ELSEVIER

European Journal of Pharmaceutics and Biopharmaceutics 44 (1997) 229–242

European Journal of Pharmaceutics and Biopharmaceutics

Review paper

Principles, tenets and notions of tablet bonding and measurements of strength

Everett N. Hiestand *

The Upjohn Company, Kalamazoo, MI, USA

Received 20 June 1996; accepted 22 April 1997

Abstract

The interactions between two particles are discussed and related to the compact properties. Compaction removes barriers to spontaneous attraction and strength. The attraction comes predominantly from dispersion forces; individual atom-to-atom bonds are believed to contribute very little to bonding. Plastic deformation is a universal component of producing tablets. Viscoelastic properties are observed in all organic materials studied; this provides additional plastic deformation. The magnitude of the elastic deformation constant has minimal influence on bonding. A special continuum is defined for porous, Mohr bodies. The contact is defined as a solid bridge; other molecular processes that add to the strength are discussed. Some deficiencies and inconsistencies of specific models and theories in the pharmaceutical literature are indicated. Problems relative to measurements of strength are discussed. © 1997 Elsevier Science B.V.

Keywords: Tablets; Compacts; Bond; Bonding; Solid bridges; Dispersion forces; Continuum; Contact area; Solid fraction; Plastic deformation; Elastic deformation; Viscoelasticity; Mohr body

---

1. Introduction

The title describes the domain considered except that, post compaction processes, that add strength, are given only limited consideration. Principles are interpretations with strong documentation. Notions, chimeric science, often sound reasonable but fail careful scrutiny. Tenets have more rationale than notions but may lack the stature of principles. (It is left to the reader to decide what arguments rank as principles.) Examples will be quoted from current literature, usually reviewed journals, to indicate that there is current use of a concept/mechanism of tablet bonding. The persistence of questionable views indicates that critical comment is needed. While in practice maximum bonding is usually unnecessary, the advantages of understanding the process(es) is important. It is hoped that this analysis will promote discussion, and perhaps reduce misinterpretations.

The discussion herein attempts to establish that: (1) Close range dispersion forces account for most interparticle attraction, the attraction is spontaneous. (2) Solid bridges, as often defined, have no common, unique features except adding strength to an existing contact. (3) Much of the increased strength from compaction is enabled by plastic deformation, even when particle fracture is present and (4) yield and/or strength descriptions should include Mohr body and viscoelastic considerations. Many of the arguments are in simplified form, e.g. most complexities of crack growth in brittle, porous, viscoelastic, compacted powders are not considered.

Because tableting involves dramatic changes of consolidation, seldom is strain used to describe the process. Elastic and plastic strain are very different processes.

---

* Corresponding address. 11 378 East G Avenue, Galesburg, MI 49053, USA. Tel.: + 1 616 6657227.

PII S0939-6411(97)00127-6

With the multiparticulate solid—the compact—some volumes may be deforming plastically while others are not. Using pressures simplifies the characterization of the processes, however, knowledge of the kind of strain becomes essential to understanding them.

2. Existing Confusion

As with most products, tableting technology developed ahead of the theoretical understanding of the physical processes involved. Inadvertently this led to choices of words and explanations, notions, that may later be recognized as inappropriate, but are entrenched and persist. For example, a capped tablet commonly is said to have poor bonding which was overwhelmed by entrapped air. This is claimed without supporting data, and without indicating causative, physical differences that exist between capping and non-capping formulations. Most often, the bonding is more than adequate, the capping was caused by brittleness. Comparison of compaction pressures in air and in vacuum was revealing [1]; only very fine powders exhibited big differences. (Compacted cylandelate, which has a near room temperature melting point, rended with decompression to form fragments dissimilar to capping). Very fine powder does impede the escape of air; but such fineness introduces unacceptable flow problems and usually is avoided. Universally, it is recognized that both slower machine speeds and/or using a pre-compression stage may abate capping. This provides more time for both air to escape or for viscoelastic decay of the crack causing stresses. Viscoelasticity is always present; it produces accompanying plastic deformation for any significant strain. It reduces stress concentration.

In numerous areas, very different views exist. For example: (a) 'Bonding with solid bridges contributes to the compact strength only for coarse plastically deforming materials that can melt during compaction'. (b) 'It is suggested that most of the so called plastically deforming pharmaceutical materials often possess inadequate plasticity for the development of large zones that could take part in the interparticulate attraction by intermolecular forces' and (c) 'the term, intermolecular forces, is used in this article as a collective term for all bonding forces that act between surfaces separated by some distance.' [2]. The credibility of these views depends on critical supporting data, viz. For (a): Since either plastic deformation or chemical decomposition may occur at lower pressures or temperatures than melting (even if melting could happen), a clear demonstration of melting is needed. (Furthermore, the definition of a solid bridge is ambiguous, see Section 3.5.). (b): The strengthening from plastic deformation may be from increased radii of curvature of surfaces, etc. The implied requirement for large zones needs justification. (c): A physical model is needed, one that would yield a maximum stress at 'some distance', not at contact. The unique 'at some distance' postulate seems to exclude, even at rest, the consideration of the major source of attraction, close range dispersion forces (See Section 5). The arguments presented below use existing concepts from physics, engineering and material science.

3. Interactions at/near interparticle contacts

3.1. Attraction and contact

Tablet bond refers to total attraction, not to a single atom-to-atom bond. The word 'bond' risks distorted visualization/interpretation from the readers familiarity with chemical bonds, to avoid this, bonding will be used instead of bond. The interparticle pores combined with crystal lattice discontinuity at contacts preserve the particulate focus of the bonding process. Thus, bonding is the summation of interatomic attraction between particles that becomes manifest as tablet strength during separation. In the absence of chemical interaction, an interatomic bond is limited to random cases where polar interactions or H-bonding would have the needed juxtapositioning of atoms across the interface and also exist at or near optimum interatomic spacing. These conditions could occur only near the perimeter of a contact; elsewhere the contact consists of atoms so close that Born repulsion counters the bonding forces. The incidence of the chance arrangements for optimum H-bonding in pharmaceutical tablets is expected to be small. That they are not the major contributor to bonding is supported in Section 5.1.

Thermodynamically the attraction between particles is universal, coming together and forming interfacial (contact) areas, bonding, is the lower free energy condition [3]. This is somewhat analogous to the common experience of bar magnets spontaneously going to their lower free energy condition, attraction. Some confusion exists in the tableting literature; for example [4]: 'Processes which consume energy during tablet compression include:....the formation of bonds...... It was further assumed..... the total network or a certain fraction of it, was used for bond formation,.....' From basic thermodynamic principles, it is clear that a site that consumed energy would be a site of repulsion, not bonding.

The above arguments indicate that tablet compaction is the disarranging of barriers that mechanically interfere with increased numbers of atoms coming close together. Tableting is the process of sliding, fracturing and deforming particles enough to fit them closely together, the attraction is inherent. Molecules deposited by various mechanisms may add to the strength produced by compaction. However, molecular diffusion mechanisms are too slow to be major contributors during the compaction process. Some may alter bonding soon after compaction or during the shelf live of the compact. Compaction induced melting–solidification is discussed in Section 8.1.

Nascent powder beds are different from compacts because of the absence of external loading, the resultant interparticle contacts are small in size and few in number. As with compacts, total attraction and Born repulsion within the contact are in balance. The number of contacts are limited by the random events of unaided (no external load) aggregation and inherent barriers to rearrangement after first contact. The energy required to break a contact inhibits rearrangement. Thus, first-collision statistics and gravitational forces determine the consolidation of a nascent powder bed. (This is similar to flocculation kinetics in suspensions.) In practice, the truly unaided condition may not exist because powder is moved to storage, etc. Even flow induced by gravity produces shear deformation within the powder bed; multiple collisions replaces first collision considerations. However, consolidation reaches a steady state condition for that stress condition, sometimes called the critical consolidation. Nevertheless, there is nothing unique about the physics of interparticle contacts in a powder bed.

Knowledge of contact changes both in number and size with stress, compression, shear and tension, is important. Principally, it is the mechanical properties that control these [5,6] whether for powders or for compacts. Without a quantitative treatment of some model case, one is left only with unreliable intuition. Qualitatively, the events at a contact become obvious from the contacting sphere model (CSM), which [7] will be used instead of intuition. Because the CSM uses the harmonic mean of the radii of curvature of the contacting surfaces, it accommodates flat, concave or convex surfaces. Also, the general mechanisms of the CSM are not restricted to isotropic, homogeneous complete spheres. (Of course, the specific properties of the interacting materials must be used for quantitative calculations.) Thus, if the curvature at and near the contact approximates a spherical segment, the CSM may give rough estimates of reality. For compacts, plastic deformation 'erases some memory' of the original shape, this improves the correspondence to spherical segments. However, with hard particles deforming softer particles and with normal, rotational and shearing stresses all present [5] the spherical similarity diminishes. The ever present viscoelastic effects add further complications. With cognizance of limitations, one can learn much from a simple model for which quantitative treatments [6,7] have been developed—the CSM. The CSM teaches: (a) The strength is determined while the contact has significant size; (b) the separation of particles may be either brittle or by ductile extension, and (c) increasing radii of curvature from plastic deformation of compression may convert sites of ductile extension to brittle [6]. These conclusions are assumed for this discussion. Some illustrative equations for the CSM are given later as examples.

3.2. Bonding strength

An arbitrary choice must be made for a mechanical property to represent the bonding strength of a compact of a given solid fraction (1-porosity). Compressibility is not used because in the fundamental sciences compressibility refers to volume change vs. pressure, not mechanical strength. (Air is highly compressible but not compactible.) Indentation hardness has been used for compactibility [8] and, indeed is a useful mechanical strength parameter [9]. However, for this discussion, tensile strength is chosen to characterize bonding strength because an adequate tensile force assures fracture. Since compacts are Mohr bodies (by definition the yield criterion for Mohr bodies is a function of both distortional and dilatational stresses), the tensile strength is a much smaller number than hardness for compacts. The tensile strength has the units of stress, force/unit area, over a cross section that includes the pores of the compact. It is the maximum stress, the stress that produces separation. The cross sectional area is not considered for two particles, strength is separation force, not stress.

For strength comparisons, a reference state of consolidation is needed. Much of the literature data is presented as the strength parameter vs. the compaction pressure used to make the compact. This may lead to unrecognized, ambiguous conclusions. The same pressure could produced very different solid fraction compacts with each material. Even with the same material, the compacts produced at a given compaction force may be different if: (a) Different compaction dwell times are used; (b) the size of the die and/or the amount of powder in the die are different; (c) the temperatures are different; and (d) lubrication conditioning of the die and punches is different. Furthermore, at very high solid fractions differences among materials occur because, a significant but different portion of the compaction pressure may appear as a macroscopic hydrostatic stress. As the free surface area diminishes during compression, a larger portion of this stress becomes INTRAparticle hydrostatic stress which contributes nothing to bonding (it cannot plastically deform the particle). It is just elastic displacement recovered during unloading [5,10]. Since compacts are not homogeneous, the mean solid fraction of the compact is not the perfect reference state, but it does reduce ambiguity. To demonstrate this, compacts of the same solid fraction, were made using separate portions of the same powder conditioned by storing at two different temperatures. Those compacts made at room temperature required a significantly lower compaction pressure than those in a −40°C environment. However, the tensile strengths measured after reaching room temperature were the same for both. Clearly the solid fraction of the compacts identified the same structure. The compaction pressures were not indicative of the similarity.

The strength differs from the interaction forces acting when at-rest, i.e. with no externally applied force (neglecting gravity). Of course the net force acting at rest is zero, the attraction equals the Born repulsion. The at-rest contact area has been studied using compacts at various solid fractions by gas adsorption. As compaction proceeded, both particle fracture and plastic deformation could be detected [11,12]. The most detected, compression induced particle fracture occurs at the lower solid fractions. For a given material, it is reasonable to assume that the larger the at-rest contact area, the stronger the bonding. Applying a tensile force induces changes in the contact area. The magnitude of the tensile force is the first derivative of the interaction energy vs. separation distance. The tensile strength is the maximum value of the derivative which occurs with the particles still in contact. Either plastic extension of the contact region or brittle separation occurs at the maximum. The contact area at the maximum is called the strength tensile-critical contact area.

When the compressed surfaces of two particles in the CSM undergo only elastic deformation, rebound would return the two surfaces to their original size and positions and no increased strength would result. However, for a compact with only elastic deformation, other processes must be considered, viz. (a) Compaction would produce denser packing, some additional contacts would remain after unloading and a modest strength increase result and (b) if particle fracture resulted in denser packing, the result would be as in (a) but with a greater strength increase. However, to obtain strengths approaching experimental values, plastic deformation is required. Neither fracture nor plastic deformation is preclusive, but, interactive in that increased plastic yielding decreases the fracture tendency. Clearly, both may occur in a tablet compaction cycle. Therefore, the cumulative effect cannot be easily predicted.

3.3. Plastic deformation during compaction

The CSM tensile strength equations require the unloaded radii of curvature of surfaces that separate. If no plastic deformation occurs at the contact, the radius of curvature would be the harmonic mean, R, of the original, contacting surfaces. Most importantly, plastic deformation in the contact region during compaction (followed by elastic unloading) increases the effective radius of curvature over that of the starting value. This brings more atoms close together and increases the strength. The new value of R is obtained by setting the plastic deformation force, the hardness, equal to the maximum applied force, f_m, in Hertz' classical elasticity equation. Elastic unloading is assumed. Eq. (1) [10,13] describes this.

$$R = \frac{4E'a_m}{3\pi H} \tag{1}$$

where all are particle, not compact values. H, hardness of softer material; a_m, the maximum contact radius for the compaction. $1/E' = (1 - \nu_1^2)/E_1 + (1 - \nu_2^2)/E_2$; E, Young's Modulus; and ν, Poisson's ratio, the subscripts indicate respective materials; R, the harmonic mean radius of curvature (the effective radius); $R = r_1 r_2/(r_1 + r_2)$, r_1 and r_2 would be the radii of curvature of the two surfaces after unloading.

When using the changed curvature concept in equations to estimate the theoretical bonding strength for compacts, the results fell somewhat short of predicting the full strength [10,13]. This model does not consider that shear induced plastic deformation may be more effective at increasing total contact area than normal stress [14]. Also, particle fracture during compaction is ignored.

3.4. Rate dependent plastic deformation

The earlier statement that viscoelasticity is always present was based on laboratory experience, not dictated by theory. Viscoelasticity is not required for compact formation. Powder metallurgy is a very important technology where the metal particles may have insignificant rate dependent properties. Because they deform plastically, significant 'green strength', before sintering, can be developed with many materials. While the hardness of metals is much higher than for organic pharmaceuticals, the adhesion forces, also, are much much higher. However additives may be useful. Ceramics are less malleable and organic binders become essential. These technologies are different from pharmaceutics; success is defined as very dense, uniform packing in desired shape with sintering or firing providing needed strength. The following quotation [15] is most revealing: 'It has been demonstrated that a soft binder or, more precisely, one with a glass transition temperature less than the room temperature results in better dimensional reproducibility than observed for a hard binder (i.e. $T_g >$ room temperature). These differences are attributed to stress relaxation differences in the organic binders and their influence during pressing and ejection. The results emphasize the importance of the mechanical properties of organic binders and clearly indicate the need for increased fundamental understanding of the organic phase during ceramic processing and fabrication.' The statement has a familiar ring. For pharmaceutics, viscoelasticity is an aid in bonding and the prevention of fracture but imposes strain rate dependency on processing. The benefit outweighs the problems.

Viscoelastic decay of stress occurring within the contact region changes both the unloaded geometry and the resultant tensile-critical radius of interparticle contacts. It is the combination of the applied stress (includes residual stress following compaction) plus the thermally induced random stress that induce the viscoelastic decay of stress. Since both are required, the decay proceeds only as long as the additive value of the two stresses is sufficiently large. The viscoelastic properties of compacts can be related to the viscoelastic properties of the particles [16]. This is reasonable, since time induced stress decay depends on random thermal fluctuations of localized energy. The total mass of the particle combined with bonding energies at contacts of a particle may be so large that whole particle response to random thermal fluctuations are extremely rare. With viscoelasticity, the time of compaction plus the time to make a measurement allows the stress distribution in the contact region to change dramatically [17–19] and results in a different tensile-critical radius of contact and tensile strength. Obviously, any equation for calculating the strength is complex [10]. To obtain reproducible experimental results, a rigid time schedule must be followed for making compacts and testing them.

3.5. The solid 'bridge' between particles

Solid bridges have been mentioned earlier and need a definition. Usually bridges connect two objects by spanning a chasm. Processes that happen at an existing contact, sintering, melting, crystallization, chemical reactions, and hardened binders [20] have been grouped as solid bridges [2]. Solid bridges so defined have no universal feature; except for being strengthening mechanisms unburdened by the inherent stresses induced by compaction. However, the kinds of attraction forces acting always include close range molecular forces. At normal compaction rates, none of those processes are common or frequent participants (Section 8.1 discusses compaction melting/solidification.) during the compaction. They occur later. The nomenclature choices are: (a) All contacts are solid bridges, i.e. any solid-to-solid contact; (b) a chasm isn't spanned; a bridge doesn't exist; or (c) solid bridges refer to post compression processes. The first is chosen by the author to emphasize that contacts are solid-to-solid. Since viscoelasticity, also, is a post compaction process, choice (c) would need refinement. Even without the strengthening mechanisms, any contact meets the criterion stated by some solid bridge proponents, viz. 'Solid bridges that contribute to the overall compact strength can be defined as areas of real contact, i.e. contact at the atomic level between adjacent surfaces in the compact.' [2].

Clearly the contact, whether between likes or unlikes, lacks crystal lattice continuity. (This is similar to the grain boundary of polycrystalline solids). Viscoelastic decay of stresses within the contacting particles results in changes of contact radius and produces stress distribution changes. Using the CSM to interpret overall plastic deformation and associated radii of curvature changes [10–13], one concludes that modest plastic deformation at contacts dramatically increases the strength; large zones of plastic deformation are not needed. Clearly, plastic deformation is a major factor in determining the size of a contact and strength of bonding.

A common observation in tableting is that two lots of the same material have very different tableting characteristics, lot-to-lot variation. This is true even when the usual specifications have been met, viz. same chemical purity, same polymorph, same hydration, same particle size, etc. Because mechanical properties, e.g. plastic yield value, which depend on defects are very sensitive to factors not in the usual specifications, it is easy to understand why lot-to-lot variations are commonplace.

3.5.1. Depositions around a contact

Since tablets are stored for significant periods before being used, events occurring after the compaction of the tablet may influence the strength. Surface diffusion, especially on surfaces with adsorbed water, and occasionally sublimation may occur so that the at-rest contact regions grow during the storage time. This deposition around the contact region results because the contact perimeter has very low curvature (normal to contact plane); thus, the free energy can be lowered by deposits increasing the radius of curvature at that site. With deposition, the free energy change diminishes and the deposition will slow, essentially cease. However, significant influence on the strength of the interparticle contact region may have occurred before it stops. Add to this the viscoelastic effect on the stresses from compaction and it becomes difficult to describe the stress state, size and tensile strength of a contact. A further complication arises when water vapor condenses and is both adsorbed and absorbed. In practice, this cannot be dismissed; however, it is a material specific behavior that is outside the usual discussion of mechanisms of tablet bonding.

4. Equations for the contacting sphere model

Despite the complexity of interparticle interactions [21], the CSM has been invoked in the preceding discussion to indicate some mechanisms/concepts. It is the separation process that helps most in understanding what determines strength; perhaps it is useful to look at some specific equations. Briefly, Hertz' law of elasticity for spheres is combined with particle attraction based on the change of surface energies [7] to obtain Eq. (2) for the pull off force for brittle separation; the definition of symbols is consistent for all equations.

$$f_a = -\frac{3}{2}\pi R\Delta\gamma \tag{2}$$

where f_a is the attraction force at pull off of two spheres and $\Delta\gamma$ is the change of surface energy (air–surface to solid interface) $\Delta\gamma = \gamma_1 + \gamma_2 - \gamma_{12}$, the subscripts on surface energy terms identify individual materials with 12 for the solid interface. Tension is given a negative sign. As tension is applied, the chordal radius of the contact area decreases to reach a critical contact radius, a_c, where catastrophic separation occurs. In some studies, viscoelastic effects are incorporated by using time dependent values of E', viz. E'_0 as the instantaneous elastic constant and $E'\infty$ as the totally relaxed value. The analogue of Eq. (2) including this viscoelastic effect on crack growth (the contact separation), is given in Eq. (3) [19,22].

$$f_{av} = -\frac{3}{2}\pi R\Delta\gamma\frac{E'_0}{E'_\infty} \tag{3}$$

where f_{av} is f_a but for viscoelastic spheres. Since $E'_0 > E'_\infty$, $f_{av} > f_a$. The influence of stress decay in the contact region [10] during long term storage is not included with this treatment of viscoelastic materials.

An alternative must be considered, e.g. under the tensile load the contact region might deform plastically, i.e. undergo ductile extension. A chordal radius, a_d, defined as the radius at which ductile extension would occur can be estimated by balancing attraction and hardness [22]. The condition $a_d > a_c$ is necessary [10]; otherwise brittle fracture would precede ductile extension. This results in a less obvious, additional criterion for this process, a maximum value of R beyond which ductile extension will not occur [10]; the brittle condition is reached before the ductile one. Thus, with larger particle materials, ductile extension may not occur. Within the compact, each contact has its own history. With compacts of lower solid fractions subjected to tensile loading, some particle contacts could undergo ductile extension while a neighboring contact is failing by the brittle mechanism. At higher solid fraction the brittle mechanism would control the strength because the plastic deformation caused a majority of contacts to have a radius of curvature larger than the criterion that allows ductile extension.

Data for compacts have been presented [10]. Single particle data were not obtained; effective mechanical properties for the non-porous solid were estimated from data obtained at lower solid fraction. With non-linear curve fitting for the plotted data, effective $\rho_r = 1$ values from the curve were used for particle properties. The compact is the sum of many contacts. Values estimated for a single contact were multiplied by the estimated total contact number in a cross section. Many problems were discussed [10]. Nevertheless, the general principles described above remain valid. The compact is an assemblage of particles that are held together by attraction at and around the areas of contact. Attempts to extend the calculations from the two particle case to the compact are difficult. Long term methods based on particle properties [23] should be the objective.

Maugis [24] reports on various separation mechanisms and other conditions that produce effects not included in the above discussion. He considers cases where the near at-rest attraction is sufficiently high to produce plastic deformation 'around the Hertz point' even without an external load. Usually this force would be relatively small compared with the applied compaction force. Thus for compacts, it may be of minor importance. However, for powder flow, this could be a significant effect.

5. Interfacial energies

Note that the energy term for attraction in the equations always is the change in surface energy, $\Delta\gamma$, the energy of forming new surfaces at separation. The following argues that the principal energy components acting at the interface of organic solids are the dispersion interactions. While the dispersion forces of particles act over relatively long distances as emphasized by some investigators [25], their magnitudes at short range are much, much greater. The short range interactions are the major contributor. This is consistent with the fact that the short range interactions contribute much to holding together the crystals of many molecular, organic materials. This is clearly stated by Kitaigorodoskii [26]. He indicates that packing in the crystal is strongly influenced by providing maximum conformity for increased dispersion interactions. Furthermore, it has been suggested that the very close range interactions at interfaces are even stronger than those calculated using surface energies. Tabor [27] states: '....the van der Waals dispersion forces are substantially increased when the orbitals are in contact this further emphasizes the importance of the interfacial atoms as distinct from the contribution of those in the hinterland.' He further indicates that '....as the orbitals come into contact extra interactive energies are involved which are about twice as large as the calculated dispersion energies.' Clearly, an understanding of dispersion forces is needed. Section 5.1 and Section 5.2 attempt to provide insight into their magnitude.

5.1. Comparing liquids and solids

Surface energy is a manifestation of cohesive energy. The absence of molecular attraction (very few molecules in air) in one direction creates the surface. Since a phase change doesn't change the kinds of atoms involved, the range of values for surface energies of organic solids are not expected to be significantly different from organic liquids, once corrected for density. Unfortunately, accurate data for the surface energy of solids is much more difficult to obtain than for liquids. The restricted motion of molecules at solid-solid interfaces inhibits the attainment of optimum orientation and positions for polar interactions across the interface. Thus, the ratio of polar to dispersion forces contributing attraction across solid interfaces should be less than with liquid interfaces.

Within the crystal, the orientation of molecules results in different surface energies for different crystal lattice planes. A particle exposes several crystalline planes. Minimizing the free energy of the system would require that the number of most active groups on the surface be minimized. However, in the absence of specific information on a given material, it is assumed that an average for all exposed faces is similar to the liquid. Adsorbed material may be attached to the surface and lower the surface energy. Fortunately, this effect is minimized because the powder surfaces bonding in compacts, seldom consist predominantly of nascent surfaces that could have adsorbed material from the mother liquor. All surfaces are exposed to water vapor which may influence the magnitude of other surface interactions. However, this may not be a serious problem. For example, various forms of lactose are used, yet, the surface energies appear to be approximately those expected from similar liquid data [10], in the 71–78 mN/m range [28,29]. Thus, examining the data for liquids can be instructive.

The data in Table 1 supports the earlier statement, dispersion forces dominate the interaction of organic materials. Water is included in this table and dramatically illustrates an important point even though it is not an organic liquid. Clearly, the relative H-bond component in water, about 70%, must be greater than for any organic material. The author is unaware of an organic structure that potentially could have a higher percentage H-bonding than glycerol and formamide, both have the polar component of less than 50% of the total. A conclusion of less than 50% polar interaction probably applies to all organic liquids and solids. The data in this table provides another insight, viz. the surface energy of a molecular, organic solid would not be expected to be many times that of water. Differences of density must be corrected since the density of 'force fields' includes total density. Of course, constituent atoms must be considered. Atoms with many electrons, e.g. bromine, can increase the dispersion force.

5.2. Fractional components, interfacial and solubility parameter data

Contact angle measurements using more than one liquid (one at a time), whose properties are known, provide enough information to permit obtaining both an estimate of the total surface energy of the solid and the fractions due to dispersion and polar forces. The latter by solving resultant simultaneous equations. Great care is needed with these studies. Corrections for spreading pressure and the effects of errors in measuring the contact angle must be considered. (Small errors in values used in simultaneous equations may yield large errors in the calculated result. It is said that contact angle errors have less influence when the liquids have very different polarities [39]). Because of these problems, some published work contains serious errors.

The theory of solubility parameters is limited to cases where polar interactions are so weak that they do not change the entropy. Ignoring this theoretical restriction, the concept has been extended empirically to include very polar materials. The data for polar materials provide a total solubility parameter, δ, and the three separate components, viz. dispersion forces, δ_d; polar forces, δ_p; and H-bonds, δ_h. It is assumed that $\delta^2 = \delta_d^2 + \delta_p^2 + \delta_h^2$. The success in practice of this empirical data has provided a strong testimonial for them [40–42]. Using extended solubility parameter values, an impressive empirical relationship with surface energy, Eq. (4), has been established [41].

$$\gamma = 0.0575 V^{1/3}\{\delta_d^2 + 0.632(\delta_p^2 + \delta_h^2)\} \tag{4}$$

For many materials, the calculated surface tension from solubility parameter data differs from directly measured surface tensions by less than 1 mN/m if classes of functional groups are considered. [41] The overall proportionality constant, 0.0575, was deduced from considerations of the change in numbers of nearest neighbors when moving between the bulk and surface. It is critical to recognize that the constant 0.632 is less than one, the relative magnitudes of the non-dispersion interactions in solutions are always a larger proportion than at interfaces. The solubility parameter data included in Table 1 illustrate this point. Thus for solid-solid interfaces, it is indeed risky to assume solubility parameter energy distribution fractions to be representative of those acting at solid interfaces; this would over-estimate the role of polar forces. Added perspective for the relationship is given by Fowkes [43].

Table 1
Surface energy γ (mN/m) and solubility parameter δ (MPa$^{1/2}$) for various materials

Material	Parameter	Total	Dispers. comp.	% Disper. energy[a]	Reference
Water	γ	72.8	21.8	30	[30]
	δ	36.2	11.7	10	[31]
Glycerol	γ	63.4	37.0	58	[30]
	γ	63.3	20.2	32	[32]
	γ	64.0	34.0	53	[33]
	δ	27.4	13.1	23	[31]
Formamide	γ	58.2	39.5	68	[30]
	γ	58.4	19.8	34	[32]
	γ	58.3	32.3	55	[33]
	δ	27.7	13.0	22	[31]
Ethyleneglycol	γ	48.9	33.4	68	[34]
	γ	48.2	18.9	39	[32]
	δ	22.9	12.2	28	[31]
1,3 Butanediol	γ	39.1	32.5	83	[34]
	δ	21.8	12.5	33	[31]
Bromobenzene	γ	36.3	36.3	100	[30]
	δ	16.4	15.5	89	[31]
Aspirin	γ	67.5	39.4	58	[34]
Hydrocortisone	γ	68.7	45.1	66	[34]
Ethinamate	γ	70.01	43.3	62	[34]
Parahydroxybenzoic acid	γ	68.3	40.6	59	[34]
Magnesium stearate	γ	3.0	23.0	100	[34]
Phenacetin	γ	58.3	45.8	79	[34]
Microcrystal-cellulose	γ	68.7	42.2	61	[35]
	δ	29.5	14.7	25	[36]
Cellulose	γ	68.5	27.5	40	[37]
Lactose (monohydr.)	γ	78		[b]	[28]
Lactose (unhydr.)	δ	30.1	14.8	24	[38]

Estimate of percentage of dispersion component. [a] Total solubility parameter may be thermodynamically determined. Empirically $\delta^2 = \{\delta_d^2+\delta_p^2+\delta_h^2\}^{1/2}$ and may be slightly different from the thermodynamic value. Those listed above are empirical data for the separated parameter.
[b] Reported value not listed because the γ^d value $<\delta_d$; value is not close to consistent with Eq. (4) relating γ and δ. The range of literature values for a given material may vary significantly. These are reasonable values but should be used with caution.

6. Number of interparticle contacts and strength

To extend from two particle interactions to compact values, the number of contacts per unit cross section or unit volume is needed. The number of interparticle contacts that determine strength will vary with the type of strength measurement being made. Elastic displacements of total compacts probably would involve all particles and contacts [14]. Plastic shearing of a compact might involve all contacts of particles in the shearing domain. Fracture strength depends only on contacts in the fracture plane, number of contacts per unit cross section, N. When assuming the strength directly proportional to the numbers of interparticle contacts, one is assuming that the mean strength per contact remains constant. More importantly, a criterion is established by noting that plots of the logarithm of most strength parameters vs. solid fraction are nearly linear. Since N is calculated from this using the same strength/contact assumption, possibly some self compensation of errors results.

For tensile strength, usually Rumpf's estimate, $\mathrm{Nr}^2 = 4.5\rho_r/\pi$, $\rho_r \leq 0.74$ (ρ_r is solid fraction, r is mean particle radius), is used [20]. For the range $0.74 \leq \rho_r < 1$, a separate, empirical relationship was developed [10], $\mathrm{Nr}^2 = (1.71\rho_r + 0.067)/(2 - \rho_r)$. The results roughly follow the semi-logarithmic relationship. The entire solid fraction range could have been represented by using an equation of the form $\log(\mathrm{Nr}^2) = k\rho_r$ (k is a constant) instead of the separate, regional calculations without introducing significantly different results. By using $\mathrm{N}' = \mathrm{Nr}^2$, the strength vs. N′ could be plotted without knowing the particle size of the material. Comparing plots of strength vs. N′ with plots of log strength vs. ρ_r is analogous to comparing plots of x vs. y with $\log x$ vs. $\log y$. Each may be useful. These provide a useful link between the particle size and the compact strength.

7. Mechanical properties of compacts

7.1. Elastic and plastic deformation

There is little evidence that the magnitude of the elastic constant is an important parameter for tablet strength. Note that the elastic modulus appears in the CSM strength equations only as a ratio to correct for viscoelastic effects. When plastic deformation occurs, it distorts the stress field so that the reversible elastic recovery process leaves residual elastic stresses, i.e. internal offsetting tensile and compression stressed regions. Consequently, the at-rest volume reduction from elastic deformation is essentially zero. Volume reduction, consolidation, during the compaction cycle may include particle fracture, plastic deformation and particle rearrangement. Unloading is not event free. Too often, it is stated that elastic recovery may '....rupture weak particle-particle bonds.....' [4]. 'This breaking of bonds' interpretation depends on both atom-to-atom bonds and separation. Elastic unloading occurs at all contacts simultaneously; and individual contacts may reach the critical size but not simultaneously. However, the contact still exists, the particle is trapped in place by others until compact fracture. Even if that contact is 'ruptured', attraction continues, i.e. attraction diminishes gradually but continues until separation by compact fracture. Compact fracture occurs when the cumulative attraction in the compact either has reached a maximum or a more local region produces catastrophic crack propagation, i.e. the strength becomes a compact property; the sum of all attractions at fracture. Some regions will be at their optimum condition some not. Reference to the rupture of bonds is too simplistic.

Since most commercial tableting machines use uniaxial compression–decompression cycles, plastic deformation occurs in both parts of the cycle. At a specific site, shear displacement may either increase or decrease the local attraction by changing the cumulative proximity of atoms. Increased strength has been observed [44] from multiple compactions to the same pressure (which induces multiple internal shear deformations) within the same die. The shapes of die wall vs. punch pressure plots provide significant insight. Consistently a positive die wall pressure intercept is obtained. This indicates that the plastic deformation during compression was significant. The intercept would have been higher but for plastic deformation during unloading[1]. During unloading, small internal fractures may occur. These may be blunted/stopped or repaired by the shear deformation occurring in the presence of large hydrostatic stress [5]. Some may remain to weaken the strength [45]. Since the combined shear-hydrostatic stress condition produces competing processes, strengthening by increasing the contact area of existing contacts and weakening micro-fracture regions, the net effect will depend on the mechanical properties of the compact. Only for brittle materials does fracture dominate.

7.2. Compact hardness

While tensile strength was selected as the measure of bonding strength, indentation hardness, *H*, provides additional, useful information. By definition, hardness is a measure of the mean stress under the indenter that produces plastic deformation of the compact. Often hardness values are nearly two orders of magnitude larger than tensile strength values. The tensile strength, σ_T, divided by H has been defined as a bonding index [46,47], and commonly exhibit the range $0.001 < \sigma_T/H \leq 0.04$. The differences of the configuration of the test combined with the Mohr body characteristics of compacts influence the magnitude. The author uses spherical indenters, to yield Meyer hardness values. H_0 is the dynamic indentation hardness, where the dents are made so rapidly that the viscoelastic effect is negligible. Plots of $\log H_0$ vs. ρ_r and of $\log \sigma_c$ vs. ρ_r, σ_c is compaction pressure, usually are nearly parallel over much of the lower solid fraction range [46,48]. With viscoelastic materials, the high strain rate of H_0 usually causes it to be a higher stress (in this lower ρ_r range) than the slower, maximum compaction pressure, σ_c, used to make the compact. However, their similar slopes indicate that both compaction and hardness are controlled by much the same mechanism, plastic deformation. The bonding index reflects the obtained strength per unit of 'refined' applied stress. Refined by using a parameter for applied pressure, H instead of σ_c, one that provides some control of both strain rate and hydrostatic stress. The dramatic increase of compaction pressure at higher solid fractions is uncontrolled hydrostatic stress in the compact in the die. With the hardness test, the hydrostatic stress is limited because of the unconfined surface surrounding the dent. The INTERparticle portion of the hydrostatic stress in the die contributes to bonding because it produces plastic deformation of the particles; the INTRAparticle portion cannot produce plastic deformation and does not promote bonding [10]. (This assumes that the particle obeys the von Mises yield criterion.) Using H instead of σ_c for the index, minimizes the distortion of INTRAparticle hydrostatic stress to the parameter inducing bonding.

For added information, a range of hardness values are obtained by using different indenter dwell times. This provides a convenient way to gain insight about

---

[1] Unfortunately data published by the author [44] reports some artifactual viscoelastic results, probably apparatus introduced. Due to destructive failure of the transducers, this could not be resolved. Fortunately, it does not effect the general conclusions cited here.

the viscoelastic behavior. In the author's laboratory, some degree of viscoelasticity has been found for all materials studied [10] including acetaminophen. As expected, single crystals of acetaminophen show viscoelastic properties [16]. Also, the magnitude of σ_c needed to obtain a given solid fraction compact varies with the speed of the compression cycle. These rate dependent characteristics confirm the presence of plastic deformation in the compaction of compacts. Also, this results in the peak compaction pressure occurring before the maximum punch displacement of a rotary press [1]. The very slow displacement at the end of the compaction does not add stress as fast as the viscoelastic decay relieves it.

The ratio H_0/E', the strain index [46,47], is obtained while measuring H_0. It provides insight on the relative amount of elastic strain during unloading [46]. Plots of $\log H_0/E'$ vs. solid fraction are essentially linear at and beyond the usual solid fraction ($\rho_r \leq 0.95$) of commercial tablets [47]. For the nine materials of the study, all values of H_0/E' were in the 0.004–0.035 range. In this study, the H_0/E' values for the materials that tended to cap were mixed among the others, e.g. methenamine ~ 0.005 and erythromycin ~ 0.03. Clearly, the magnitude of the strain during stress unloading does not correlate with the capping tendency. This supports the earlier conclusion that the size of the elastic modulus has very little impact on tableting success. Capping tendency correlates with brittleness as indicated by the brittle fracture index (BFI). The BFI is based on change of tensile strength when a macro-sized defect is added to the compact [46,47].

7.3. The compact as a continuum in fracture

The calculations of hardness, compaction pressure, etc. have assumed that the porous compact is a continuum; linear elastic equations are used for calculating stresses and strength. To interpret the sudden, catastrophic failure of compacts, a more careful examination of the compact as a continuum becomes necessary. The crack propagation under tensile loads may in its details be very different from that in homogeneous solids. The compact fracture plane is not smooth but is an irregular surface from one particle to the next; many of the newly exposed surfaces are not normal to the applied tensile stress. (Possibly one should consider this as structure induced brittleness.) The classical continuum neglects a 'grain' size, the atom. A much larger domain, the particles and/or pores, become the neglected 'grain' size for powders and compacts. Herein, as a reminder of this difference, a subscript, c, is added when the compact is the continuum. This restricts the use of linear elastic equations to larger volumes/areas, sizes $\gg$ particle size. Fortunately, the size of the transducer that provides numbers used usually exceeds this minimum.

The success of the BFI as a measure of brittleness [47] depends on the use of stress concentrations following classical continuum mechanics values, approximately a factor of three for a round hole. (A rare case of values outside the range of classical mechanics theory have been observed[2]). At the perimeter of each interparticle contact, a multitude of micro-dimensional stress concentrators exist, the pores, making the compact a 'bed of micro-stress concentrators'. However for the continuum$_c$, the stress concentration around a much larger hole (as used for the BFI measurement) macroscopically, is essentially the same as expected for the classical continuum. Nevertheless, differences in the fracture processes must exist. For example, within the compact, neighboring particles may have very different histories; first formed contacts are different from last formed contacts. Fracture becomes complex, especially if some contacts undergo ductile extension while neighboring ones are brittle. Ductile extension has some of the classical elements of crack blunting. Certainly, one must be cautious when applying classical mechanical concepts to this continuum$_c$.

Because of the unique properties of the continuum$_c$, the calculation of compact strength by summing the strengths of individual contacts in a cross section of a compact is defensible [10,13] for providing strength estimates. With the classical continuum uncontrolled, random, micro-defects are expected to distort the results. Here, micro-defects are integral to the continuum$_c$. What would be the effect of another random micro-defect? How large would the random defect have to be to produce the classical distortion? Clearly, the magnitude of the stress concentration of a single defect becomes lost as multiple, similar defects become close neighbors. Consequently, the use of summing strengths of contact areas should not be rejected categorically. In the author's use of this method, the calculated strengths from the summation [10,13] predicted a lower theoretical strength than the experimental value, the opposite result from that expected by the random defect criticism. Other assumptions and estimates needed and used to calculate the strength, leave in doubt any conclusions suggested by it. Nevertheless, the very limited success indicates that the process is worthy of further consideration. At least it can teach by expanding imagination.

7.4. Tensile strength and shear strength measurements

Measuring the shear and tensile strength of compacts depends on the classical linear elastic equations. Within the continuum$_c$, they describe the stress state at the time of catastrophic failure at the strain rate used. Only limited shear strength measurements of compacts have

---

[2] Dr G. E. Amidon, Pharmacia and Upjohn Company, personal communication.

Table 2
Variation of tensile strength observed with time constant (used to indicate stress application rate)

Material	H_0/H^{a}_{30}	Solid fraction[b]	Tensile strength (MPa)[c]	Time constant (s)[d]
Sucrose	5.91	0.9071 ± 0.0004	2.043 ± 0.094	26.50 ± 0.08
		0.9073 ± 0.0002	2.274 ± 0.179	7.70 ± 0.30
		0.9069 ± 0.0008	2.400 ± 0.085	3.32 ± 0.08
		0.9068 ± 0.0003	2.481 ± 0.075	1.14 ± 0.02
		0.9074 ± 0.0005	2.608 ± 0.114	0.57 ± 0.01
Sorbitol	4.01	0.9055 ± 0.0014	1.745 ± 0.024	43.38 ± 1.92
		0.9038 ± 0.0008	2.049 ± 0.038	13.40 ± 0.48
		0.9037 ± 0.0002	2.342 ± 0.040	4.70 ± 0.19
		0.9044 ± 0.0010	2.782 ± 0.063	1.70 ± 0.17
		0.9045 ± 0.0006	3.021 ± 0.059	0.80 ± 0.02

[a] H_0, is impact hardness; H_{30}, is hardness with 30 min dwell time. This ratio would be one if the material were not viscoelastic.

[b] Equal to (1 − porosity).

[c] Compression applied through platens covering central 0.4 of compact.

[d] Time between applied stress equal 1/e of fracture stress and fracture.

Measurements used square compacts with transverse compression on central 0.4 of edge. Each value from five test ysamples made using triaxial decompression.

been done. When a long, narrow compact was subjected to uniaxial compression, end-to-end of a column-compact, the failure of the compact appeared brittle [44]. However, it exhibited the angle of failure, > 60°, expected for shear deformation of a Mohr body, i.e. the angle at which the shear strength equals the applied shear stress. (Because both the applied stress and the strength of Mohr bodies varies with the direction, failure is not in the direction of the maximum shear stress.) Perhaps this is structure induced brittleness. With sucrose, the uniaxial compression stress on the column to produce 'shear' failure was approximately ten times more than the tensile stress at fracture [44]. Recall that the hardness reported for tablets is approximately 100 times the tensile strength, the rank order of the three are consistent with the Mohr body concept.

When using the transverse compression of square compacts [46,49] for tensile strength, as is done with the BFI, the crack is initiated from the center of the compact because maximum tensile stress is applied only in the central region of the compact. The crack may or may not progress outside this central region. Complete fracture is more common and may be accompanied by secondary fractures (probably caused by redistribution of stresses after the initial fracture). Using different rates of stress application when doing tensile tests lead to different strength values, the compact is viscoelastic. For this reason a time constant is used with the BFI measurements. A constant time interval, the time between fracture and the application of 1/e (0.368) of the fracture stress, is used. Hence, the time for stress increase to fracture becomes similar for all materials. (This is not the ideal correction, but is believed to be much better than no correction.) Most importantly, it prevents distortion of the results by the very rapid viscoelastic decay of stress. Table 2 lists some results obtained in the author's laboratory that illustrate the effect. The ratios of two hardness values are included in the table, but note that the time intervals for the hardness and tensile strength values are very different. The hardness ratio is listed to indicate the viscoelastic nature of the materials. In more detailed studies, the viscoelastic, initial decay rates of stress is much more rapid for the sorbitol than for sucrose; thus, the relative magnitude in short intervals could be very different from those shown. As with all Mohr bodies, the tensile strength observed depends on the stress state induced by the method used to measure it. Clearly, comparisons among materials is meaningful only when a very similar stress state is used for each material. This is the basis for using the time constant with the tensile strength test, i.e. to induce comparable conditions when comparing very different materials. Experimental procedures that do not control the strain rate may produce ambiguous results, e.g. centrifugal force detachment of particles from surfaces.

8. Miscellaneous bonding mechanisms

Clarification of various, often listed, bonding mechanisms is needed. The fear of leaving out a possible mechanism doesn't dictate this list. The items listed have appeared in the literature. A careful analysis of the proposed mechanism could be fruitful.

8.1. Melting-solidification caused by tablet compaction

Contrary to some expressed views [50], theoretical arguments against melting during the compaction of a tablet from applied pressure alone are known. (When the melting point is very close to room temperature, friction, work of plastic deformation, etc. could cause melting to occur, air entrapment accompanies it; with unloading fracture, the fragments produced are very different from capping [1]). The molecular level events that would produce equilibrium conditions are sufficiently fast to prevent significant deviations from the Clapeyron–Clausius equation even when the liquid is not confined by the die. Consider that: (a) Rarely is the volume change that needed to make it thermodynamically driven to produce melting, i.e. density of liquid > density of solid (as it is with water); (b) plastic deformation usually occurs at pressures too low to produce melting; and (c) some organic materials that form good tablets decompose before they would melt from heat produced by the work of compaction. Except for materials whose melting point is very near ambient temperatures, there is little evidence that melting–solidification is an important bonding mechanism.

8.2. Bonding by fracture

An oxymoron, fracture bonding (bonding by fracture), appears in the literature. Clearly, bonding and fracture are opposites. Probably, this refers to consolidation by fracture and the resultant increased numbers of contacts. The mechanisms at the contact regions are not described by this phrase. Probably, glass powder would fracture when compressed. However, at the pressure that initiated the particle fracture, strong bonding or a strong compact of glass particles would not be produced. The material hardness and roughness would limit the bonding even though the surface energy of glass (the attraction) is much larger than for organic materials, ~ 200 mN/m. In the absence of plastic deformation during compaction, the Born repulsion, elastic stresses in some of the contacts may be sufficient to produce the separation of surrounding contacts. For large surfaces of rigid materials, plasticity indices [51] have been devised to help describe this mechanism. A criterion is described for when the plastic deformation will be sufficient for adhesion. That criterion is useful especially with materials harder than those commonly used for pharmaceuticals. Thus, it is not described further. Nevertheless, it could be of interest for cases like powder flow where the applied pressures may be insufficient to produce significant plastic deformation. The literature on contact mechanics [17,18,22,24] has application in pharmacy and should not be ignored.

8.3. Mechanical interlocking of particles

Mechanical interlocking is often listed as of minor importance as a bonding mechanism. Perhaps the best insight on its potential role is obtained from studies with adhesives. It has been shown to be important only when fibrous surfaces are involved, e.g. fiber–rubber interfaces. Also, high peel strengths of polymeric adhesives were observed when fibrous type oxide layers on metals have been produced. In the absence of surviving fibrous structure, no conclusive evidence of mechanical interlocking being significant is known [52]. The word surviving is important. It appears that most polymers that have a somewhat fibrous surface deform plastically and the fibrous surface is destroyed. Needle crystals are not equivalent to fibers. Furthermore, they tend to fracture during the compaction. Needles seldom are used in tableting because they impart other undesirable properties such as poor flow. Usually, needle crystals are milled to break them into more symmetrical fragments. Mechanical entanglement should not be considered to be a contributing bonding mechanism except in some very special cases, cases unlikely to arise with pharmaceutical systems.

8.4. Static electrification

By definition, insulators have their electrons in energy levels that prevent spontaneous transfer. Yet, electrostatic charging of insulators on a dry day is common; it is reasonable to expect that it may be an important interaction. Defects or impurities on the surfaces may provide locally, electron energy states that enable electron transfer between unlike sites. Here unlike has a special meaning, it refers to the unlike (unequal) energy levels of the electrons. Most organic materials are insulators; thus, the charging process is defect dependent. Both contacting particles could be of the same compound but crystal defects or impurities in the surface would make the microscopic contact regions unlike and locally have low barriers to electron transfer. The direction of the charge transfer may be site specific, i.e. defect dependent. Thus after separation of surfaces, a mosaic of both charges may exist on each particle. This makes measurements of the magnitude of charge transfer extremely difficult. A further complication is that powder processing, e.g. milling, may change the charging characteristics by introducing many additional defect sites.

When it occurs, the work done during the separation of the surfaces, the separation of the charges, provides a bonding strength that must be added to the other interactions. However, there is little evidence that for most materials, charge transfer contributes greatly to the interparticle forces during separation. This could be a result of the improbability of favorable juxtaposition of defects on two surfaces brought together during compaction. More probably, adsorbed moisture provides enough surface conductivity that the charge sites become readily neutralized. Thus, the contribution could be minimal. Indeed, the absence of evidence to the contrary leads to the conclusion that with organic materials the electrostatic charges on separated surfaces seldom are major contributors to the strength of the bonding. Special cases are known. Thus, one should not ignore the possibility until observations justify it.

9. Conclusions

Compaction is a method of destroying or removing barriers that prevent close contact between spontaneously attracting particles. The compact consists of packed particles that have several contacts with near neighbors. The innate interparticle attraction, primarily dispersion forces, at these contacts results in a perimeter in tension and a mid-region in compression—Born repulsion. The at-rest compact has the attraction forces equal the repulsion forces. These contacts are solid 'bridges', connections. Other mechanisms may act to enlarge the contact area. The relative strength of the bonding is measured as the magnitude of a tensile stress that produces fracture. Since all compacts are Mohr bodies, the observed strength depends on the method of measurement used. There are a myriad of observations that indicate the prominence of plastic deformation enabling bonding. For example, all die wall vs. punch pressure plots, attest to this. Also, all organic materials studied have viscoelastic characteristics both in compression and tension conditions. This is a clear indication that a (thermodynamically) irreversible process, plastic deformation, is involved. Since not all contact sites are equal, their strengths are not equal. Furthermore, some contacts may fracture in a brittle manner while their immediate neighbors may undergo ductile extension. With so many contact conditions existing simultaneously at different contact sites, the complexity of calculating the tensile strength becomes formidable. Mechanical properties are the controlling properties, they determine success or failure for tableting.

Acknowledgements

The author is especially appreciative of the input and guidance with the text, given by Randy Wald, research scientist, Pharmacia and Upjohn, Kalamazoo, MI 49001.

References

[1] E. Hiestand, D. Smith, Time dependent factors of compaction. Proceedings of the International Powder and Bulk Solids Handling and Processing Conference/Exhibit, Rosemont, IL., Powder Advisory Centre, London NW11 OPG, UK, 1980 May 13-15

[2] C. Nyström, G. Alderborn, M. Duberg, P. Karehill, Bonding surface area and bonding mechanism—two important factors for the understanding of powders and compactibility, Drug Dev. Ind. Pharm. 19 (1993) 2143–2196.

[3] D. Coffin-Beach, R.G. Hollenbeck, Determination of the energy of tablet formation during compression of selected pharmaceutical powders, Int. J. Pharm. 17 (1983) 313–324.

[4] A. Nokhodchi, M. Rubenstein, H. Larhrib, J. Guyot, The effect of moisture content on the energies involved in the compaction of ibuprofen, Int. J. Pharm. 120 (1995) 12–20.

[5] E.N. Hiestand, Mechanical properties of compacts and particles that control tableting success, J. Pharm. Sci. 86 (1997) 985–990.

[6] E.N. Hiestand, Tablet Bond. I. A theoretical model, Int. J. Pharm. 67 (1991) 217–229.

[7] K.L. Johnson, K. Kendall, A.D. Roberts, Surface energy and the contact of elastic solids, Proc. R. Soc. London A324 (1971) 301–313.

[8] H. Leuenberger, E. Hiestand, H. Sucker, Ein beitrag zur theorie der pulverkompression, Chem.-Ing.-Tech. 53 (1981) 45–47.

[9] D. Tabor, The Hardness of Metals. Oxford University Press, London, 1951.

[10] E.N. Hiestand, D.P. Smith, Tablet Bond. II. Experimental check of model, Int. J. Pharm. 67 (1991) 231–246.

[11] C.L. Huffine, A study of bonding and cohesion achieved in the compression of particulate material. Dissertation–Engineering, Ph.D., Columbia University, 1953.

[12] N.A. Armstrong, R.F. Haines-Nutt, Elastic recovery and surface area changes in compacted powder systems, Powder Technol. 9 (1974) 287–290.

[13] E. Hiestand, Dispersion forces and plastic deformation in tablet bond, J. Pharm. Sci. 74 (1985) 768–770.

[14] W. Duncan-Hewitt, Uniaxial compaction modelled using the properties of single crystals, Drug Dev. Ind. Pharm. 19 (1993) 2197–2240.

[15] C.W. Nies, G.L. Messing, Binder hardness and plasticity in granule compaction. Forming of Ceramics in: J.A. Mangels, G.L. Messing, (Eds.), Advanced Ceramics 9, The Am. Ceram. Soc., Columbus, OH, 1984, pp. 58-66

[16] L. Meng-Chih, W. Duncan-Hewitt, Deformation kinetics of acetaminophen crystals. Int. J. Pharm. 106, 1994, 187-200.

[17] E.H. Lee, J.R. MRadok, The contact problem for viscoelastic bodies. J. Appl. Mech. 27, Trans. ASME, 82, series E, (1960) Sept 438-444.

[18] K.L. Johnson, Contact Mechanics, Cambridge University Press, Cambridge, 1985

[19] J.A. Greenwood, K.L. Johnson, The mechanics of adhesion of viscoelastic solids, Phil. Mag. A43 (1981) 697–711.

[20] H. Rumpf, The strength of granules and agglomerates, in: W.A. Knepper (Ed.), International Symposium on Agglomeration, Interscience, New York, 1962, pp. 379-414.

[21] H. Krupp, Particle adhesion. Theory and Experiment, Adv. Colloid Interface Sci. 1 (1967) 111–239.

[22] K.L. Johnson, Adhesion at the contact of solids, in: W.T. Koiter, (Ed.), Theoretical and Applied Mechanics, North-Holland, Amsterdam, 1976, pp. 133-143.

[23] W.C. Duncan-Hewitt, Modeling the compression behavior of particle assemblies from the mechanical properties of individual particles, in: G. Alderborn, C. Nyström, (Eds.), Pharmaceutical Powder Compaction Technology, Marcel Dekker, New York, 1996, pp. 375-417.

[24] D. Maugis, H. Pollock, Surface forces, deformation and adherence at metal microcontacts, Acta Metall. 22 (1984) 1323–1334.

[25] C. Nyström, P.-G. Karehill, The importance of intermolecular bonding forces and the concept of bonding surface area, in:G. Alderborn, C. Nyström, (Eds), Pharmaceutical Powder Compaction Technology, Marcel Dekker, New York, 1996, pp.7-53.

[26] A.I. Kitaigorodskii, Molecular Crystals and Molecules. Academic Press, New York, 1973.

[27] D. Tabor, Attractive surface forces, in: J.W. Goodwin (Ed.), Colloidal Dispersions. Dorset Press, Dorchester, Dorset, 1982 (for Royal Society of Chemistry).

[28] P. York, Studies of the effect of powder moisture contents on drug release from hard gelatin capsules, Drug Dev. Ind. Pharm. 6 (1980) 605–627.

[29] C. Lerk, A. Schoonen, J. Fell, Contact angles and wetting of pharmaceutical powders, J. Pharm. Sci. 65 (1976) 843–847.

[30] F.M. Fowkes, Attractive Forces at Interfaces. I&E. chap. 56 (1964 # 12) 40-52; also in Chem. Phys. Interfaces, ACS Symposium, Washington, D.C., 1964, ACS, Washington, D.C., 1965, pp. 1-12.

[31] A.F.M. Barton, Solubility parameters, Chem. Rev. 75 (1975) 731–753.

[32] B. Janczuk, T. Bialopiotrowicz, W. Wojcik, The components of surface tension of liquids and their usefulness in determinations of surface free energy of solids, J. Colloid Interface Sci. 127 (1989) 59–66.

[33] J. Dann, Forces involved in the adhesion process II. Non-dispersion forces at solid–liquid interfaces, J. Colloid Interface Sci. 32 (1970) 321–331.

[34] G. Zografi, S. Tam, Wettability of pharmaceutical solids: estimates of solid surface polarity, J. Pharm. Sci. 65 (1976) 1145–1149.

[35] S. Lee, P. Luner, The Wetting and interfacial properties of lignin, Tappi 55 (1972) 116–121.

[36] N. Huu-Phuoc, H. Nam-Tran, M. Buchmann, U. Kesselring, Experimentally optimized determination of the partial and total cohesion parameters of an insoluble polymer (microcrystalline cellulose) by gas–solid chromatography, Int. J. Pharm. 34 (1987) 217–223.

[37] B.S. Westerlind, J.C. Berg, Surface energy of untreated and surface-modified cellulose fibers, J. Appl. Polym. Sci. 36 (1988) 523–534.

[38] N. Huu-Phuoc, R. Tan Luu, A. Munafo, P. Ruelle, H. Nam-Tran, M. Buchmann, U. Kesselring, Determination of partial solubility parameters of lactose by gas–solid chromatography, J. Pharm. Sci. 75 (1986) 68–72.

[39] E.N. Dalal, Calculation of solid surface tensions, Langmuir 3 (1987) 1009–1015.

[40] C.M. Hansen, The universality of the solubility parameter, I&EC PR&D 8 (1969) 2–10.

[41] A. Beerbower, Surface free energy: a new relationship to bulk energies, J. Colloid Interface Sci. 35 (1971) 126–132.

[42] A.F.M. Barton, CRC Handbook of Solubility Parameters and Other Cohesion Parameters. CRC Press, Boca Raton, FL, 1983.

[43] F.M. Fowkes, Predicting Attractive Forces at Interfaces, Analogy to Solubility Parameter. Chem. Phys. Interfaces II. Ed. Sydney Ross; Am. Chem. Soc., Washington, DC. 1971

[44] E.N. Hiestand, J.E. Wells, C.B. Peot, J.F. Ochs, Physical processes of tableting, J. Pharm. Sci. 66 (1977) 510–519.

[45] E.G. Rippie, W.T. Morehead, Structure evolution of tablets during compression unloading, J. Pharm. Sci. 83 (1994) 708–715.

[46] E. Hiestand, Rationale for and the measurement of tableting indices, in: G. Alderborn, C. Nyström, (Eds.), Pharmaceutical Powder Compaction Technology. Marcel Dekker, New York, 1996, pp. 219-244.

[47] E.N. Hiestand, D.P. Smith, Indices of tableting performance, Powder Technol. 38 (1984) 145–159.

[48] E. Hiestand, Physical processes of tableting, 2. Proceedings of the International Conference on Powder Technology and Handling, Basel, Switzerland, June 6–8, 1978.

[49] E.N. Hiestand, C.B. Peot, Tensile strength of compressed powders and an example of incompatibility as end-point on shear yield locus, J. Pharm. Sci. 63 (1974) 605–612.

[50] A.S. Rankell, T. Higuchi, Physics of tablet compression XV. Thermodynamics and kinetics aspects of adhesion under pressure, J. Pharm. Sci. 57 (1968) 574–577.

[51] J.A. Greenwood, J.B. Williamson, Contact of nominally flat surfaces, Proc. R. Soc. London A295 (1966) 300–319.

[52] A. Kinloch, The Science of adhesion; part 1, surface and interfacial aspects., J. Mater. Sci. 15 (1980) 2141–2166.