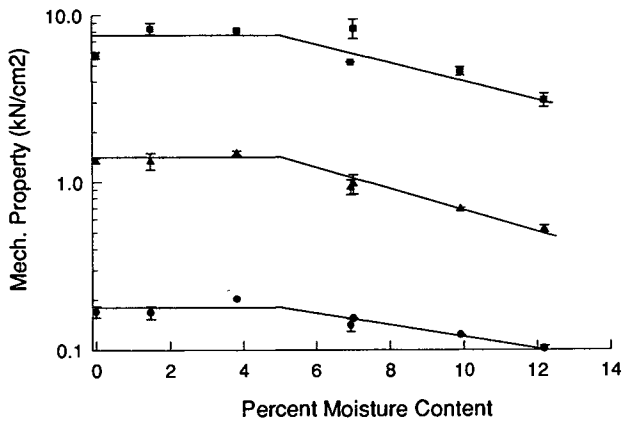

Fig. 3. Mechanical properties of microcrystalline cellulose as a function of moisture content at a solid fraction of 0.6. (■) worst case hardness, H_w; (▲) best case hardness, H_b; (●) tensile strength, σ_t; Error bars indicate 95% confidence interval.

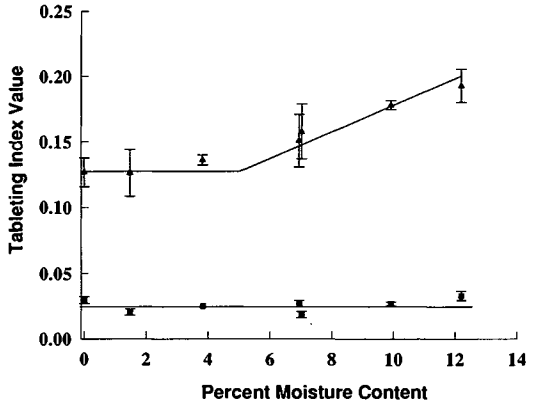

Fig. 4. Tableting indices of microcrystalline cellulose as a function of moisture content. (▲) Best Case Bonding Index, BI_b; (■) Worst Case Bonding Index, BI_w. Error bars indicate 95% confidence interval.

seen to remain essentially constant below 5% moisture then to increase. In contrast, the Worst Case Bonding Index, BI_w, appears to be unchanged over the range studied here.

The flow properties of microcrystalline cellulose were also investigated. Figure 5 shows changes in the bulk and tapped density of the material while Figure 6 shows the Compressibility Index determined from these parameters. A plot of shear cell index value, n, defined in Equation 2 above versus moisture content is shown in Figure 7. The shear cell index value is just one measure of powder flow: it is a measure of the curvature of the yield locus and as such is an indication of the extent to which a material can be overconsolidated.

DISCUSSION

The results of this study demonstrate that a significant change in the mechanical properties of microcrystalline cellulose occurs when moisture content exceeds approximately 5%. Clearly, water is altering the mechanical properties of microcrystalline cellulose, making it more easily deformed and also strengthening the tablet bond. Similar results have been observed by others. Khan and coworkers (1) suggested that, for microcrystalline cellulose, disruption of the hydrogen bonds which cross-link the hydroxyl groups on the cellulose chains occurs with moisture sorption above 3%. They and others (2) have observed the yield pressure of microcrystalline cellulose to decrease with increasing moisture as determined from Heckel plots. As we have seen, they have also observed a plateau in the tensile strength of compacts up to about 3 to 5% moisture, followed by a significant decrease as moisture was further increased.

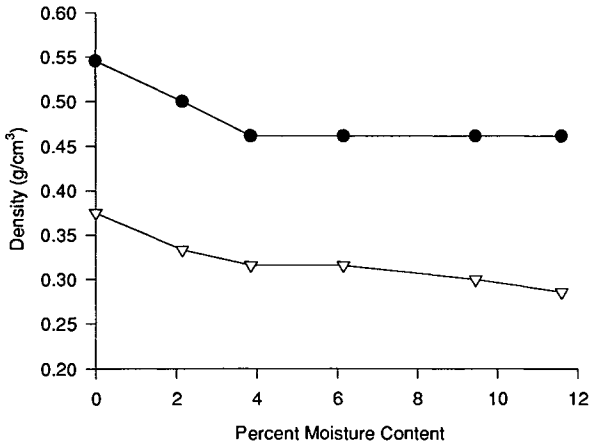

Fig. 5. Density of microcrystalline cellulose as a function of moisture content. (▽) bulk density, g/ml; (●) tapped density, g/ml.

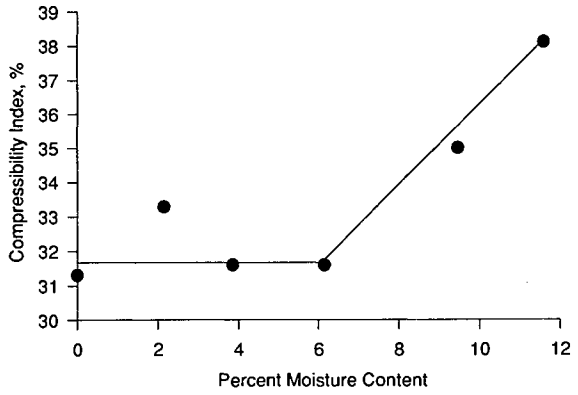

Fig. 6. Compressibility Index of microcrystalline cellulose as a function of moisture content.

While it is difficult to ascribe the changes seen here to a thermodynamic transition with certainty at this point, recent work with amorphous polymers has suggested that water can act as a plasticizer and lower the glass transition temperature, T_g, of the polymer (4). Based on isothermal moisture sorption studies of PVP at several temperatures, Zografi, et al. (4) concluded that the point in the sorption isotherm where upward curvature began to occur correlated with the point at which the T_g was lowered to the experimental temperature (e.g. room temperature). In other words, at the point of upward curvature, the polymer appears to be undergoing a transition from the glassy to the rubbery state with a corresponding increase in moisture uptake.

Based on the work of Oksanen and Zografi for cellulose (23), this point appears to occur at approximately 2 times W_m and is referred to as W_g. If this is true for microcrystalline cellulose, then one would expect it to undergo this ther-

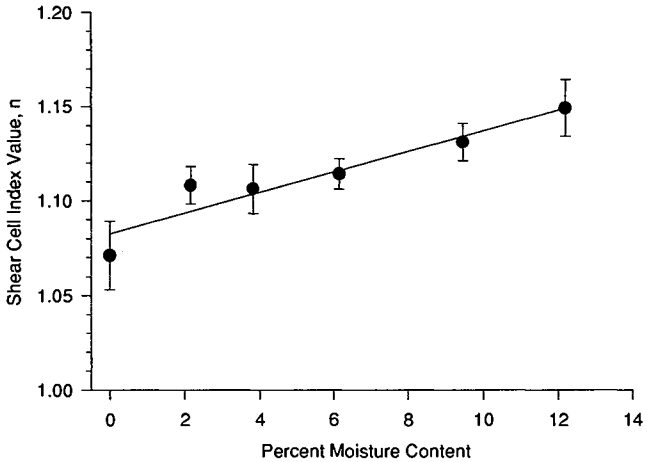

Fig. 7. Shear cell index value, n, of microcrystalline cellulose as a function of moisture content. Error bars indicate 95% confidence interval.

modynamic transition when the moisture content of microcrystalline cellulose (not corrected for crystallinity) reached approximately 7.2% moisture. This is consistent with the lot of microcrystalline cellulose studied here as upward curvature occurs between approximately 5% and 7% moisture in Figure 1. The effect of water on the glass transition temperature can also be estimated by applying the Simha-Boyer approximation to the Gordon Taylor equation (24,25) if the densities of the two components and the glass transition temperatures of the pure components are known. Assuming the glass transition temperature of microcrystalline cellulose is 412°K (26), that for water is 135°K, and correcting for the fact that microcrystalline cellulose is approximately 63% crystalline (27,28), the glass transition temperature of the amorphous regions would be predicted to equal 25°C when the moisture content is equal to 5%. This is very close to the point at which the mechanical properties are seen to change significantly.

Still more recent work by Hancock and Zografi (29) applying regular solution theories to moisture sorption has suggested that W_m may be related to T_g. However, it is notable that significant changes in the tableting and mechanical properties of microcrystalline cellulose are observed as the moisture content exceeds approximately 5% moisture as seen in Figure 3. Based on this work, it is difficult to argue convincingly that either W_m or W_g is the critical value beyond which an abrupt change in properties is to occur. In fact, one might expect that there would be a region over which a transition in mechanical properties could occur. However, it is safe to say that changes would logically be expected to occur between W_m and W_g and, in fact, it is in this region that changes in the deformation pressure (H_b, H_w), bonding (BI_b), and the tensile strength (σ_T) of compacts are seen.

Figure 4 shows the changes in the Bonding Indices. The Best Case Bonding Index, BI_b, shows significant changes while the Worst Case Bonding Index, BI_w, shows little or no change. An increase in the Bonding Index might be expected, a priori, as one would expect that a material which is more easily deformed (lower permanent deformation pressure) would form better bond since the true area of contact between particles would likely be increased (note, however, that this may not necessarily be the case (16,9)). This is the case for the Best Case Bonding Index in Figure 4. The Worst Case Bonding Index, however, does not change even though the permanent deformation pressure decreases. In part, this occurs because, while there is a decrease in the deformation pressure, H_w, there is also a significant decrease in the tensile strength of the tablets. One explanation is that there is a decrease in the "bond" between individual particles as moisture increases such that, even though the material is more easily deformed, the strength of the compact after decompression is reduced. This is seen as a decrease in the tensile strength of the tablets since it is a measure of the strength of interparticle bonds. This can occur through disruption of the hydrogen bonds which cross-link the hydroxyl groups on the cellulose chains as moisture content increases. This leads to no net gain in bond under dynamic conditions and perhaps less of an increase in bond under the quasi-static conditions used here. Finally, microcrystalline cellulose appears to be quite viscoelastic as evidenced by the large differences between the dynamic permanent deformation pressure, H_w, and the quasi-static deformation pressure, H_b. Viscoelastic properties can also influence the tensile strength and Bonding Index values.

Also of interest is the observed change in the Strain Index as seen in Table I. A monotonic decrease in the SI is noted over the range of 0 to about 5% moisture, followed by a plateau region above 7% moisture where no further change in the Strain Index is detected. This data shows, as does the compaction pressure data, that changes in the tableting properties do in fact occur below the critical moisture content of about 5%. The lower SI as moisture increases indicates that the material exhibits less dimensional change as the moisture content increases. The SI at all moisture levels is not large when compared to materials such as methenamine and erythromycin which exhibit large dimensional changes (8).

It is well documented in the literature that microcrystalline cellulose is not a brittle material and the values of the Brittle Fracture Index (BFI) in Table I show this to be the case for the range of moisture contents studied here as all the BFI values are less than 0.1. Consistent with the hypothesis that microcrystalline cellulose is plasticized as moisture content is increased, a decrease in the brittleness is noted as moisture content increases from the 3.9% level to 12.2% in Table I.

Since bulk and tapped density are important physical properties, they were also measured as a function of moisture content and the results shown in Figure 5. The Compressibility Index (30) was calculated and is seen to increase substantially as moisture content is increased above 6% moisture. For bulk and tapped density, a decrease is seen until the critical moisture content is reached, followed by a plateau. Here again, there appears to be a break in the critical moisture range between W_m and W_g.

Flow properties were also measured using a simplified shear cell. A plot of shear cell index value, n, versus moisture content is shown in Figure 7. The shear cell index value is just one measure of powder flow: it is a measure of the curvature of the yield locus and as such is an indication of the extent to which a material can be over-consolidated. An index value greater than 1 indicates deviation from linearity and the greater the value, generally the poorer flowing the material is. Previous experience indicates that materials with an n value greater than 1.1 are not very free flowing. As seen in Figure 7 there is a clear increase in shear cell index value with increasing moisture content. These observations are consistent with previous work from this laboratory on ibuprofen lots (31,32) in which materials with lower deformation pressures and/or higher Bonding Indices were poorer flowing materials. Again, this is expected since materials which are easily deformed would be expected to bond together during even the more limited consolidation which occurs in a powder bed. These data also demonstrate that the mechanical properties of a material alone, can influence powder flow since the particle size and shape are effectively a constant in this case.

CONCLUSIONS

Mechanical property characterization carried out in this study has shown that the mechanical properties of micro-

crystalline cellulose are significantly influenced by the amount of moisture present. The powder flow properties were also influenced by moisture content. These mechanical property data are consistent with the hypothesis that water acts as a plasticizer and influences the mechanical properties of microcrystalline cellulose over the range of moisture studied. Furthermore, at moisture levels above about 5%, the material exhibits significant changes consistent with a transition from the glassy state to the rubbery state. At moisture levels below 5%, less change in mechanical and flow properties were detected.

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