DRUG DEVELOPMENT AND INDUSTRIAL PHARMACY, 16(1), 31-54 (1990)

THE EFFECT OF PARTICLE AND POWDER PROPERTIES ON THE MECHANICAL PROPERTIES OF DIRECTLY COMPRESSED CELLULOSE TABLETS

Timo Pesonen and Petteri Paronen

Department of Pharmaceutical Technology,
University of Kuopio
POB 6, 70211 Kuopio, Finland

ABSTRACT

The inherent material properties of four cellulose powders were evaluated and the effect of these properties on the mechanical strength and surface hardness of direct compression tablets was studied. Two of the materials studied were microcrystalline celluloses, Emcocel and Avicel PH 101, whereas the other two were experimental cellulose powders, an agglomerated cellulose and a depolymerized cellulose.

The agglomerated cellulose powder formed the strongest as well as the hardest tablets. Also both microcrystalline celluloses formed clearly stronger tablets than depolymerized cellulose, but surface hardness of the tablets compressed using these three cellulose powders was, however, quite similar.

The most important material property affecting the breaking strength of tablets was the spesific surface area of the starting material. No correlation between crystallinity, particle size or particle shape of starting material and the strength of tablets was observed.

The surface hardness of tablets showed no simple correlation with the breaking strength of tablets or with any single material property of cellulose powders. It is obvious, that an extensive consolidation of tablet structure during compaction could affect markedly the hardness of the compact surface, thus possibly masking the effect of a single material property.

INTRODUCTION

Because of its fibrous nature, the untreated wood cellulose is not useful in tableting. Both mechanical and chemical processes have been used to convert the wood cellulose into powdered form. These processes have included various stages, such as grinding, milling, granulation, spray drying, homogeneous or heterogeneous hydrolysis and depolymerization of cellulose (1,2,3). Although the celluloses produced using different methods do not differ from their chemical nature, their physical properties such as crystallinity, degree of polymerization, particle size and size distribution, apparent particle density and spesific surface area are, depending on the manufacturing method used, different.

Microcrystalline cellulose is the best binding materials available for direct compression. Extensive hydrogen bonding, large particle surface area and mechanical interlocking of irregular particles have been mentioned to contribute the excellent binding properties of this material (4,5), but on the other hand, the effect of crystallinity, particle size and shape on the mechanical properties of cellulose tablets have been questioned (6). Fuhrer (7), however, has stated the importance of crystallographic state of material saying, that it affects even more than the chemical nature of the material the tendency of the material to undergo plastic deformation, which is essential in the formation of a strong tablet (8,9,10).

Recently Pesonen et al. (11,12) reported the excellent tableting properties of a new microcrystalline cellulose powder, Emcocel, and a novel agglomerated cellulose powder. The aim of this study was to evaluate the effect of the crystal, particle and powder properties of these two cellulose powders and those of two other cellulose powders on the strength and hardness of direct compression tablets.

MATERIALS AND METHODS

Materials

Four cellulose powders with different crystal, particle and powder properties were studied. Microcrystalline celluloses, Avicel PH 101 and Emcocel were manufactured by FMC Corporation, Philadelphia, USA and Finnish Sugar Ltd, Kantvik, Finland, respectively. Experimental agglomerated cellulose powder and experimental depolymerized cellulose powder used in this study were both supplied by Finnish Sugar Ltd. (Kantvik, Finland). The agglomerated cellulose powder was manufactured from purified cellulose flocs using a physico-chemical agglomerating process and this material is referred in this study as ACP. The manufacturing method of the depolymerized cellulose powder involves first a dissolution of a cellulose, then a homogeneous hydrolyse in both amorphous and crystalline parts of cellulose and after that a precipitation of cellulose from the solvent. This material is referred in this study as DCP.

Methods

The crystal properties of the cellulose powders were studied with the X-ray diffractometric EDXD-method (13). Background index was calculated by dividing the intensity of the background level corresponding the largest peak in pattern with the intensity of the largest peak in pattern (the reflection of the crystal plane 002). The larger the background index the more amorphous the material (14).

Projected and volumetric size distributions as well as the particle shape factor, circularity, were measured as previously (11). Circularity is the ratio of a diameter of a circle having the same projected area as the projected area of the particle to the maximum diameter of the particle. The largest theoretical value for this parameter for an absolutely spherical particle is unity.

Water content, apparent particle density and bulk density using pouring method for the cellulose powders were determined as previously (11). The specific surface area for the cellulose powders was determined both using the adsorption of nitrogen gas at the boiling point of liquid nitrogen, BET-method (Orr Surface Area and Pore Volume Analyzer, Model 2100, Micromeritics, Georgia, USA) and using the penetration of mercury at high pressures (Pore Sizer 9310, Micromeritics, Georgia, USA). Bulk density, cumulative surface area and intraparticle pore size distribution were also determined using the latter method.

The parameter cohesiveness, which is related to the cohesion of the cellulose powders was obtained with a tapping density treatment using a modified Neumann apparatus and treating the data with Kawakita's equation (11,12).

Separately pre-weighed quantities of 300 mg of cellulose powders were manually filled into 13 mm die and compressed at the speed of 35 tablets/min using an instrumented Korsch EK-O single punch tablet machine (FRG).

The mechanical strength of tablets was determined about 24 hours after compression. The diametrical breaking strength of ten tablets was measured with Schleuniger 2E-apparatus (Switzerland). Friability of six tablets was tested with Roche friabilator (Erweka, FRG).

The surface hardness of the tablets was determined using an apparatus originally constructed to determine the elastical properties of a cartillage (15). The load of 0.2 N was transmitted onto the tablet surface through a cylindrical plane-ended steel intender with a diameter of 400 um. The depression on tablet surface was measured after 15 seconds loading by the means of an inductive displacement transducer connected to the upper part of the intender. The smaller the depression the harder the tablet is. The measurement was carried out at three different points across the tablet surface. Both upper and lower punch faces of three tablets produced using either 30 MPa or 90 MPa compressional pressure were examined.

RESULTS AND DISCUSSION

Crystal Properties

The degree of crystallinity, measured with X-ray diffraction method, has previously been noticed to be between 53 % and 82 % for microcrystalline celluloses and between 26 % and 61 % for powdered celluloses (16). The degree of crystallinity measured in this study was 63 % and 68 % for microcrystalline celluloses, Avicel and Emcocel, respectively. The crystallinity of DCP was 61 %. Thus the differences between these three materials were rather small. DCP, however, owned the largest intensity peak at the 002 reflection, but also a significant high background level at the point of pattern. This pointed out the dualistic nature of this cellulose material. There seems to be both rather crystalline and amorphous regions in this material.

The degree of crystallinity for ACP, 49.5 %, was smaller than previously measured for microcrystalline celluloses (16). Thus this material was clearly more amorphous than the three other celluloses studied.

Particle Properties

According to scanning electron micrographs both Avicel and Emcocel were consisted of rather irregular large particles and

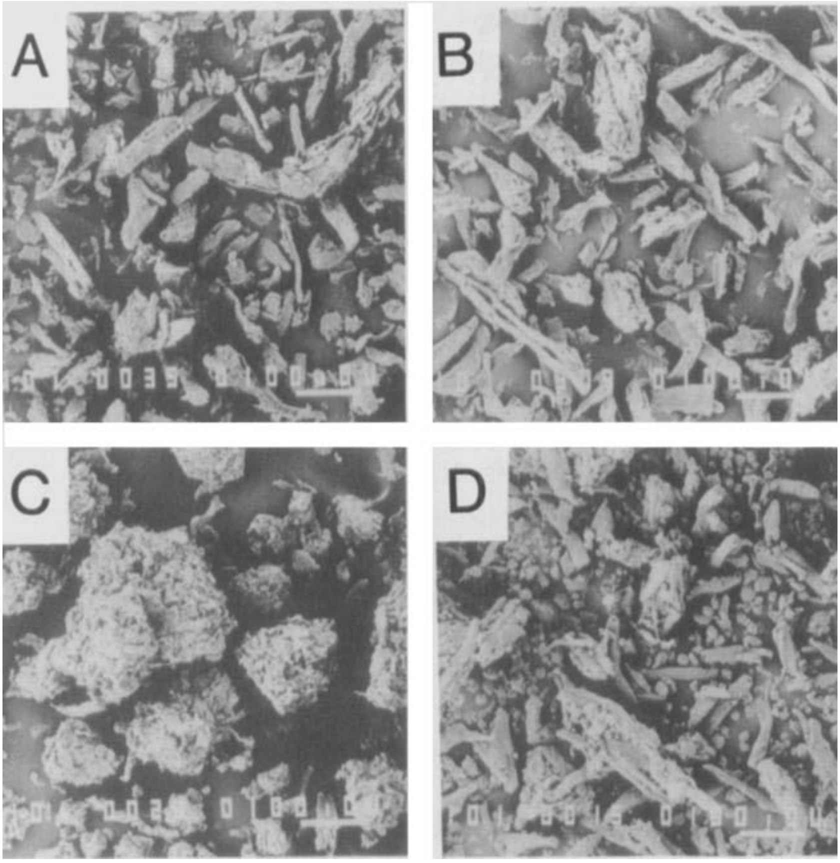

FIGURE 1
Scanning electron micrographs. Avicel PH 101 (A), Emcocel (B), ACP (C) and DCP (D). Bar is 100 um.

more regularly shaped small particles (Fig. 1). DCP powder contained a large amount of small and spherical particles and among them larger rod-like particles. The surface of all the DCP particles seemed to be clearly more even than in any other cellulose powders studied. ACP contained spherical large agglomerates of particles and among them smaller spherical particles. Although the agglomerates of ACP were spherical in form, their surface was very uneven indicating a large porosity of these particles.

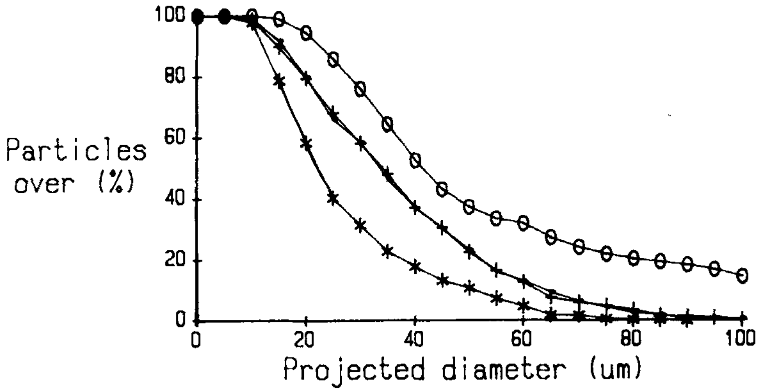

FIGURE 2
Cumulative particle size distribution based on projected particle diameter. Avicel PH 101 (—●—), Emcocel (+), ACP (-θ-) and DCP (✱).

The particle size distributions based on projected and volumetric particle diameters (Fig. 2 and 3) showed that the particle size was clearly largest for ACP and smallest for DCP. ACP also had the widest and DCP the narrowest size distribution. Projected particle size distribution was identical for Avicel and Emcocel. The volumetric size distribution for Avicel was, however, clearly smaller than that of Emcocel. The difference in the volumetric size distributions between Avicel and Emcocel has previously suggested to be due to the difference in the amount of real aggregates of particles and also in the bonding strength of these aggregates (11). Loosely bonded particle flocs of Avicel were obviously more prone to be broken during the ultrasonic procedure than the flocs in Emcocel prior to the volumetric size distribution measurement.

The circularity values (Table 1) pointed out that the mean particle shape was most spherical for ACP and DCP. However, when circularity was plotted against the projected particle diameter it was clearly seen that the large circularity value of DCP was strongly affected by the large amount of very small and spherical particles (Fig. 4). The mean circularity of Avicel and

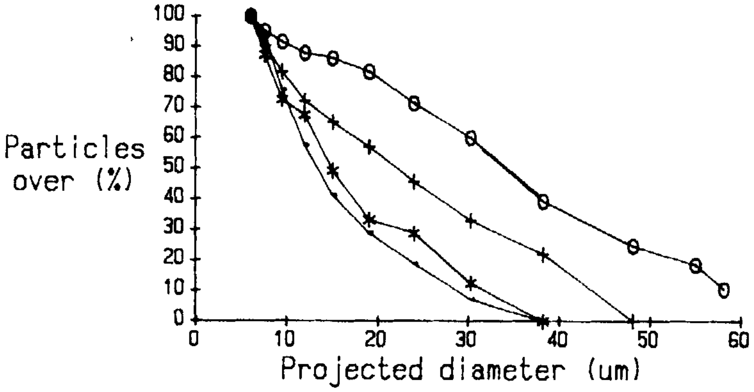

FIGURE 3
Cumulative particle size distribution based on volumetric particle diameter. Key as in Fig. 2.

TABLE 1

The values of particle and powder properties with the standard error of the mean for Avicel PH 101, Emcocel, ACP and DCP.

	Avicel PH 101	Emcocel	ACP	DCP
circularity(-)	0.78(0.01)	0.78(0.01)	0.84(0.01)	0.84(0.01)
intraparticle porosity (cm^3)	0.14	0.09	0.37	0.02
cumulative surface area (m^2/g)[1]	1.34	0.81	13.99	0.40
specific surface area (m^2/g)[2]	1.26(0.03)	1.27(0.01)	63.03(0.28)	0.47(0.01)
bulk density (g/cm^3)[3]	0.26(0.00)	0.23(0.00)	0.28(0.01)	0.40(0.01)
bulk density (g/cm^3)[4]	0.35	0.31	0.42	0.41
apparent particle density (g/cm^3)	1.52(0.00)	1.52(0.00)	1.50(0.00)	1.52(0.00)
cohesiveness(-)	7.5(0.2)	7.3(0.3)	5.6(0.3)	5.1(0.3)
water content (%)	4.9(0.0)	4.6(0.1)	3.5(0.1)	4.3(0.2)

[1] mercury penetration
[2] adsorption of nitrogen gas
[3] measured by pouring a preweighed sample into measuring cylinder
[4] measured by mercury penetration at zero pressure

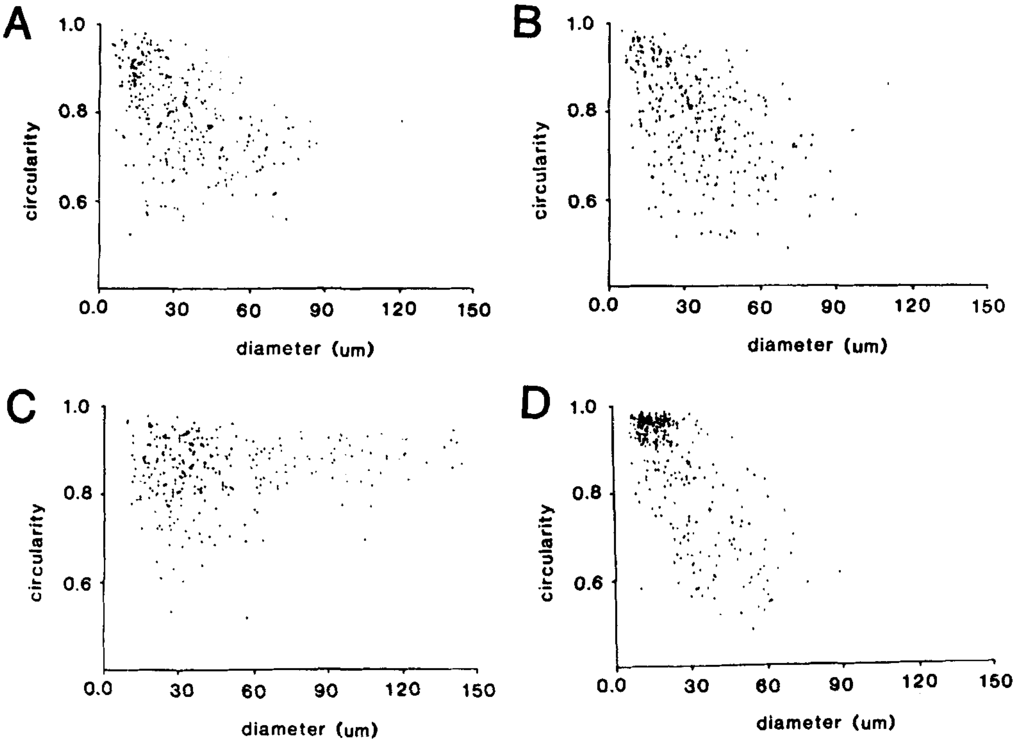

FIGURE 4
Particle shape factor, circularity, as a function of projected particle diameter key as in Fig. 1.

Emcocel particles was smaller and thus their mean particle shape was more irregular than those of ACP and DCP, but not so irregular as sometimes described (4). The calculated circularities for a rectangular having the longer side either three times or two times the length of the shorter side are 0.767 and 0.836, respectively. Thus the definition match-like for microcrystalline cellulose particles is rather misleading. The mean circularity without the distribution data might also lead to wrong conclusion as in the case of ACP and DCP. The correlations based on regression analysis between the particle shape and diameter were -0.72, -0.48 and -0.44 for DCP, Emcocel and Avicel respectively, but +0.11 for ACP showing a strong dependence between these two factors ($|r|$ >0.6) for ECP, moderate dependence (0.3< $|r|$ <0.6) for Avicel and Emcocel and practically no dependence for ACP.

Powder Properties

Water content and apparent particle density were rather similar for all the celluloses, but the specific surface area varied remarkably between the materials (Table 1). There was a clear correlation between the visually seen eveness of particle surface and specific surface area. ACP with a rough and very porous inner and outer surface of agglomerates owned markedly larger spesific surface area than the other three celluloses studied. Avicel particles have been described to be porous (1). However, in comparison with ACP both Avicel and Emcocel had only a moderate intraparticle porosity and only a small specific surface area (Table 1). The surface of DCP particles was very even with very small inside porosity and thus the specific surface area of this materials was only one third of those of Avicel and Emcocel. The pore size distribution inside the cellulose particles i.e. intraparticle porosity at the region of pore diameter below 2 um, showed that DCP had no pores with the diameter smaller than 0.85 um resulting to the cumulative surface area of 0.4 m^2/g, which correlated well with the specific surface area measured using the BET-method (Fig. 6).

Both the intraparticle pore size distribution and specific surface area, obtained with mercury penetration, were different between Avicel and Emcocel (Fig. 5 and 6). The surface area obtained using the BET-method was, however, the same for these materials (Table 1). The adsorption of nitrogen took into account also the smallest intraparticle pores, having diameters clearly below 10 nm, into which mercury could not penetrate. Thus the intraparticle pore size distribution of Avicel and Emcocel was different. Emcocel may own volumetrically very small, but on the basis of surface area larger amount of small

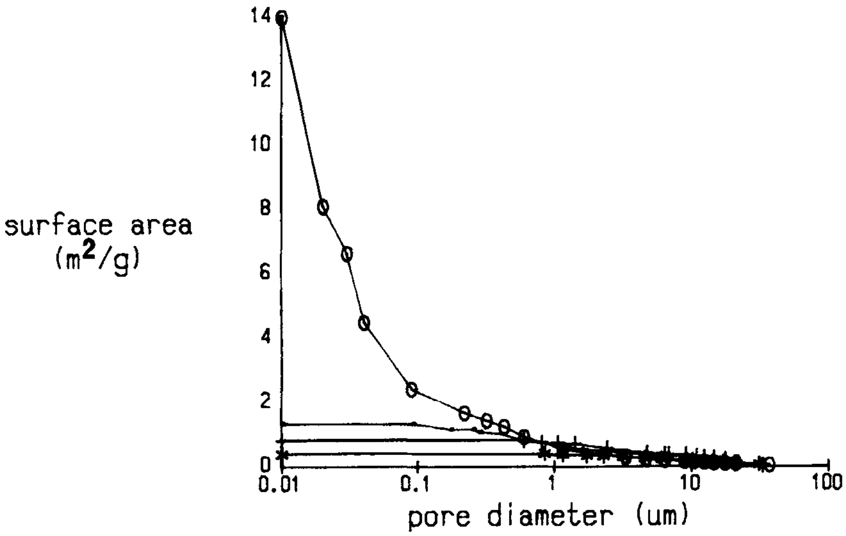

FIGURE 5
Cumulative surface area of cellulose powders as a function of pore diameter. Key as in Fig. 2.

pores than Avicel. The effect of these pores, having a diameter clearly smaller than 10 nm, is not possible to see in Figure 6. The cumulative surface area of Avicel powder obtained using mercury penetration as well as the specific surface area measured using adsorption of nitrogen gas were nearly the same, correlating well with the values obtained by Zografi et al. (17). However, at very high pressures the mercury penetration method gave to Avicel powder little larger surface area than the BET-method did (Table 1). This phenomen, which did not occur with other cellulose materials studied, could indicate a relaxation in particle structure of Avicel at high pressures when mercury was forced into smaller and smaller pores. Thus the pore diameter of 10 nm was taken to lower limit, when intraparticle porosity was studied with the mercury penetration method.

Both the values of surface area as well as intraparticle porosity were markedly different for ACP than for any other

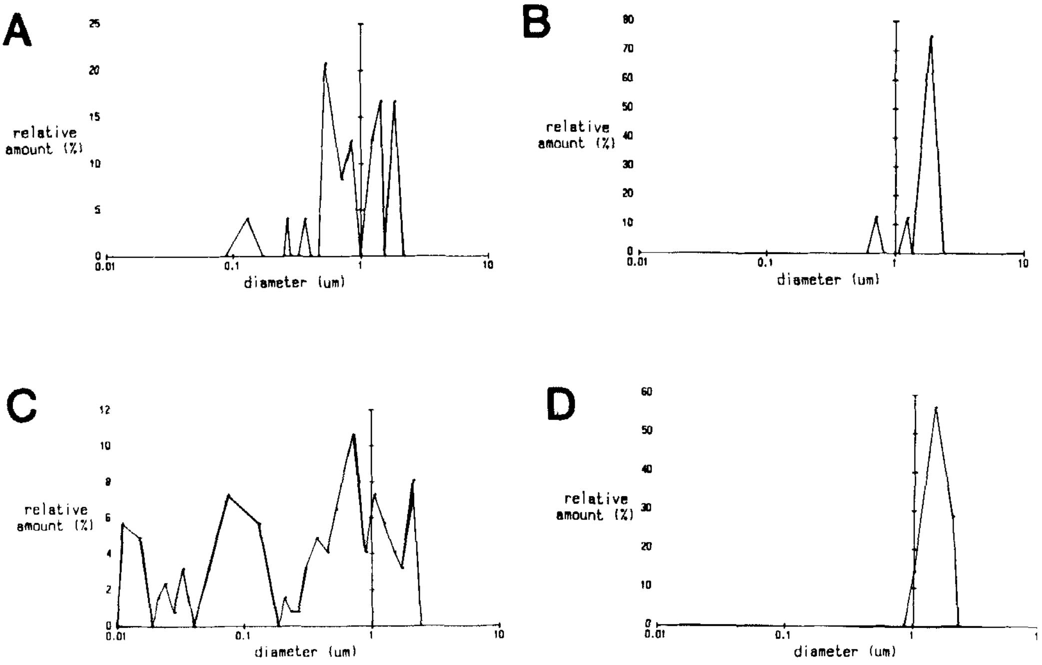

FIGURE 6
Inraparticle pore size distribution as a function of pore diameter. Key as in Fig. 1.

celluloses studied. The cumulative surface area at the point corresponding to the pore diameter of 2.5 um was smaller for ACP than for Avicel and Emcocel (Fig. 5). This was due to the clearly smaller particle size of Avicel and Emcocel. Thus their interparticle surface, which did not took into account the pores, was larger than that of large agglomerates of ACP. However, at the region of intraparticle pores the surface area of ACP became clearly largest and at the point corresponding to the pore diameter of 10 nm it was about 14 m^2/g and at the point of pore diameter of 6 nm over 36 m^2/g (fig. 5). As mentioned earlier, at high pressures there might occur relaxation in the structure of the studied material. The mercury penetration results, however, showed a good correlation with the huge specific surface area obtained with BET-method for ACP confirming the visual conclusions (Fig. 1) of the very porous structure of agglomerated cellulose particles or agglomerates.

Bulk density value measured by pouring method was clearly largest for DCP powder (Table 1). This was due, to the regular particle shape and even particle surface. Thus at the bulk state the cohesion between the particles was small. The term cohesiveness calculated from the tapping treatment also showed smallest cohesion for DCP particles (Table 1). The possible mechanical interlocking between DCP particles should thus be small compared to that of Avicel and Emcocel particles. The bulk densities measured by pouring method for the other three celluloses did not differ remarkably. The term cohesiveness showed, that ACP had smaller cohesiveness and thus mechanical interlocking between particles should be smaller than in Avicel and Emcocel powders. It could thus be expected, that ACP would be packed more closely than Avicel and Emcocel. The bulk density value for ACP obtained with the pouring method was obviously affected by the large particle size. Thus a great amount of air existed between the particles. This assumption was supported by the bulk density values measured using mercury penetration at the minimum pressure (Table 1).

Mechanical Strength Of Tablets

According to Huttenrauch's activation theory (18) small particles usually lead to larger friction during compression causing greater activation of particles. These activated particles are more capable of bond forming and thus formation of strong tablets. Huttenrauch, however, pointed out that compact lattice and lattice energy affect significantly the situation during tableting and only when these factors are known it may be possible to estimate the effect of particle size on tablet strength. Wallace et al. (19) did not, despite the clear difference in particle size, observe a significant difference in tablet strength between the tablets compressed from Avicel PH

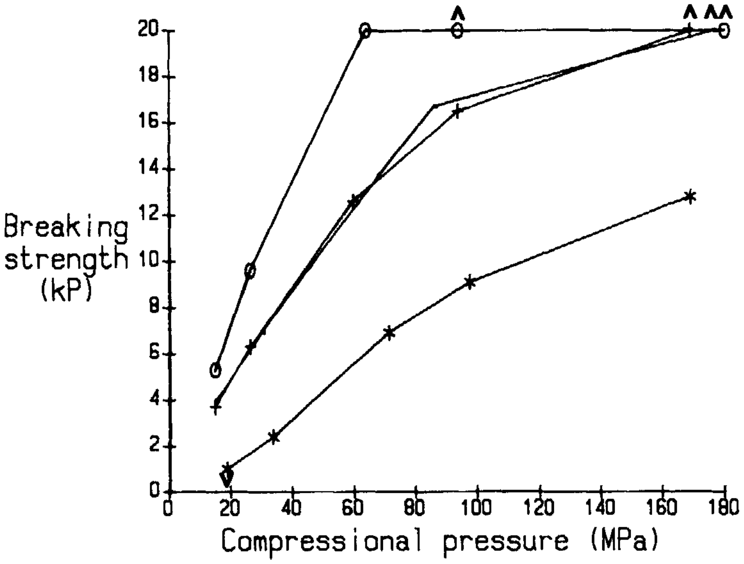

FIGURE 7
Breaking strength of plain cellulose tablets as a function of compressional pressure. The arrows indicate values over 20 kp and the bars indicate the standard error of the mean. Key as in Fig. 2.

101 and from Avicel PH 102. Also our results disagreed with the concept, that smaller particles produce stronger tablets (Fig. 2,3 and 7). In fact DCP owned the smallest particle size but produced the weakest tablets and ACP owned the largest particle size, but produced the strongest tablets.

Bolhuis and Lerk (4) have related the ability of microcrystalline cellulose to produce strong tablets with the match-like particle structure of this material. According to their results the mechanical interlocking of irregular cellulose particles should lead to effective hydrogen bonding. Doelker et al. (6), however, pointed out in their study concerning four microcrystalline celluloses and four powdered celluloses, that particle shape and size had no definite effect on the mechanical properties of cellulose tablets and that the mechanical interlocking of particles does not play a significant role on

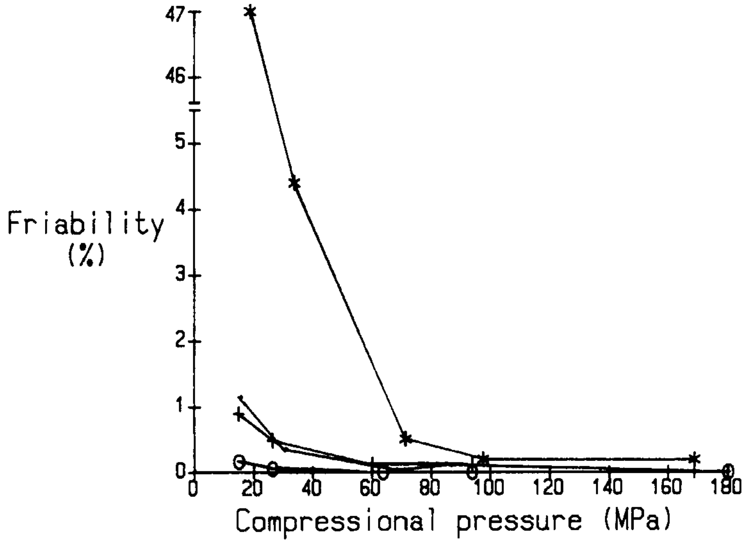

FIGURE 8
Friability of plain cellulose tablets as a function of compressional pressure. The bars indicate the standard error of the mean. Key as in Fig. 2.

the mechanical strength of cellulose tablets. According to the results of the present study Avicel and Emcocel owned the most irregular particle shape, but formed clearly weaker tablets than ACP (Fig. 7 and 8). On the other hand, Avicel and Emcocel formed significantly stronger tablets than DCP. The difference in tablet strength between Avicel, Emcocel and DCP may partially be due to the more uneven particle surface of Avicel and Emcocel particles. However, this difference could be actually described as a difference in rugosity in particle surface and not in particle shape. Thus in agreement with the results of Doelker et al. (6), no clear relationship between tablet strength and particle size and shape of cellulose particles was observed.

The energy produced by compressional pressure is partially stored in the form of lattice defects (18). This leads to an activated state of a solid material. Solid particles own an increased physical reactivity and may reach a sinter-like coherence during compression. Also the initial dislocations in the lattice of the material to be compressed support the plastic deformation of this material. Some manufacturing processes, e.g. spray drying, often produce very imperfect or even amorphous substances, which in accordance with the activation theory own high deformability and form strong compacts. ACP, with the most amorphous crystal structure might posses the most activated inherent structure and thus the greatest tendency to deformate. The difference in the total degree of amorphous phase between Avicel, Emcocel and DCP was only trivial. Thus according to inherent crystal properties these materials should be equal prone to deformation and formation of a strong compact. Avicel and Emcocel, however, produced clearly stronger tablets than DCP. Thus no clear correlation between the crystallinity of cellulose powders and the strength of tablets was observed.

Huttenrauch (11) pointed out, that a large contact area between particles performs a pre-requisite to bring binding forces into effect. Summers et al. (20) concluded their study concerning the strength of tablets compressed using three differently crystalline materials, that the wideness of the contact area between particles had an overriding influence compared to the influence of bond types and corresponding bond strength on the mechanical strength of the compressed tablet. Hiestand (21) has pointed out that for nearly all organic materials the attraction per unit area of true contact is of the same order of magnitude. Thus the differences in bond strength must mainly result from differences in the area of true contact.

Marshall and Sixsmith (22) have shown, that surface energies are of the same order for four grades of Avicel. Lamberson and Raynor (1) have related the ability of microcrystalline cellulose to form strong tablets especially, firstly, to the ability to deform plastically and, secondly, to the large surface area brought into contact during plastic deformation. The observed properties of the cellulose powders evaluated in this study were in accordance with the above mentioned references. ACP owned a very porous structure with a wide intraparticle or intra-agglomerate pore size distribution resulting to a huge specific surface area. Due to both the possible ability to deform easily and the very large surface area it is easy to understand, that this material produced very strong tablets.

The clearly smallest strength of DCP tablets agreed well with the extent of surface area of cellulose powders. DCP had only one third of the surface area of Avicel and Emcocel and thus much smaller true contact area for bonding. In addition the even particle surface of DCP particles created a minimal possibility for particles to stick together as well as for the mechanical activation of particles by frictional forces during compression. Thus a clear correlation between the strength of cellulose tablets and the surface area of cellulose powders was observed.

Hardness Of Tablets

Aulton (23) and Ridgway et al. (24) have pointed out that, despite the precise measuring method the deviation of indentation hardness results is large, about 10-20 %. This is an inevitable consequence of employing a point determination method on heterogeneous and anisotropic surface (23). Thus the relatively large scatter observed in the present study, below 12 % in every case, agreed with the above mentioned values.

Aulton (23) noticed, that the variation in hardness across the tablet surface was less with some materials than with other materials. He therefore suggested , that indentation hardness is an easy, although indirect, method of predicting pressure transmission and distribution in tablets during compaction. The deviations in the hardness values across the tablet surface was smallest in ACP tablets. Thus the compressional pressure was most effectively transmitted and most uniformely distributed in ACP tablets. This was due to the effective plastic deformation

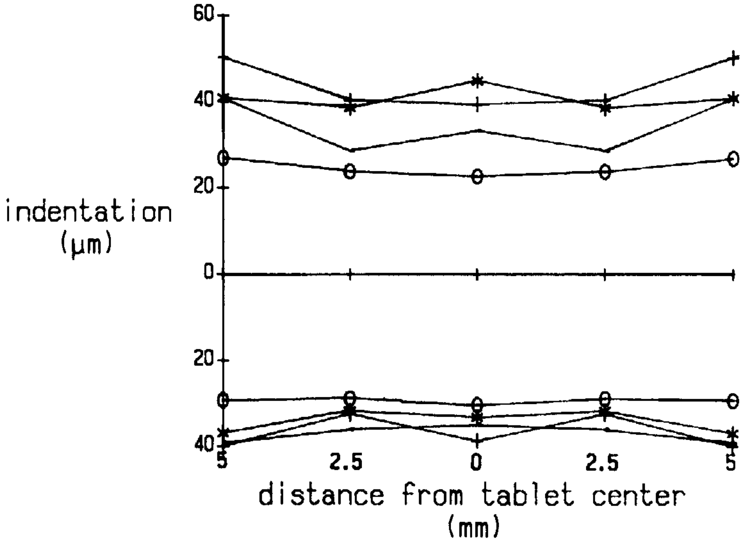

FIGURE 9
Surface hardness of a tablet across the tablet surface. Upper punch surface on the top and lower punch surface on the bottom. Tablets were compressed at 30 MPa compressional pressure. Key as in Fig. 2.

of agglomerates, which resulted in a homogeneous and dense tablet surface. The difference between ACP tablets and other cellulose tablets was most pronounced when tablets were compressed using a small compressional force (Fig. 9). No clear difference between the other cellulose materials was observed (Fig. 9 and 10).

Hardness is a measure of the resistance of a solid material against lattice destruction and is considered to be a function of the interatomic forces and the stress required to move dislocations (23). ACP tablets owned the hardest surface in all the tablets studied (Fig. 9 and 10). Thus according to the above mentioned description this material should own the most rigid crystal structure and thus have had the largest resistance against lattice destruction. The most amorphous crystal structure of ACP and thus the obvious ability of this material

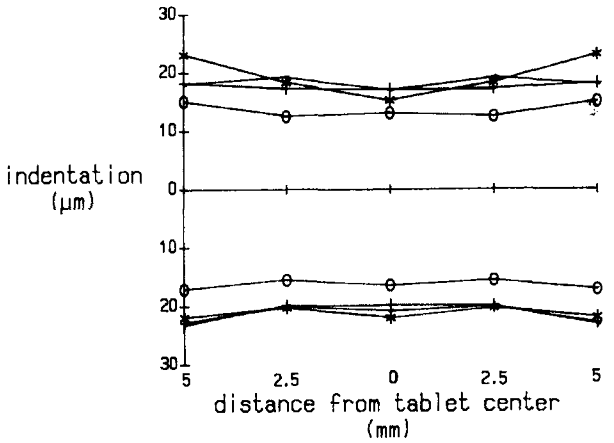

FIGURE 10
Surface hardness of a tablet across the tablet surface. Upper punch surface on the top and lower punch surface on the bottom. Tablets were compressed at 90 MPa compressional pressure. Key as in Fig. 2.

to deform easily, however, does not support this conclusion. Aulton (25) has shown, that the resistance of a compacted tablet against indentation is a function not only of the constituent material, but also of the degree of consolidation and interparticle adhesion and the amount of deformation that has occurred during compression. Therefore the hardness is besides the inherent property of the material affected also by the rigity of the tablet as a whole (23). The surface of ACP tablets was more consolidated than the surface of other cellulose tablets (Fig. 11). Thus the partial disappearing of the original boundaries of agglomerates indicated an extensive deformation and possibly also cold working between particles in some extent. Also the largest breaking strength of ACP tablets supported the concept of a rigid structure of these tablets, which obviously was more important reason than the inherent properties of the crystal lattice to the large surface hardness of ACP tablets.

According to the breaking strength and friability (Fig. 7 and 8) and scanning electron micrographs (Fig. 11) it could be

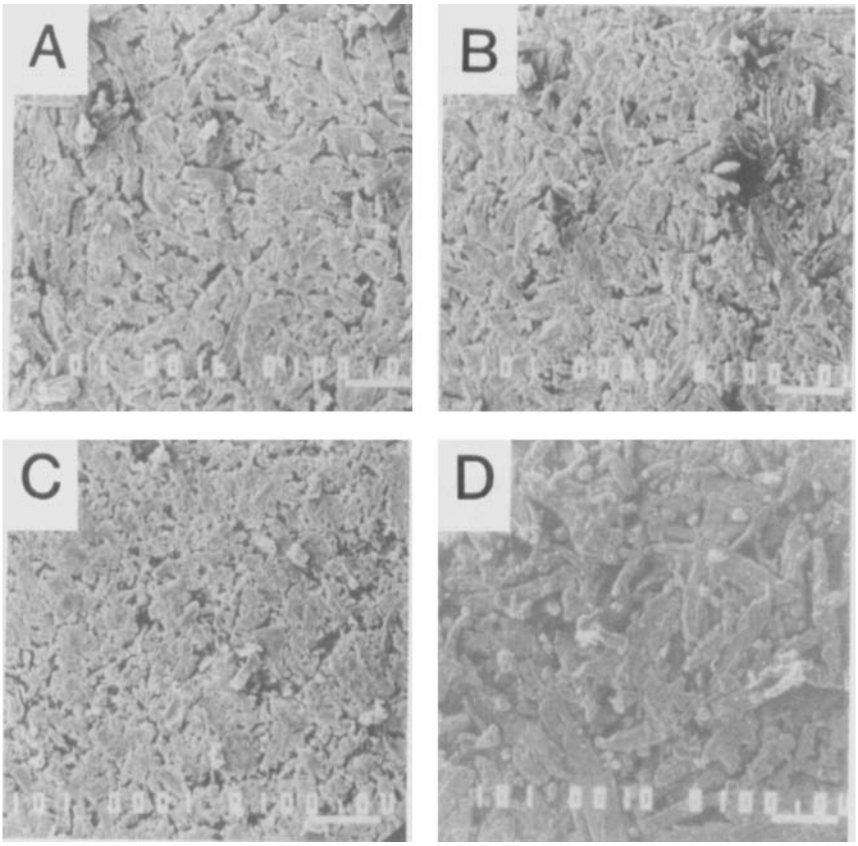

FIGURE 11
Scanning electron micrographs taken from the top surface of the tablets compressed using 30 MPa compressional pressure. Key as in Fig. 1.

expected, that the hardness of DCP tablets would have been clearly smaller than those of Avicel and Emcocel tablets. However, the surface hardness of tablets of these materials was nearly the same. Thus the clearly looser DCP tablets owned practically the same resistance against the penetration of an intender than Avicel and Emcocel tablets. The surface area of the intender covered a large number of particles, about a hundred, in each determination point. Thus the voids in DCP tablets did not essentially reduce the hardness of these tablets compared to those of Avicel and Emcocel tablets. It seems, that the hardness of the tablets of these three cellulose materials was primarily affected by the inherent material properties than the rigidity of a tablet as a whole. This suggestion agrees with the crystal structure of the materials. Avicel, Emcocel and DCP owned quite the same degree of crystallinity, whereas the degree of crystallinity was clearly smaller for ACP. The hardness of ACP tablets must be affected markedly by the rigity of the tablet structure as a whole.

Doelker et al. (6) found, that the tensile strength and indentation hardness of eight cellulose powders showed positive correlation, but according to our results such a conclusion could not be drawn. Hardness test is best considered as a comparative test and it inherently measures the properties of the material surface, and only if a sufficiently large volume of the material is deformed during the test it can be used as a quide to the overall extent of resistance to deformation of the compact as a whole. On the other hand, the tensile or breaking strength of a tablet is primarily affected by the bonding of the individual particles. According to our results the hardness of Avicel, Emcocel and DCP tablets was primarily affected not by bonding but by the inherent properties of a single cellulose particle. On the contrary, the surface hardness measured for ACP tablets was strongly affected by the tablet structure as a whole and thus a correlation between hardness and breaking strength could be observed.

CONCLUSIONS

The inherent material properties of the cellulose powders differed markedly in some cases. The experimental agglomerated cellulose (ACP) owned the most amorphous crystal structure. It also had the largest particle size and clearly largest intraparticle porosity and specific surface area. The experimental depolymerized cellulose (DCP) consisted of very even particles with minimal intraparticle porosity. Both microcrystalline celluloses, Avicel PH 101 and Emcocel, had clearly larger specific surface area than depolymerized cellulose. The particle shape was most irregular for microcrystalline celluloses. According to the breaking strength and friability depolymerized cellulose powder tablets were clearly weakest. The surface hardness of depolymerized cellulose powder tablets was, however, equal to those of Avicel and Emcocel tablets. Agglomerated cellulose powder formed both the strongest and the hardest tablets.

The most important inherent material property contributing to mechanically strong tablets was the specific surface area of the cellulose powders, whereas no correlation between crystallinity, particle size or particle shape and the tablet strength was observed. In accordance with the measured specific surface areas agglomerated cellulose powder formed the strongest and depolymerized cellulose the weakest tablets. A clear correlation between specific surface area and the breaking strength of tablets was thus observed. The clearly more amorphous crystal structure of agglomerated cellulose powder could also, due to the greater ability of this material to deform plastically, contribute to the strength of these tablets.

The surface hardness of cellulose tablets showed no simple correlation with the breaking strength of tablets or with any single material property of cellulose powders. Obviously the consolidation of tablet structure during compaction had an important effect on the measured surface hardness, thus masking the possible correlation between a single material property and the surface hardness of compressed tablets.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to Ensio Laine, Ph. D. in Physics, for his help in crystal structure studies and to Jukka Jurvelin, Ms. in Physics, for his help in surface hardness measurements. TP thanks also Ilmari Hyvärinen Foundation for financial support and Finnish Sugar Ltd for the supply of cellulose materials.

REFERENCES

1.Lamberson, R,L, Raynor, G,E, Manuf. Chem. 47,55 (1976)

2.Shangraw, R,F, Wallace, J,W, Bowers, F,M, Pharm. Technol. 5,69 (1981)

3.Swiss patent WO 80/00843

4.Bolhuis, G,K, Lerk, C,F, Pharm. Weekblad 108,469 (1973)

5.Sixsmith, D, J. Pharm. Pharmacol. 29,33 (1977)

6.Doelker, E, Gurny, R, Mordier, D, Hart, J,P, Rees, J,E, Aulton, M,E, Poster presented at the 1987 Symposium on Tablet Technology in Stockholm

7.Fuhrer, C, Acta Pharm. Tech. 24,129 (1978)

8.Hiestand,E,N, Wells, J,E, Peot, C,B, Ochs, J,F, J. Pharm. Sci. 66,510 (1977)

9.Cole, E,T, Rees, J,E, Hersey, J,A, Pharm. Acta Helv. 50,28 (1975)

10.David, S,T, Augsburger,L,L, J. Pharm. Sci. 66,155 (1977)

11.Pesonen, T, Paronen, P, Puurunen, T, Pharm. Weekblad, accepted for publication

12.Pesonen, T, Paronen, P, Drug Dev. Ind. Pharm. 12,2091 (1986)

13. Laine, E, Lähteenmäki, J, Kantola, M, X-ray Spectrom. 1,93 (1972)

14.Ahtee,M, Paakkari, T, Puikkonen, K, Hattula, T, Paperi ja Puu 33,167 (1980)

15.Jurvelin, J, Kiviranta, I, Arokoski, J, Tammi, M, Helminen, H, Engn. Med. 16,15 (1987)

16.Doelker, E, Gurny, R, Schurz, J, Janosi, A, Matin, N, Powder Techol. 52,207 (1987)

17. Zografi, G, Kontny, M,J, Yang, A,Y,S, Brenner, G,S, Int. J. Pharm. 18,99 (1984)

18.Huttenrauch, R, Pharm. Ind. 45,435 (1983)

19.Wallace, J,W, Capozzi, J,T, Shangraw, R,F, Pharm. Tech. 7,94 (1983)

20.Summers, M,P, Enever, R,P, Carless, J,E, J. Pharm. Sci. 66,1172-1175 (1977)

21.Hiestand, E, N, A Ph A 15,38 (1985)

22.Marshall, K, Sixsmith, D, Drug Dev. Comm. 1,51 (1974-75)

23.Aulton, M, E, Pharm. Acta Helv. 56,133 (1981)

24.Ridgway, K, Aulton, M,E, Rosser, P,H, J. Pharm. Pharmacol. 22,70S (1970)

25.Aulton, M, E, Pharm. Acta Helv. 56,332 (1981)