Assessing Tablet Bond Types from Structural Features that Affect Tablet Tensile Strength

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Received September 18, 2000; accepted November 8, 2000

Purpose. The aim of this article was to study the possibility of assessing the structural features affecting tablet tensile strength to obtain information on the dominating bond types, i.e. interparticulate attractions, in tablets.

Methods. The features of the internal tablet structure considered to be important for tablet tensile strength were assessed using a simple tablet model for tablets made from seven materials: potassium chloride, sodium chloride, sodium bicarbonate, lactose, sucrose, microcrystalline cellulose, and ascorbic acid.

Results. Tablet porosity and particle size (measured as external specific surface area by permeametry) were the structural features that best correlated with tablet tensile strength. These features were described by a "structural factor," which was combined with tablet tensile strength, as an "interaction factor," to reflect the dominating bond types in tablets.

Conclusion. The qualitative results gave dominating bond types in the tablets studied that matched the results of earlier studies, thus supporting the applicability of the method.

KEY WORDS: tablet tensile strength; bonding mechanisms; tablet model; tablet structure

INTRODUCTION

Pharmaceutical tablets consist of powder particles compacted into coherent compacts. These compacts have been described as solid powder particles dispersed in air (1). Bonds between the solid particles in the powder bed are responsible for the coherence of the tablet. Changes in the internal structure of the tablets, e.g. tablet porosity, pore size distribution, and the size and shape of the particles, as well as changes in the bonds between the particles, e.g. bond type, frequently have been reported to affect tablet properties, such as mechanical strength and disintegration.

The particles in pharmaceutical compacts generally are assumed to bond together by one or more bonding mechanisms. These are often divided into three main types: distance forces, solid bridges, and mechanical interlocking (2,3). Distance forces, i.e. van der Waals forces, hydrogen bonds, and electrostatic attractions, are considered to be the dominating bonding mechanism for most pharmaceutical compacts. They are reported to act over distances up to approximately $1 \cdot 10^3$ Å at an interaction force that is affected by the interaction distance (4,5). Solid bridges, the strongest bond type, are described as areas in which particles are partially fused together and can thus be considered as a continuous phase between two particles. The term mechanical interlocking is used to describe the hooking and twisting together of particles in a packed material and may occur in tablets of particles with a fibrous or irregular structure.

In the pharmaceutical literature, the tensile strength of tablets traditionally has been assessed according to the bond summation concept proposed by Rumpf (6). However, in recent years, the fracture mechanics concept (7–9) has been introduced in this field (10,11). It has been argued that this concept offers a more adequate way of assessing tablet tensile strength and that bond summation tends to overestimate the tablet tensile strength because it fails to take into account such parameters as kinematics processes and the stress concentration phenomenon (8).

The tensile strength of a tablet (σ_t) can be calculated from the force needed to fracture the tablet (F_t) and the cross sectional area of the fracture plane (A_t).

$$\sigma_t = \frac{F_t}{A_t} \tag{1}$$

According to the bond summation concept, the force needed to break a tablet is dependent on the number of interparticulate bonding points in the fracture plane (n_{bt}), and the average breaking force of such a bonding point (F_b) (6).

$$F_t = n_{bt} \cdot F_b \tag{2}$$

Consequently, the tablet tensile strength can be expressed as:

$$\sigma_t = \frac{n_{bt} \cdot F_b}{A_t} \tag{3}$$

The terms "bond strength" and "bonding surface area" are often used in connection with the bond summation concept. The bond strength, i.e. the average tensile strength of a bonding point (σ_b), can be expressed as the average force (F_b) needed to break a bonding point of an average area (A_b). σ_b can be considered to reflect the bond type, where a low value indicates bonding by weak forces and a high value indicates the presence of strong bonds (solid bridges).

$$\sigma_b = \frac{F_b}{A_b} \tag{4}$$

By using the concept of bond strength, i.e. by combining Equations 3 and 4 the tablet tensile strength can be expressed as:

$$\sigma_t = \frac{n_{bt} \cdot \sigma_b \cdot A_b}{A_t} \tag{5}$$

The "bonding surface area" is often defined as the effective surface area taking part in the interparticulate attraction. If only solid bridges are present, the bonding surface area may be defined as the area in which particles are fused together. For materials bonding with distance forces, the bonding surface area is more difficult to define (1). From the bond summation model, the bonding surface area (A_{bt}) can be calculated from the number (n_{bt}) and average area (A_b) of the bonding points in the fracture plane:

$$A_{bt} = n_{bt} \cdot A_b \tag{6}$$

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By combining Equations 5 and 6, the tablet tensile strength may be described as:

$$\sigma_t = \sigma_b \cdot \frac{A_{bt}}{A_t} \quad (7)$$

where the average tensile strength of a bonding point (σ_b) reflects the bond strength and consequently the bond types of the tablet, and A_{bt}/A_t reflects the relative bonding surface area of the tablet.

Several attempts have been made to estimate the bonding surface area of tablets. A common approach has been to assume that the bonding surface area of a tablet is proportional to its specific surface area (1,12,13). Another approach has been to estimate a factor denoted "effective contact area" from the yield pressure values of the materials (14).

The mechanisms and strength of the bonds in tablets have also been studied in several ways, e.g. in conductivity measurements (15) or by compacting tablets in media with differing dielectric constants (3,13,16–19). Attempts have also been made to calculate bond strength from tablet tensile strength and bonding surface area (13,20).

According to fracture mechanics, the tensile strength of a compact is dependent on the critical stress intensity factor (K_{ic}) and the size of the flaw (c) where the fracture is initiated (9).

$$\sigma_t \propto \frac{K_{ic}}{\sqrt{c}} \quad (8)$$

The flaw where the fracture is initiated is often considered to be the largest flaw in the direction of the fracture. In experiments designed to obtain K_{ic} values, a macroscopic flaw is introduced into the compact to control the starting point of the fracture. The size of the fracture-initiating flaw in unnotched compacts has been calculated (9,10) and been found to be affected by the internal structure (e.g. porosity) of the compact (8,9).

K_{ic}, the critical stress intensity factor, reflects resistance to fracture propagation and is affected by such factors as tablet porosity and particle size, i.e. the internal tablet structure (9). K_{ic} has also been related to the interactions between particles in the tablet (8–11).

When comparing the bond summation and fracture mechanics concepts, some unifying components can be detected. In both Equation 7 and Equation 8, two types of factor are present: those reflecting the internal structure of the tablet and those reflecting the interactions between the particles in the tablet. In the bond summation concept these factors are represented by A_{bt}/A_t and σ_b, respectively. In the fracture mechanics concept, the interaction factor may be considered reflected by K_{ic}, and the structural factor by both K_{ic} and c.

In this study, a simplified tablet model was used to assess theoretically features of the internal tablet structure likely to affect tablet tensile strength. These features were combined into a single so-called "structural factor." A high value for the structural factor indicated a high resistance to tablet fracture in the model. The tablet tensile strength was then combined with this structural factor, and the average interaction between the particles in the compact (the "interaction factor," reflecting the dominating bond types) was deduced.

The aim of this study was to investigate the possibility of assessing the structural features affecting tablet tensile strength in order to obtain information on the dominating bond types in tablets.

MATERIALS AND METHODS

Materials

Seven tableting materials were studied (Table 1). The materials may be divided into two major groups according to their bonding structure. Potassium chloride (crystalline, puriss, Kebo-lab, Sweden), sodium chloride (crystalline, puriss, Kebo-lab, Sweden), and sodium bicarbonate (crystalline, puriss, Kebo-lab, Sweden) can form solid bridges (3,13,15,17,19). Lactose, fine (crystalline, α-monohydrate, Pharma course, Borculo, The Netherlands) and coarse (crystalline, α-monohydrate, Svenskt socker AB, Sweden), sucrose (crystalline, Svenskt socker AB, Sweden), L(+)-ascorbic acid (crystalline, puriss, Merck, Germany), and microcrystalline cellulose (Avicel PH101, FMC, USA) represent materials with a low probability of forming solid bridges. (3,13,17,19).

At least two size fractions were prepared of each material (Table 1). The size fractions exceeding 90 μm were prepared by dry sieving of the raw material (laboratory sieves, Retsch, Germany). The fine grades of microcrystalline cellulose, lactose, and ascorbic acid were prepared by air elutriation (Alpine 100 MZR, Alpine AG, Germany) of the raw material, whereas the fine grades of potassium chloride, sodium chloride, sodium bicarbonate, and sucrose were prepared by milling in a pin disc mill (Alpine 63C, Alpine AG,

Table I. Primary Characteristics of the Test Materials

Material	Sieve size fraction (μm)	Apparent particle density (g/cm^3)[a]	Specific surface area (cm^2/cm^3)
Potassium chloride	10–20	1.973 (0.000)	6300 (80)[b]
	40–60		2770 (60)[b]
	90–150		290 (0)[c]
Sodium chloride	10–20	2.152 (0.000)	6070 (270)[b]
	40–60		2510 (20)[b]
	90–150		790 (10)[c]
Sodium bicarbonate	10–20	2.215 (0.001)	4990 (420)[b]
	40–60		2470 (120)[b]
	90–150		680 (0)[c]
Microcrystalline cellulose	10–20	1.569 (0.003)	10290 (80)[b]
	40–60		4800 (20)[b]
Sucrose	10–20	1.588 (0.001)	7350 (10)[b]
	40–60		2360 (30)[b]
	90–150		1900 (20)[c]
Lactose	20–40	1.537 (0.000)	6754 (127)[b]
	40–80		2850 (73)[b]
	90–180		569 (11)[c]
Ascorbic acid	20–40	1.695 (0.000)	8246 (171)[b]
	40–80		4138 (30)[b]
	90–150		899 (50)[c]

[a] Measured using a helium pycnometer (AccuPyc, 1330, Micromeritics, USA). Mean value of three determinations; standard deviations in parantheses.

[b] Measured by Blaine permeametry. Mean value of three determinations; standard deviation in parantheses.

[c] Measured by Friedrich permeametry. Mean value of three determinations; standard deviations in parantheses (23).

Germany) followed by air elutriation (Alpine 100 MZR, Alpine AG, Germany).

The powders were stored at room temperature for at least 48 hours in a desiccator over saturated chrome trioxide in water (40% relative humidity) (21) before use.

Methods

Apparent Particle Density

The apparent particle densities (22) of the materials were measured using helium pycnometry (Accu Pyc 1330, Micromeritics, USA) (Table I).

Powder Surface Area

The external volume-specific surface areas of the materials were measured using a permeametry technique (Table 1). A Friedrich permeameter was used for the coarse materials (23), whereas a Blaine permeameter was used for the fine materials (n = 3).

Compaction of Tablets

Tablets were compacted at four different compaction loads (maximum upper punch pressure) for each material and each of the size fractions in an instrumented single punch press (30 rpm) (Korsch EK 0, Germany), using flat-faced punches with a diameter of 11.3 mm. Before each compaction, the die and punch faces were lubricated with magnesium stearate powder. The powder for each tablet was weighed on an analytical balance, and the die was manually filled. The compaction loads were adjusted by having a constant distance between the punches (3.0 mm at 0 MPa) and varying the amount of powder in the die.

Tablet Porosity and Solid Proportion

The porosity of the tablets (ε) was calculated from the apparent particle density of the material and the dimensions and weight of the tablet. The results are presented in terms of the proportion of solid material in the tablets, i.e. $(1 - \varepsilon)$ (Fig. 2).

Tablet Tensile Strength

The tablets were stored at room temperature for at least 48 hours at 40% relative humidity before their tensile strength was tested. The radial tensile strength was calculated using the diametral compression test (24). The tests were performed on eight tablets from each compaction load, size fraction, and material at a speed of 4 mm/min (Holland, C50, Great Britain) (Fig. 1).

Specific Tablet Surface Area and Mean Pore Radius Estimated by Permeametry

The specific tablet surface areas were estimated by permeametry using a Blaine apparatus (n = 3). Each tablet was fitted to the top of the apparatus using a device described by Alderborn et al. (25). The surface area was calculated from the Kozeny–Carman equation corrected for slip flow, i.e. both viscous and molecular flow were considered (26) (Fig. 3).

RESULTS AND DISCUSSION

Compactibility and Volume Reduction Behaviour of the Test Materials

The tensile strength of the tablets increased with increasing compaction pressure and decreasing particle size for all materials and size fractions (Fig. 1). Microcrystalline cellulose, potassium chloride, and sodium chloride were the most compactible materials, i.e. tablets of these materials demonstrated greater absolute increases in tensile strength with increasing compaction pressure than did those of sodium bicarbonate, ascorbic acid, lactose and sucrose.

The materials used can be divided into two main groups according to their volume reduction behavior (Figs. 2 and 3). In the first group, the pronounced compressibility of potassium chloride, sodium chloride, and sodium bicarbonate (Fig. 2) is caused by the rearrangement and plastic deformation of the particles at pressure (Fig. 3); in the second, lactose, sucrose, and ascorbic acid, whose less pronounced volume reduction (Fig. 2) is caused by rearrangement and fragmentation (Fig. 3) of the particles.

The increase in tablet surface area with increasing compaction pressure was comparatively high for tablets made from microcrystalline cellulose (Fig. 3). This material had a high tendency to fragment ,and its compressibility was pronounced (Fig. 2). The highest tablet compactibility was associated with materials with this combination of factors (Fig. 1), followed by materials undergoing volume reduction preferentially by plastic deformation of the powder particles.

Assessment of a Structural Factor by a Simplified Theoretical Tablet Model

The maximum interaction range for distance forces between particles (approximately $1 \cdot 10^3$ Å) (5) implies that, in a simplified model, only surfaces that are closer to each other than this can take part in the bonding and affect the tablet's resistance to fracturing (20). Consequently, if a tablet had smaller pores, its tensile strength would increase. Smaller pores implies that the particle surfaces inside the tablet are brought closer to each other, increasing the proportion of the tablet surface area available for bonding. A simplified tablet model was used to estimate this proportion.

The underlying premise of this model was that tablets are assumed to fracture around the particles in the compressed bed rather than through individual particles (27–29). Furthermore, tablets were, in this context, described as homogeneous, isotropic aggregates of spherical, non-deformable particles (Fig. 4), which is obviously a simplification in that, for example, the effect of microscopic irregularities of the particle surfaces (protrusions) on the tensile strength of tablets is ignored. Then, if it is assumed that each particle in the fracture plane corresponds to one bonding point, the surface area of that part of the fracture plane of a tablet that participates in bonding (A_{bt}) may be calculated as the product of the number of bonding points (particles) in the fracture plane (n_{bt}) and the surface area of the portion of each particle that is located close enough to another surface for bonding to occur, i.e. the average bonding area of a particle (A_b) (Eq. 6).

The number of particles and consequently the number of bonding points in a cross section of a tablet (n_{bt}) can be described as:

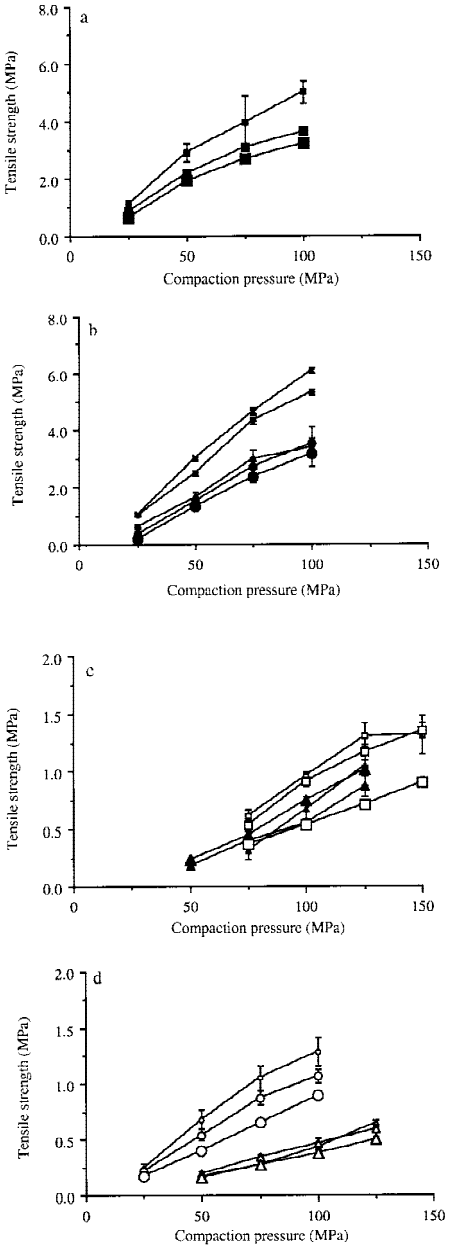

Fig. 1. Radical tensile strengt of the tablets, as a function of compaction pressure. (a) ■, potassium chloride 10–20 μm; ■, potassium chloride 40–60 μm; ■, potassium chloride 90–150 μm. (b) •, sodium chloride 10–20 μm; ●, sodium chloride 40–60 μm; ●, sodium chloride 90–150 μm; ♦, microcrystalline cellulose 10–20 μm; x, microcrystalline cellulose 40–60 μm. (c) ▲, sodium bicarbonate 10–20 μm; ▲, sodium bicarbonate 40–60 μm; ▲, sodium bicarbonate 90–150 μm; □, lactose 20–40 μm; □, lactose 40–80 μm; □, lactose 90–180 μm. (d) ○, sucrose 10–20 μm; ○, sucrose 40–60 μm; ○, sucrose 90–150 μm; △, ascorbic acid 20–40 μm; △, ascorbic acid 40–80 μm; △, ascorbic acid 90–150 μm. Standard deviations are given when they exceed the dimensions of the symbols.

$$n_{bt} = \frac{A_t(1-\varepsilon)}{A_{pp}} \tag{9}$$

where $(1 - \varepsilon)$ is the proportion of the material that is solid and ε is the porosity (14). A_{pp} is the projected surface area of a particle, which for a sphere is one quarter of the surface area, i.e.:

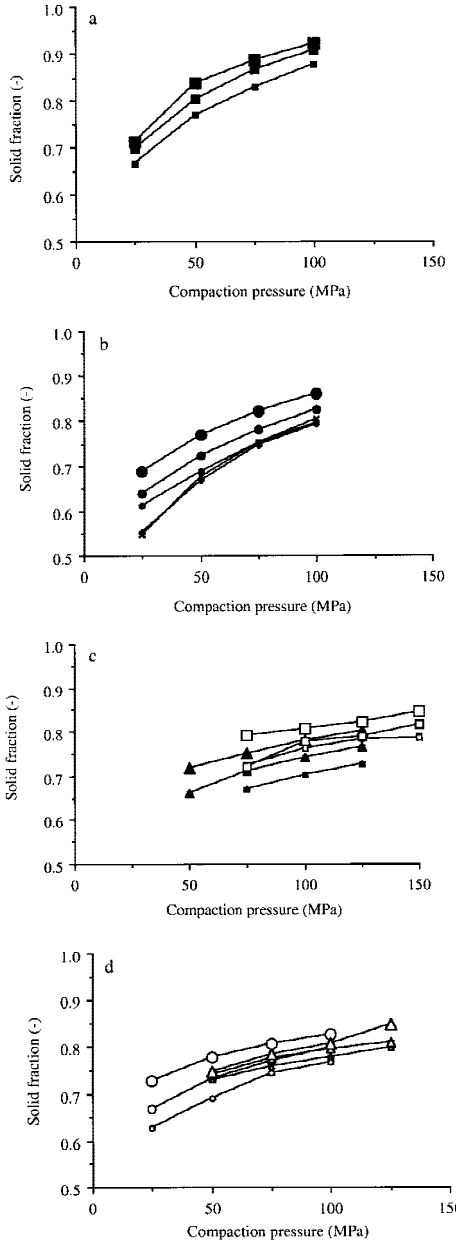

Fig. 2. Proportion of solid material in the tablets as a function of compaction pressure. Symbols as in Fig. 1. Standard deviations are given when they exceed the dimensions of the symbols.

$$A_{pp} = \frac{A_s}{4} = \frac{1}{4} \cdot \pi \cdot d_s^2 \tag{10}$$

where A_s and d_s are the surface area and diameter of a sphere. Thus the number of bonding points is:

$$n_{bt} = 4 \cdot A_t \cdot \frac{(1-\varepsilon)}{\pi \cdot d_s^2} \tag{11}$$

The size of the area on each particle's surface that may take part in bonding (A_b), may be assessed by assuming that the shape of this surface is that of a spherical cap (Fig. 4). The area of a spherical cap can be calculated from pi (π), the particle diameter (d_s), and the longest distance between the vaulted and the plane surfaces of the spherical cap, perpen-

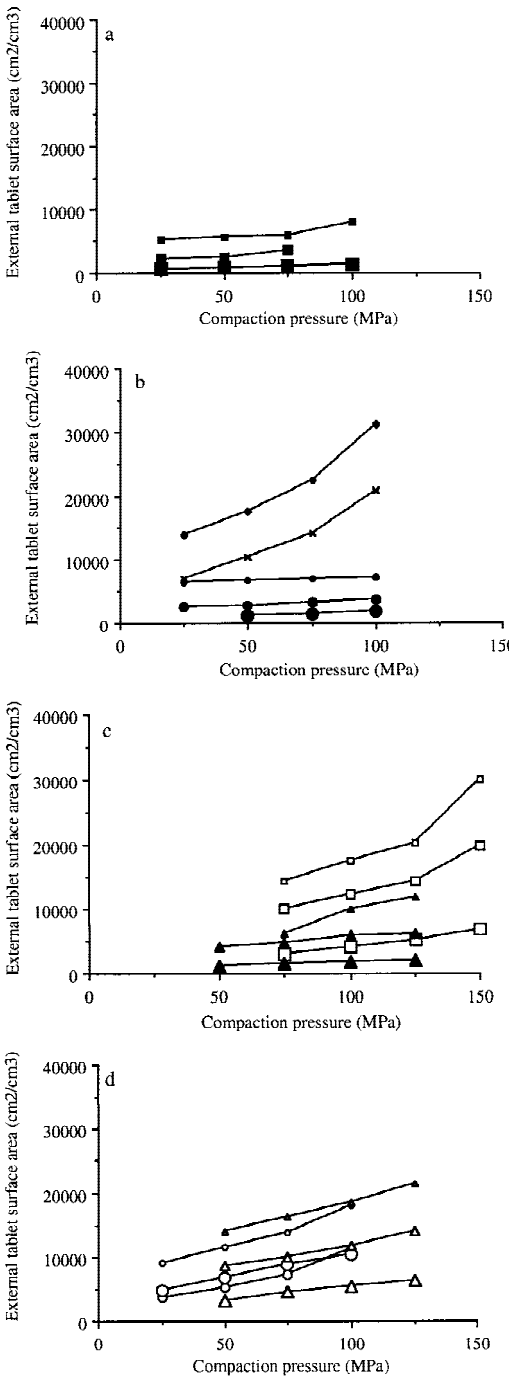

Fig. 3. External specific tablet surface area measured by Blaine permeametry as a function of compaction pressure. Symbols as in Fig. 1. Standard deviations are given when they exceed the dimensions of the symbols.

dicular to the plane surface (h). h can be considered constant since it is proportional to the maximum interaction distance (Fig. 4).

$$A_b = \pi \cdot d_s \cdot h \tag{12}$$

By inserting the expression for n_{bt} (Eq. 11) and the expression for A_b (Eq. 12) in Equation 6, the following expression for A_{bt} was obtained:

$$A_{bt} = A_t \cdot \frac{(1-\varepsilon)}{d_s} \cdot h \tag{13}$$

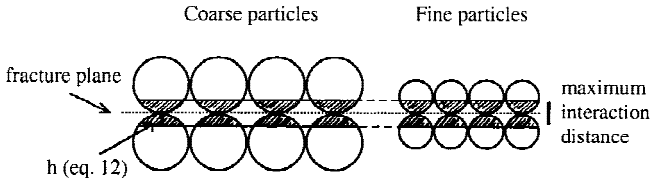

Fig. 4. Schematic drawing of the tablet model used to estimate a structure factor according to Equation 16. The hatched areas represent surfaces located within the maximum interaction distance (approximately $1 \cdot 10^3$ Å) from surfaces on the other side of the fracture. The area of the hatched surfaces is proportional to the solid fraction $(1 - \varepsilon)$ and the particle diameter (d_s) and can be obtained from Equation 13. The hatched area of one particle corresponds to A_b. In the figure, the maximum interaction distance equals $2 \cdot h$, where h is the longest distance between the vaulted and plane surfaces of the spherical cap.

According to Allen (30), the particle size is inversely proportional to the specific surface area of a particle:

$$d_a = \frac{\alpha_{sy}}{S_V} \tag{14}$$

where S_v is the volume specific surface area of the powder, α_{sv} is Heywood's surface to volume shape factor and d_a is the particle diameter defined according to Allen (30).

If, for simplicity, the maximum bonding distance, reflected in h, and Heywood's surface to volume shape factor are considered constant for the different materials, size fractions, and compaction pressures used, and the external volume specific surface area (S_{ve}) obtained from permeametry is used, the following proportionality is obtained:

$$\frac{A_{bt}}{A_t} \propto (1-\varepsilon) S_{ve} \tag{15}$$

A_{bt}/A_t is, in this article, defined as the structural factor, i.e. a combination of structural features such as tablet porosity and specific surface area which will affect the tensile strength of the tablets. As the structural factor increases in value, the pore-size distribution shifts towards smaller pores with a probable subsequent increase in the tensile strength of the tablets.

Assessment of an Interaction Factor

Equations 7 and 15 may be combined to obtain an interaction factor (σ_{b*}), which reflects the bond types that may be obtained in the various tablets. Because h and α_{sv} are not quantified, the value of σ_{b*} should be regarded as a qualitative description of the bond types in the tablet, and not a quantitative value of average bond strength (α_b).

$$\sigma_{b*} \propto \frac{\sigma_t}{(1-\varepsilon) S_{ve}} \tag{16}$$

The interaction factor, (σ_{b*}, is expected to be higher for tablets of materials bonding with strong bonds, i.e. solid bridges, than for tablets of materials bonding solely with weaker forces, i.e. distance forces. Previous results from this laboratory show that the proportion of solid bridges in a compact of plastically deforming materials increases with increasing compaction pressure and particle size (19). Consequently, the average bond strength in tablets made from materials

bonding with solid bridges is expected to increase with increases in these factors. Previous studies from this laboratory have also shown that the bond strength differs with the different propensities of materials to form solid bridges. (3,13,17,19). Furthermore, it has been suggested that the average bond strength in tablets of materials bonding solely with distance forces is not likely to be affected to the same extent by the type of material, particle size and compaction pressure (3,13,17,19).

After assessing S_{ve} with permeametry, the interaction factors obtained from Equation 16 were plotted against compaction pressure (Fig. 5). Particle size and compaction pressure had no significant effect on the interaction factors for sucrose, lactose and ascorbic acid (Fig. 5). The values of the interaction factors for these materials were similar. These results were in agreement with earlier studies, which indicated that lactose and sucrose bond mainly with distance forces (3,13,17,19). The chemical structure of ascorbic acid also implies this bond type.

The values of the interaction factors for potassium chloride and sodium chloride increased with increasing compaction load and particle size (Fig. 5). The values for the coarse size fractions tended to reach a plateau at high pressures, as indicated in earlier studies (17,19), which reported that the proportion of solid bridges may increase to a restricted level with increasing compaction pressure and particle size. The interaction factor for sodium bicarbonate also increased with increasing particle size and compaction pressure. Compaction pressure had a more pronounced effect on tablets of the coarse sodium bicarbonate particles than on those of the fine particles, which has also been reported previously from our laboratory. However, the interaction values were lower than for sodium chloride and potassium chloride, which is probably due to the more complicated chemical structure of this material compared to that of sodium chloride or potassium chloride (3,17,19).

Compaction pressure and particle size had less effect on the interaction values for microcrystalline cellulose tablets. However, the values were higher than those for sucrose, lactose and ascorbic acid, which may indicate that hydrogen bonds are an important aspect of the tensile strength of tablets of microcrystalline cellulose.

It could be asserted, especially if fracture mechanics are included in the argument, that the model is oversimplified. However, the structural features that were considered to relate to tablet tensile strength (i.e. the proportion of the tablet that is solid and the particle size; Eq. 16), are also found in fracture mechanics, albeit with a different emphasis. Both K_{ic} and c have been reported to be affected by compact porosity and particle size. The effects of these features on K_{ic} have been shown in Equation (9). However, no such equations have to our knowledge been presented for c.

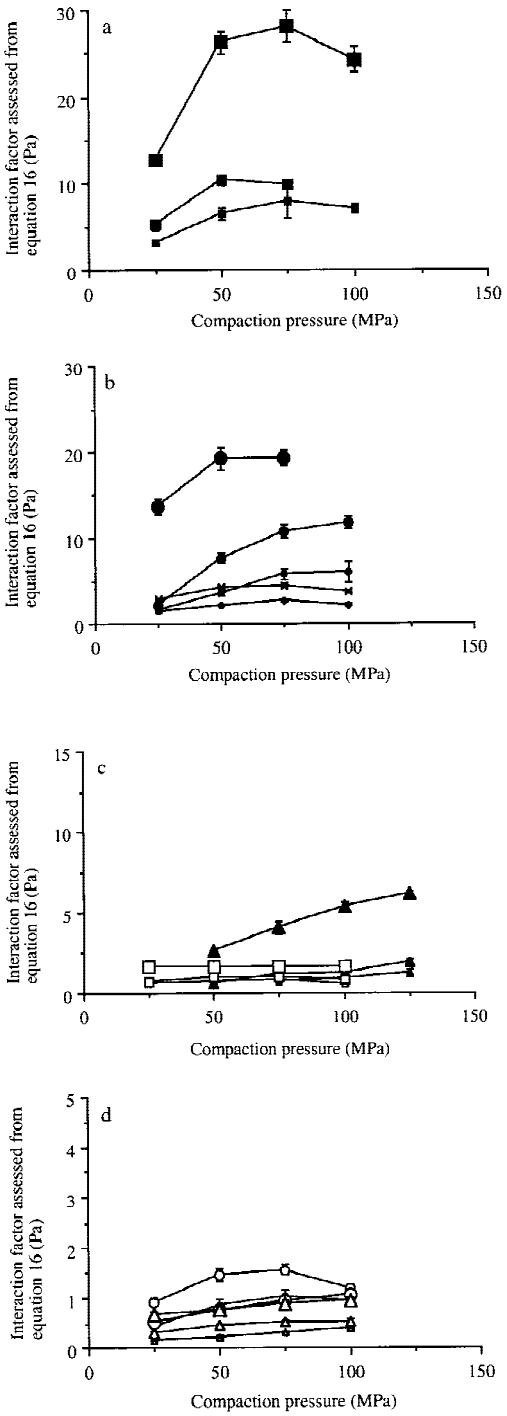

Fig. 5. Interaction factor (σ_{b*}), assessed from Equation 16, as a function of compaction pressure. Symbols as in Fig. 1. Standard deviations are given when they exceed the dimensions of the symbols.

CONCLUSIONS

Tablet tensile strength, in both fracture mechanics and the bond summation theory, is considered to depend on a "structural factor" and an "interaction factor." The structural factor reflects the features of the internal tablet structure that will affect the tensile strength of the tablet. The interaction factor reflects the interparticulate interactions. Because of the heterogeneous and non-isotropic nature of pharmaceutical compacts, exact quantification of these factors is probably impossible. However, structural features affecting tablet tensile strength can be assessed by applying a simplified, but theoretically based, tablet model. These features can then be combined into a structural factor which, in turn, can be used with the tablet tensile strength to obtain an interaction factor to provide qualitative information on the dominating bond types in tablets.

The features affecting tablet tensile strength were, as pre-

dicted by the model, the proportion of the tablet that is solid and the size of the particles (specific tablet surface area). The positive effect of an increase in the solid proportion of a tablet on its tensile strength is well known. However, opinions on the effect of particle size differ. Studies have suggested that particle size does (1,12,13) and does not (14) have an important effect on the tensile strength of tablets.

Also, this study indicates that the measurement of external specific surface area by permeametry is a useful tool in studies of surface-related particle phenomena such as particle interactions.

The interaction factor, σ_{b*}, was obtained from a simplified model in which several factors, e.g. *h,* α_{sv}, were not quantified. Consequently, the numerical values obtained from Equation 16 should not be considered absolute values of bond strength. However, because the obtained profiles, in Figure 5, correlated well with results from earlier studies of bond types in tablets, it is proposed that this method may be used as a qualitative estimation of bond types in tablets.

APPENDIX

A_b, average area of a bonding point (m^2); A_{bt}, bonding surface area of a tablet (m^2); A_{pp}, projected surface area of a particle (m^2); A_s, surface area of a sphere (m^2); A_t, cross sectional area of the failure plane of a tablet (m^2); α_{sv}, Heywood's surface to volume shape factor (–); c, length of the fracture-initiating flaw (m); d_s, diameter of a sphere (m); d_a, particle diameter defined according to Allen (1997) (m); ε, porosity of tablet (–); F_b, bonding force of an interparticulate bond (N); F_t, fracture force of a tablet (N); h, longest distance, along the radius, between the vaulted and plane surfaces of a spherical cap peripendicular to the plane surface (m); K_{jc}, critical stress intensity factor (Pa $m^{0.5}$); n_{bt}, number of interparticulate bonds in the fracture plane of a tablet (–); S_v, volume specific surface area (m^2/m^3); S_{ve}, external volume specific surface area of tablets, obtained by permeametry (m^2/m^3); σ_b, average tensile strength of interparticulate bonds (Pa); σ_{b*}, interaction factor, reflecting the dominating bond type of a compact (Pa); σ_t, tablet tensile strength (Pa).

ACKNOWLEDGMENTS

The authors are grateful to Ms Lucia Politi for skillful experimental assistance and also Dr Åsa Adolfsson, Mrs Christina Gustafsson, and Mrs Susanne Bredenberg for kindly letting us use some of their experimental data. AB Astra (Sweden), Pharmacia & Upjohn (Sweden), and the Knut and Alice Wallenberg Foundation are gratefully acknowledged for financial support.

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