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The Effect of Particle Fragmentation and Deformation on the Interparticulate Bond Formation Process During Powder Compaction

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Purpose. The compression behaviour and the compactability of particles have been studied. In addition, an expression describing the bond strength over a tablet cross section was derived and these calculated values were compared with the experimentally determined tablet tensile strength values. ***Methods.*** The compression behaviour of particles of a series of size fractions of four materials were assessed by tablet surface areas (particle fragmentation propensity) and by yield pressures (particle deformability), derived from in die Heckel profiles. The porosity and the tensile strength of the tablets were also determined. ***Results.*** Sodium chloride and sodium bicarbonate possessed limited fragmentation while the converse applied for sucrose and lactose. Sodium chloride and sodium bicarbonate were the extreme materials with respect to particle deformability and compactability. Except for sodium chloride, a limited effect of original particle size on the compactability of the particles was observed. ***Conclusions.*** The observations on the compactability of the powders was explained by postulating that fragmentation affects mainly the number of bonds in a compact cross section, while deformation affects mainly the bonding force of these bonds, through a relationship with the contact area between a pair of particles. The deviations between the predicted strength of particle-particle bonds and the determined tensile strength values was explained by a high bonding capacity of some particles, e.g. due to an unpredicted high surface deformability, or by a fracture mechanic effect during tablet strength determination.

KEY WORDS: compactability; deformability; tensile strength; compression.

INTRODUCTION

A tablet formed from pharmaceutical powders under normal tabletting conditions can be described physically in terms of an aggregate of more or less individual particles (1) which however, possess significant areas of interparticulate contact. The interparticulate bond structure will thus contribute significantly to the tensile strength of the compact.

With respect to the compression behaviour of the particles, plastic particle deformation has by tradition been considered the most important interparticulate bond forming compression mechanism (2). It is then assumed that permanent particle deformation can produce relatively large areas of interparticulate contact and thus high particle-particle bonding forces. However, studies on the compactability of lactose particles (3, 4) have indicated that fragmentation is also an important bond forming compression mechanism. This suggestion was later explained (5) in terms of a relationship between the degree of fragmentation and the number of interparticulate bonds in a cross section of the compact.

Although the importance of the compression behaviour of particles for their compactability has been recognised there is still a shortage of experimental studies on the relative contribution of particle deformation and fragmentation during compression for the interparticulate bond formation process. There is thus a need for studies focused on both the compression behaviour of particles and their compactability which is the theme of this study.

MATERIALS AND METHODS

Materials

Materials possessing a low degree of fragmentation during compression (6): *Sodium chloride* (crystalline, puriss, Kebo-lab, Sweden) and *sodium bicarbonate* (crystalline, puriss, Kebo-lab, Sweden)

Materials possessing an intermediate or a high degree of fragmentation during compression (6): Lactose (crystalline, alpha-monohydrate, Pharma coarse, Boroculo, Netherlands) and sucrose (crystalline, Svenskt socker AB, Sweden)

For each material, three or four particle size fractions were prepared (Table 1). Particle examination in microscopes showed that the powders consisted generally of individual particles with a crystalline appearance. However, the coarsest lactose particles were aggregates of smaller particles, strongly cohered to each other. These aggregates were probably formed during the drying of lactose crystals.

The powders were stored at 0% relative humidity (desiccators with phosphorous-pentoxide) and room temperature for not less than 7 days before compaction.

Compaction and Determination of Porosity, Tensile Strength and Surface Area of Tablets

Powders were compressed in an instrumented single punch tablet machine (Korsch EK 0, Germany) equipped with 1.13 cm flat-faced punches at an applied pressure of 150 MPa. The distance between the punch faces at the lowest position of the upper punch was in all cases 3 mm at zero pressure. External lubrication with 1w/w % magnesium stearate suspension in ethanol was performed before each compression. The powder for each compact was individually weighed on an analytical balance and manually poured into the die. The motor of the machine was then started when the upper punch was in its highest position and the motor was stopped and the flywheel manually arrested directly after the compaction.

During the compression phase, the upper punch pressure and position were monitored each ms. By pressing the punches against each other under normal movement rate of the upper punch, the elastic deformation of the punch and punch holder was assessed. After correction for this deformation, the changes in in-die tablet porosity as a function of

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applied pressure were calculated. The porosity data were treated according to the Heckel expression (1) and the reciprocal of the slope in the linear part of the Heckel profile, i.e. in the range 50-150 MPa, was determined (n = 3). This value is referred to as the yield pressure.

Compacts were prepared in the instrumented single punch tablet machine, as described above, at applied pressures of 25, 50, 75 and 100 MPa. Immediately after compaction (t ≈ 45 seconds), the compacts were loaded diametrically (Holland C50, Great Britain) until they fractured in tension. From the fracture force, a compact tensile strength (n = 5) was derived (7). A compact porosity was also derived from the weight and dimensions of the compacts and the apparent particle density of the materials.

Compacts were also prepared in the instrumented single punch tablet machine at applied pressures of 25, 50, 75 and 100 MPa by compressing the powder in a special die, placed on the die table as described earlier (6). The air permeability of the tablets was measured with a Blaine apparatus immediately after compaction (t ≈ 45 seconds) and the volume specific surface area of the compacts (n = 5) was calculated with the permeability equation, corrected for slip flow (6).

RESULTS AND DISCUSSION

Fragmentation Propensity, Deformability and Compactability of Particles

Generally, the *specific surface area of the tablets* related linearly to the applied pressure (6, 8, 9). For compacts of sodium chloride and sodium bicarbonate, a limited increase in surface area with compaction pressure was obtained, while compacts of lactose and sucrose showed a more marked increase in surface area with applied pressure (Table I). These results confirm the expected compression behaviour of the materials. However, one can notice that sodium bicarbonate was clearly more prone to fragment than sodium chloride. The compression behaviour of the materials was also supported by the fragmentation propensity coefficients (Table I), calculated from the surface area-applied pressure relationship as given by Alderborn and Nyström (9). These obtained coefficients compare favourably with coefficients obtained earlier for these materials (9).

Sodium chloride gave generally the lowest *yield pressure values* while sodium bicarbonate gave the highest values (Table I). There was also a general trend that the yield pressure values decreased with an increased original particle size, i.e. the ability of the powder bed to reduce in volume with applied pressure is facilitated by an increased particle size before compression. There seemed also to be a slightly more marked effect of particle size on the porosity-pressure relationship for the low fragmenting materials compared to the high fragmenting materials.

The yield pressure values (Table I) were derived from the linear part of the compression profiles and are thus reflections of the compressibility of the beds of particles. A series of factors can contribute to the derived yield pressures, i.e. interparticulate rearrangement, friction between particles and die wall, fracturing of particles, elastic and plastic deformation and, finally, resistance against an increased proximity between particle surfaces due to interparticulate bonding (which can be described as interparticulate friction). If it is assumed that interparticulate repositioning and particle fragmentation is limited in the linear part of the Heckel function-applied pressure relationship (1), these factors can be neglected. Furthermore, since a well-lubricated

Table I. Primary Powder Characteristics Together with Yield Pressures from Heckel Plots, Slope Values from Applied Pressure-Specific Surface Area Relationships and Fragmentation Propensity Coefficients for the Various Size Fractions

Material (−)	Size fraction (μm)	Apparent particle density (g/cm^3)	Powder surface area (cm^{-1})	Yield pressure (MPa)	Slope values (cm^{-1}/MPa)	Fragmentation propensity coefficient (cm$^{-1/3}$/MPa) (%)
Lactose	250–300[a]	1.54	543	130	70.8	8.6
	125–180[a]		757	127	53.8	7.6
	40–60[b]		2130	132	90.3	8.6
	10–20[b]		6692	149	145	6.6
Sucrose	250–300[a]	1.59	274	138	29.3	7.0
	125–180[a]		548	140	33.3	7.3
	40–60[b]		2624	148	87.7	8.1
	10–20[b]		6926	166	150	6.6
Sodium chloride	250–300[a]	2.16	231	86	2.66	2.7
	125–180[a]		488	88	1.62	1.3
	40–60[b]		2536	107	5.06	0.77
	10–20[b]		6041	118	16.9	1.3
Sodium bicarbonate	250–300[c]					
	125–180[a]	2.22	588	170	16.6	5.1
	40–60[b]		2357	194	21.2	3.6
	10–20[b]		6144	218	56.2	3.4

[a] Prepared by milling the raw material in a pin disc mill (Alpine 63C Alpine AG, Germany) followed by air classification (Alpine 100 MZR, Alpine AG, Germany).

[b] Prepared by dry sieving of the raw material.

[c] Not measured.

die wall was used during the compression, it seems reasonable that the contribution of particle-die wall friction to the resistance against powder compression is limited. Thus, the main factors contributing to the yield pressure value might be the resistance of particles to compress by deformation and the resistance against compression due to increased interparticulate bonding with a reduced porosity. However, the material (sodium chloride) which formed the strongest compacts (Fig. 1) gave the lowest yield pressure values (Table I) while the material (sodium bicarbonate) which showed the lowest compressibility gave the weakest tablets. It seems thus not likely that the compression process is governed by the formation of interparticulate bonds which suggests that the yield pressure value is a measure of or reflects the deformability of the material. Thus, the results indicate that sodium chloride is more deformable than lactose and sucrose, showing similar deformability, while sodium bicarbonate is the least deformable material. The consequence of the conclusion is also that a decreased original size of the particles reduces the degree of particle deformation which takes place during compression, i.e. a decreased particle size will reduce the deformability of the particles.

Since the yield pressures were derived from in-die porosity data, the yield pressures reflect both elastic and plastic deformation of particles. The materials used in this study was chosen to represent materials with different compression behaviour in terms of fragmentation propensity and deformability. However, the materials were chosen also due to the suggestion (1) that they possess limited elasticity. It is thus suggested that the yield pressure reflects mainly the propensity of these materials to deform permanently during compression.

The *tensile strength of the tablets* related nearly linearly to the applied pressure (Fig. 1). There was a tendency that a decreased original particle size gave a more marked deviation from a straight line, especially for sodium chloride.

For compacts of sodium chloride, a reduced original particle size generally increased the tablet strength (10) (the opposite effect has also been reported (11) during compaction of relatively coarse sodium chloride particles). For the other materials, a limited effect of original particle size for the compactability was obtained. For sucrose and lactose, there was a tendency that a reduced original particle size increased the tablet strength. For sodium bicarbonate, the two coarser size fractions gave similar compact strength values while the smallest size fraction gave a reduced compact strength. Generally, sodium chloride gave the strongest compacts, while sodium bicarbonate gave compacts of the lowest strength, i.e. the low fragmenting materials represented the extremes in this study in terms of the compactability of

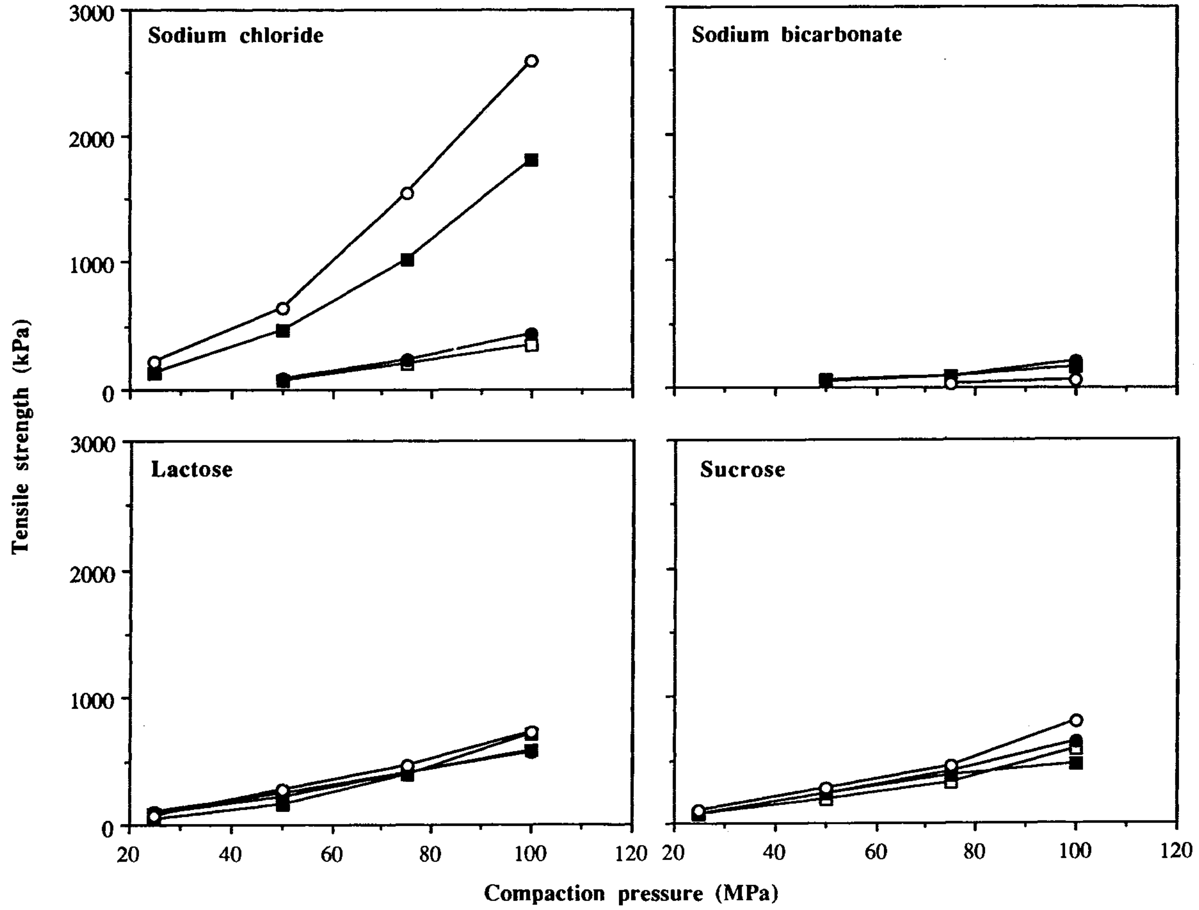

Fig. 1. Tablet tensile strength as a function of compaction pressure for all materials and particle size fractions used. (□) Tablets of 250-300μm particles; (●) Tablets of 125-180μm particles; (■) Tablets of 40-60μm particles; (○) Tablets of 10-20μm particles.

the materials. Thus, the material related differences in compactability were generally related to the deformability of the materials, as assessed by the yield pressures.

The results obtained on the compactability of the powders indicate thus firstly, that the compactability was generally related to the deformability of the particles and, secondly, that the original particle size had generally a limited effect on the compactability of the powders. The following discussion is an attempt to mechanistically explain these findings. The aims with the discussion are also to summarize this explanation in an expression which quantifies the strength of the interparticulate bonds in a tablet cross section, to compare this with the experimentally determined tensile strength of the tablets, and to identify probable reasons for a discrepancy between experimentally determined and theoretically derived tensile strength values.

A Theory on the Interparticulate Bond Formation Process During Powder Compaction

The literature indicates that a pharmaceutical compact can be described in terms of a large aggregate of particles which are strongly co- or adhered to each other (1). The consequence of this model is that bonds within particles will be stronger than bonds between particles and the compact will thus fail mainly around rather than across particles. This is probably valid at least for relatively porous compacts which is applicable to the compacts used in this study. The tensile strength of the compact will thus theoretically be governed by the sum of the bonding forces of all individual interparticulate bonds in the failure plane of the compact (12, 13), i.e.:

$$\sigma_t = n_b F_b \qquad (1)$$

The validity of Eq. (1) requires probably, that the fracture plane is formed instantaneously, i.e. all bonds over the whole cross sectional area of the fracture plane are broken simultaneously. However, the process of fracturing a compact is kinematic in its character, i.e. the fracturing is a result of a crack initiation-propagation process. The consequence might be a discrepancy between the measured tablet tensile strength and the strength of the bonds over the fracture surface.

The determination of the variables on the right side in Eq. (1) requires a detailed knowledge of the characteristics of the particles which constitutes the compact with respect to their size and size distribution, shape and relative positions. Such a detailed analysis of the physical structure of a compact is difficult to make. A simplified approach will instead be adopted here involving the use of measures which reflects the variables in Eq. (1). This simplified approach involves the assumption that the bonds between "compact particles" are uniformly distributed over the fracture surface of a compact. In practice, compacts are non-uniform with respect to their local porosity which probably means that the interparticulate bonds over a plane in a compact shows a distribution in bonding force. However, in order to derive a quantitative approximation of the bonding force of the interparticulate bonds, the question of the distribution in interparticulate bonding force is here neglected.

For a porous specimen, it is normally assumed that the fraction of solid material in the fracture plane of the specimen can be estimated as $(1-\epsilon)A_c$. The number of particles per cross sectional area of tablet fracture surface can then be estimated from the projected area of the particles which is a function of the particle size:

$$n_p \propto (1-\epsilon)\, S_v^2 \qquad (2)$$

It is reasonable that the number of interparticulate bonds in the cross section is proportional to the number of projected particles in that section. Due to the lack of a detailed description of the packing characteristics of the particles, the relationship between number of bonds and number of particles, i.e. the co-ordination number, cannot be defined. However it has been suggested that for loosely packed aggregates, the number of bonds per projected particle is proportional to $1/\epsilon$ (12) and this value will here be applied on the more dense aggregates used in this study. The following measure of the number of bonds per cross sectional area of the tablet fracture surface will then be obtained:

$$n_b \propto [(1-\epsilon)/\epsilon]\, S_v^2 \qquad (3)$$

Thus, an increased tablet surface area will theoretically increase the number of interparticulate bonds in a compact cross section and explain why fragmentation can be described as a bond forming compression mechanism.

As discussed, the surface area of the compact reflects the size of the compact particles. Generally, an increased tablet surface area corresponded to an increased tablet strength (Fig. 2). However, due to the marked effect of original particle size on the relationships, it is not possible to describe the results in general terms as a relationship between tensile strength and surface area of tablets.

In Fig. 3, the tablet tensile strength is shown as a function of the number of bonds in a cross section of the tablet, as assessed by Eq. (3). Generally, there are reasonable linear relationships between tensile strength and number of bonds. The low fragmenting materials have generally a considerably lower number of bonds compared to the fragmenting material and thus, a marked difference between the different materials with respect to the relationship between number of bonds in a tablet cross section and the tablet tensile strength exists. Furthermore, a reduced original particle size will give a relatively more marked effect on the estimate of the number of bonds compared to the tensile strength, i.e. an increased bonding potential due to an increased number of bonds in a cross section had a limited effect on the tensile strength.

It is thus suggested that an increased surface area of the tablet improves the interparticulate bonding potential of the specimen due to an increased number of bonds per compact cross sectional area. However, the relationships between tensile strength of the tablet on the one hand and surface area or number of bonds per cross sectional area of the tablets on the other, indicate that compacts prepared of comparatively small particles gave an unexpectedly low tensile strength. This can be explained by assuming that the coarser particles have the potential to locally develop stronger interparticulate bonds. Moreover, sodium chloride particles gave generally

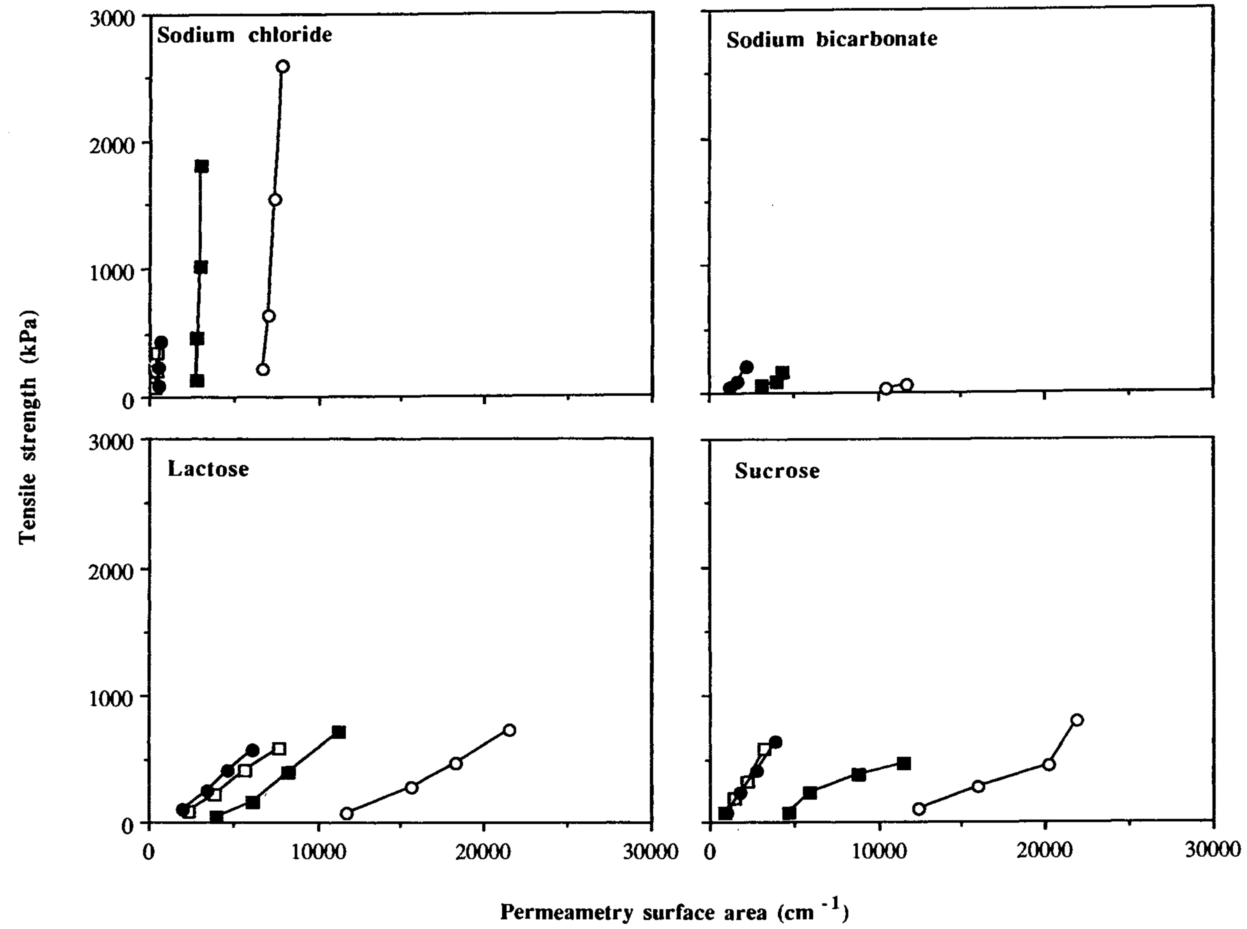

Fig. 2. Tablet tensile strength as a function of tablet surface area for all materials and particle size fractions used. Symbols as in Fig. 1.

stronger compacts than the other materials in relationship to the number of interparticulate bonds, i.e. it seems that this material has the potential to develop comparatively strong interparticulate bonds during compression. Thus, the parameter bonding force in Eq. 1 (F_b) seems to be dependent on the material and on the original particle size.

Some reasons for a variable bonding force dependent on material and original particle size can be identified. Firstly, the nature of the interparticulate bonds may vary which can affect the bonding force. Surfaces may interact over some distance with intermolecular forces but is has also been suggested (13) that compression might set up conditions for local fusion of particle surfaces. It has also been suggested that sodium chloride is a material which is prone to develop solid bridges during compression (1). Secondly, the strength of intermolecular attraction forces may vary between materials due to differences in surface energy (14, 15). Thirdly, different materials and different particle sizes for one specific material can possess differences in the propensity to develop interparticulate contacts during compression, i.e. the bond strength is similar but the bonding force varies due to differences in contact area.

During uniaxial compression of an assembly of particles, it is normally assumed that the force applied to the powder is transmitted through the powder bed at points of interparticulate contact. An increased size of the particles of the assembly will reduce the number of force transmission points (compare Eq. 3). Thus, the contact force at each interparticulate contact point will increase which might set up favorable conditions for an increased local particle deformation and hence, an increased interparticulate contact area. Deformation is governed by the stress conditions within the solid material. Since the contact force in practice is distributed over an area of contact, which is unknown, the stress conditions at the interparticulate contact points is difficult to define. However, by estimating in a simplified way the contact force between particles during compression and by assuming that local particle deformation is similar to plastic flow during indentation of a specimen into a particle (16), an estimate of the area of contact between particles developed during compression can be calculated.

The compression of an assembly of particles involves a number of processes including rearrangement of particles, particle deformation and fragmentation. Neglecting an initial phase of repositioning of particles, it has been suggested (1) that during compression of more or less non-porous particles, the compression process can be simply described as a sequence of two processes which result in irreversible changes of the particles: Fragmentation and deformation of the original particles in the first part of the compression

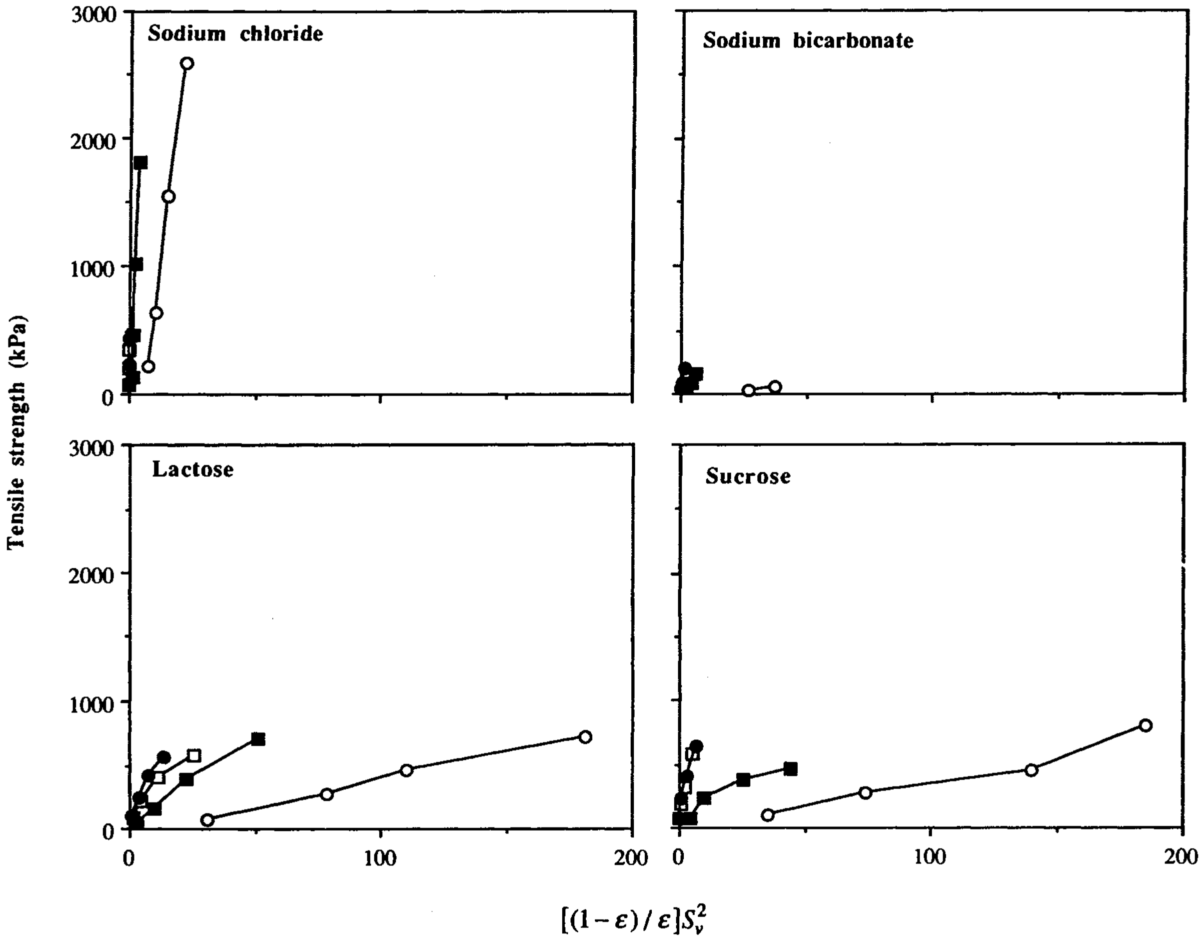

Fig. 3. Tablet tensile strength as a function of number of interparticulate bonds per tablet cross sectional area (as calculated with eqn. 3) for all materials and particle size fractions used. Symbols as in Fig. 1.

phase followed by deformation, mainly plastic, of the particle fragments in the second part of the compression process. By this description of the compression process, an estimate of the contact force between particles during the particle plastic deformation phase can be calculated as:

$$F_c = F_a/n_c \qquad (4)$$

and

$$n_c \propto [(1-\epsilon)/\epsilon]A_u\, S_v^2 \qquad (5)$$

The area of contact between particles can be estimated from the contact force and the indentation hardness of the material as (16):

$$a_c = F_c/H \qquad (6)$$

In this study, the yield pressure (P_y) rather than the indentation hardness (H) was measured to represent the deformability of the material, since this allows the determination of a measure of particle deformability for particles of a wide range of sizes under tabletting strain rate conditions. However, both values are essentially measures of particle deformability (17) and in this paper, P_y is used to replace H in Eq. (6). Combining Eqs. (4), (5) and (6) gives:

$$a_c = F_a\epsilon/[(1-\epsilon)\, A_u\, S_v^2\, P_y] \qquad (7)$$

Eq. (7) indicates thus, that a reduced size of the particles during the plastic deformation phase will reduce the area of contact developed between the particles and thus reduce the bonding force which is consistent with the conclusion above.

With a measure of the mean area of contact between particles, Eq. (1) can be rewritten as:

$$\sigma_t = n_b\, a_c\, \sigma_b \qquad (8)$$

Combining Eqs. (3), (7) and (8) gives the final expression for the tensile strength of a compact:

$$\sigma_t = [\sigma_a/P_y]\sigma_b \qquad (9)$$

If the expression is valid, a linear relationship between the tensile strength of the compact and the expression on the right hand side of the equation should exist. The ratio between applied stress and yield pressure is in the following discussion, denoted the bonding potential of the compact. In Figs. 4 and 5, the tensile strength of the compacts is shown as a function of this ratio. The relationships were generally nearly linear and the slope of the line represents theoretically, the tensile strength of a particle-particle bond.

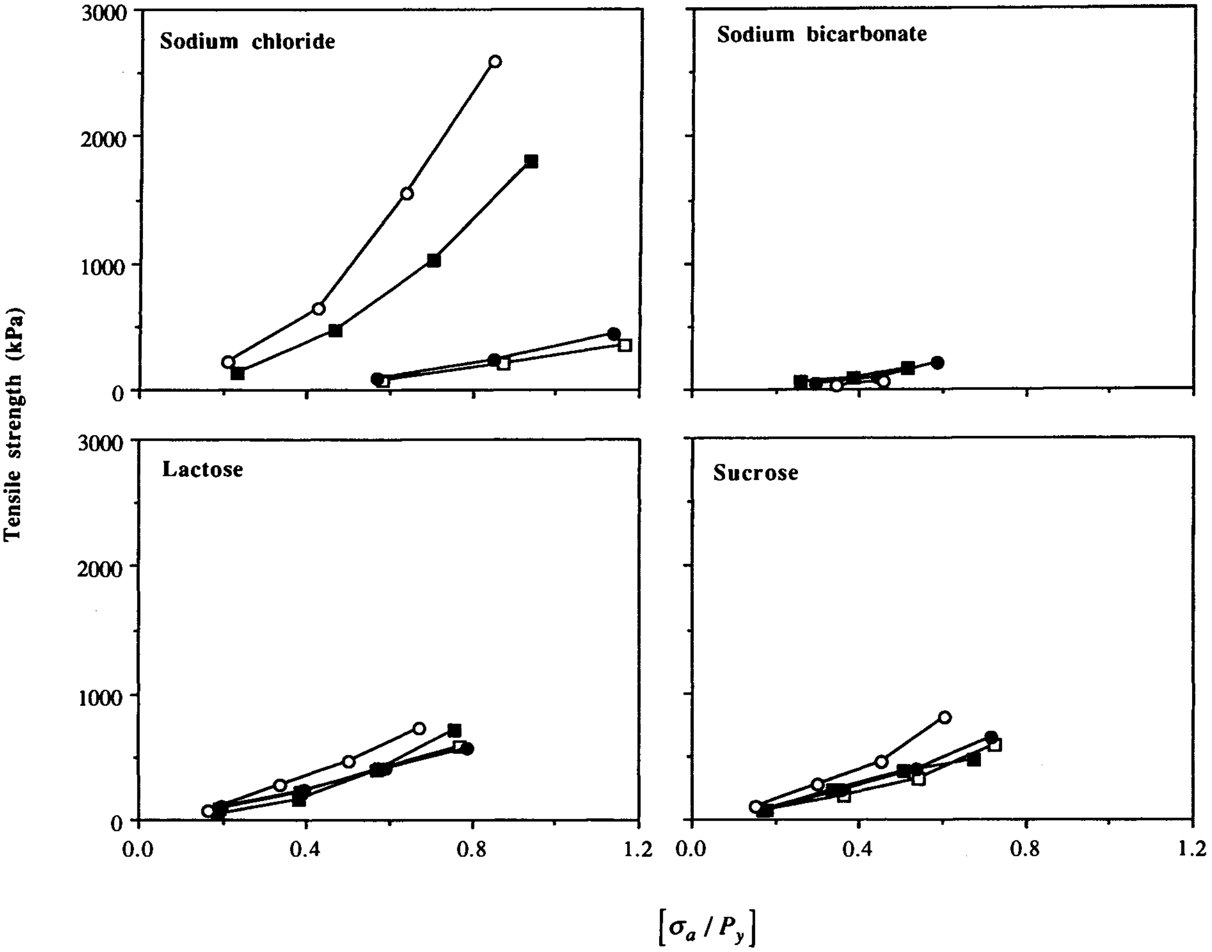

Fig. 4. Tablet tensile strength as a function of bonding potential (as calculated with eqn. 9) for all materials and particle size fractions used. Symbols as in Fig. 1.

A surprising consequence of the expression is that the tensile strength of a tablet is theoretically independent of the tablet surface area, although a decreased compact particle size will increase the number of bonds in a compact. The reason is that the increased number of bonds will be balanced by a reduced bonding force with a reduced compact particle size.

Generally, the bonding potential values correlated better to the determined tablet tensile strength values compared to the compaction pressure or the tablet surface area (Fig. 1, 2, 4 and 5). If the milled sodium chloride particles are ignored, which formed tablets of superiour and thus unpredicted high strength, the values of tablet strength conform reasonably well into a relationship with the bonding potential values if the data is classified into two groups depending on the compression behaviour of the materials, i.e. fragmenting and non fragmenting materials (Fig. 5, the relationships between tablet strength and compaction pressure are given as a comparison). One can notice that tablets of the fragmenting materials gave a relationship with a higher slope.

The lack of a general correlation between tablet strength and bonding potential values can be due to either errors in the quantification of the total strength of the bonds over the fracture plane of the compact or by a discrepancy between the theoretically derived strength and the assessed strength due to the character of the fracture event during determination of the tablet strength.

Concerning the quantification of the strength of the bonds, it is possible that small particles can form unexpected strong bonds due to a high particle surface deformability. The smallest size fractions used were prepared by milling. In addition, particles of the fragmenting materials will break down during compaction. Two consequences of these size reduction processes can occur: Firstly, on a molecular level, the surface of the particles will probably show a disordered, amorphous structure (18) and, secondly, on a microscopic level, the surface of the particles will probably show a rough texture with surface protuberances. These two phenomena might lead to a change in the mechanical properties of the surface and markedly increase the surface deformability (19), i.e. the surface deformability might be higher than the bulk deformability of the particles. Consequently, the bonding force will increase due to an increased area of bonding between particles which is larger than could be predicted from Eq. (7). This suggestion thus forms an alternative explanation for the observation that a reduced particle size can improve the compactability of a powder.

The unpredicted high strength of particle-particle bonds

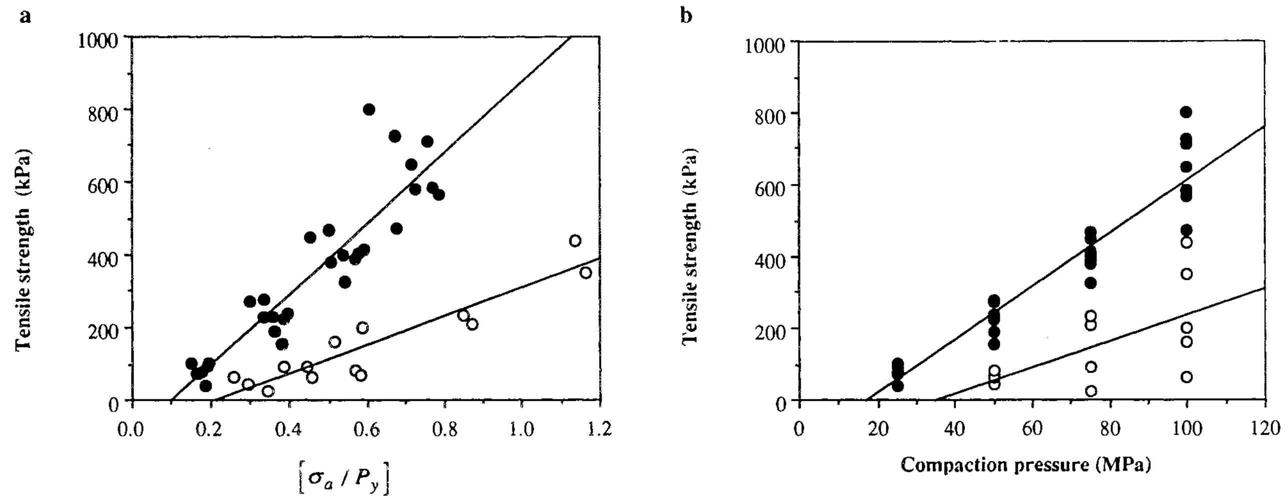

Fig. 5. Tablet tensile strength as a function of bonding potential (left graph, correlation coefficients 0.92 and 0.93 for fragmenting and non-fragmenting materials respectively) and compaction pressure (right graph, correlation coefficients 0.96 and 0.61 for fragmenting and non-fragmenting materials respectively). (○) Tablets of sodium chloride (except the milled size fractions) and sodium bicarbonate; (●) Tablets of lactose and sucrose.

for the fragmenting materials might also be due to higher strength of intermolecular bonding forces, e.g. due to the formation of clean, uncontaminated surfaces during the fracturing of the particles. Another explanation is that the fragmenting materials are more proned to locally fuse together and form solid bridges than the non fragmenting, e.g. due to high surface temperatures developed during particle fracturing.

Concerning the importance of the fracture event during determination of the tablet strength, a possible explanation is that tablet formed of small particles or of fragmenting particles are more homogeneous with respect to their pore size and bonding force distribution. A less marked effect of the crack initiation-propagation process might thus be the result.

It seems finally that tablet strength-bonding potential relationships for the coarser size fractions of sodium chloride coincide with the relationships for sodium bicarbonate powders. This indicates that the nature of the bonds in tablets of sodium chloride and sodium bicarbonate is the same, probably intermolecular attraction forces, or that both intermolecular attraction forces and solid bridges might bond particles together, but the strength of the bonds is similar between different bond types.

CONCLUSIONS

The derivation of the bonding expression (Eq. 9) summarises the theoretical considerations put forward in this paper on the process of forming bonds between particles during compaction of single-component powders:

i) The interparticulate bond structure in a pharmaceutical compact can be described simply in terms of the number and the bonding force of interparticulate bonds. The product of these will theoretically govern the tensile strength of the compact.
ii) Particle fragmentation and particle deformation are both bond forming compression mechanisms and their physical significance is to affect the number and the bonding force of the interparticulate bonds, respectively.
iii) The original particle size will affect both the number and the bonding force of the interparticulate bonds. Thus, the compactability of a powder will be influenced mainly by the deformability of the particles while the original particle size and the fragmentation propensity of the material will have a limited effect on the tablet strength. However, due to surface protuberances and surface amorphization, particles formed by milling or fragmentation might possess a surface deformability which is higher than that of unmilled particles,i.e. particle fragmentation can lead to a bonding potential of particle surfaces which is higher than can be predicted from bulk particle deformability.

The development of the expression required simplifications regarding the compression process and, in addition, the measures used are mostly specimen values with a certain variability. Nevertheless, an improved correlation between bonding potential and tablet strength values was obtained compared to correlations between tablet strength and compaction pressure or tablet surface area. Thus, the derivation supports the mechanistical conception summarized above and supports that the compactability of the particles was related primarily to their deformability. Particle deformability measures might be obtained from powder compression data, from indentation measurements of single particles or of compacts, or from the calculation of hardness of particles from the molecular structure of the material (17). It seems however that an important issue for the future is the question of surface versus bulk deformability of particles in relationship to bond formation during compaction.

ACKNOWLEDGMENTS

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NOTATIONS

Symbol	Meaning
A_c	Cross sectional area of fracture surface of tablet (m^2)
A_u	Cross sectional area of upper surface of tablet (m^2)
a_c	Contact area between particles in the tablet (m^2)
F_a	Applied compression force (N)
F_b	Bonding force of interparticulate bond (N)
F_c	Contact force between particles during compression of powder (N)
H	Indentation hardness (Nm^{-2})
n_b	Number of interparticulate bonds per cross sectional area of fracture surface (m^{-2})
n_c	Number of interparticulate contacts in an axial cross section of the tablet (m^{-2})
n_p	Number of particles per cross sectional area of fracture surface (m^{-2})
P_y	Yield pressure (Nm^{-2})
S_V	Volume specific surface area of tablet (m^{-1})
ϵ	Porosity of tablet (−)
σ_a	Applied compression pressure (Nm^{-2})
σ_b	Tensile strength of interparticulate bond (Nm^{-2})
σ_t	Tensile strength of tablet (Nm^{-2})

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