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Estimation of Elastic Recovery, Work of Decompression and Young's Modulus Using a Rotary Tablet Press*

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Abstract—Capping and lamination occur when the bonds within a tablet cannot withstand the elastic recovery during decompression. To estimate tablet recovery, it is necessary to subtract the machine recovery from the total recovery during decompression. A direct relationship between the force and machine deformation is applied in a novel fashion to calculate in-die tablet recovery on a Manesty Betapress and to estimate the Young's modulus, E, of various solids from the recovery data. The E values of about twenty-five pharmaceutical solids were found to be in reasonable agreement with literature values. This procedure allows in-process analysis of tablet recovery and gives E without the use of specialized equipment.

The tablet compression cycle can be divided into a compression and a decompression phase. During compression, the distance between the punch faces decreases as the tablet press does work on both the powder bed and the press (including the punches and die). The work done on the press deforms it elastically such that the elastic energy is recovered during decompression. By contrast, only a small portion of the work done to the powder bed is recoverable. The rest of the work is lost to friction, particle deformation, heat and other irreversible processes in forming a tablet. Capping and lamination can occur when the interparticulate bonding is too weak to withstand the stresses induced by the recovery of the tablet during decompression and ejection (Ritter & Sucker 1980).

Tablet expansion during decompression has been studied using isolated punch and die assemblies mounted in stress-strain analysers (Travers et al 1983; Malamataris et al 1984; Bangudu & Pilpel 1985; Celik & Travers 1985) and compaction simulators (Yu et al 1988). Single punch presses fitted with linear variable differential transformers (LVDTs) have been used to measure punch displacements and press deformation (Ho et al 1979; Juslin & Paronen 1980; Lammens et al 1980; Kaneniwa et al 1984; Cook et al 1988). Since tablet expansion during decompression is very small relative to the elastic recovery of the press, it is essential that the LVDTs are mounted and calibrated such that tablet recovery can be differentiated from that of the press.

It is technically more difficult to measure the punch displacement on a rotary tablet press (Ridgway Watt 1983, 1988; Walter & Augsburger 1986; Oates & Mitchell 1990). As an alternative to direct measurements, Rippie & Danielson (1981) and Charlton & Newton (1984) calculated punch displacement from machine and punch head geometry assuming no machine deformation and recovery. By contrast, the present work extends the relationship between punch force and machine deformation developed for the compression phase of the tableting cycle of a Manesty Betapress (Oates & Mitchell 1989, 1990) to punch force and machine recovery during the decompression phase. Preliminary studies suggested that small differences between the decompression curves of an incompressible solid and various pharmaceutical materials (Fig. 1) might be used to calculate the in-die tablet expansion and estimate the Young's modulus, E, of the material whilst running the press under normal operating conditions.

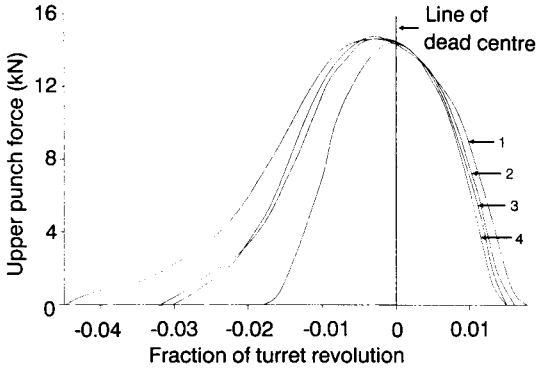

FIG. 1. Upper punch force vs fraction of turret revolution curves for: (1) Avicel PH102, (2) spray-dried lactose, (3) Emcompress, and (4) steel + Emcompress tablets. At a turret revolution time of 1 s, the x-axis also gives the time for compression and decompression in fractions of a second.

The Young's modulus and other elastic moduli of composites have been derived from physical models consisting of spherical or nonspherical pores homogeneously distributed in an isotropic matrix (Rossi 1968). Tablets are anisotropic, heterogeneous bodies in which the pore shape and structure differ from the ideal nature required by the theoretical models. Therefore, their recovery and modulus at a given porosity, E_p, must be determined experimentally for each formulation and each set of tableting conditions. The E_p of various compacted pharmaceutical materials has been determined in flexure tests (Church & Kennerley 1982, 1983; Mashadi & Newton 1987; Bassam et al 1988; Agbada & York 1990) and compressive tests (Kerridge & Newton 1986). Roberts & Rowe (1987a, b) used yield strengths estimated from Heckel plots (Heckel 1961) and tablet

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indentation hardness values determined by Jetzer et al (1983) in an equation given by Marsh (1964) to calculate E_p. The modulus at zero porosity, E, was estimated by Kerridge & Newton (1986), Roberts & Rowe (1987a) and Bassam et al (1988) using E_p in the equation of Spriggs (1961), and by Roberts & Rowe (1987a) using E_p in the equation of Wachtman (1969).

Problems associated with the comparison of E_p obtained from compacts of differing porosities and uncertainties in values of E obtained by extrapolating the values of E_p to zero porosity are avoided by single crystal tests. Ridgway et al (1969) used a microtensile testing machine modified for use in compression and estimated Young's modulus from the stress-strain curves of a number of substances. Single crystal microindentation measurements were made by Duncan-Hewitt (1988) and Wong & Aulton (1987) to determine E for sucrose and α-lactose monohydrate, respectively. The modulus was found to vary with crystal face illustrating the anisotropic nature of these crystals. The moduli of some pharmaceutical solids and the methods used to obtain them are summarized in Table 1.

Materials and Methods

Materials

Tablets were made from acetylsalicylic acid (Monsanto), chlorpromazine hydrochloride (Rhone Poulenc), dextrates (Emdex, Mendell), dicalcium phosphate dihydrate (Emcompress, Mendell), direct compression starch (STA-Rx-1500, Colorcon), lactose (α-monohydrate, BDH; spray-dried, Foremost), mannitol (Atlas), microcrystalline cellulose (Avicel PH102, FMC; Emcocel, Mendell), powdered cellulose (Elcema G250, Degussa), potassium chloride (Fisher), sodium chloride (Allied), sucrose (crystalline, BDH; direct compression forms: Di-Pac, Amstar; Sugartab, Mendell), after mixing each material for 5 min with 0·5% magnesium stearate (Mallinckrodt) in closed jars on a Fisher Kendall mixer.

Tablets of crystalline paracetamol (Acetaminophen USP Granular, Powder and Fine Powder; Mallinckrodt), direct compression paracetamol (acetaminophen) formulations (Rhodapap DC-P3, Rhone Poulenc; Compap CG, Compap Coarse L, Compap Coarse 73L, Compap L; Mallinckrodt), crystalline ibuprofen (Apotex) and direct compression ibuprofen (DCI-63, Mallinckrodt) were made after lubricating the die wall and punch faces with a 5% solution of stearic acid in chloroform.

Equipment

A Manesty Betapress with 1/2 in (1·270 cm), flat faced IPT tooling was used for all experiments as described previously (Dwivedi et al 1991). The press was operated at a turret revolution time of 1 s. The average velocity of the upper punch at this turret revolution time in a vertical direction during the compression phase was 21 cm s^{-1}.

Instrumentation and computer-interfacing of the Betapress

Details of instrumentation of the Betapress and its interfacing with an IBM compatible computer for data acquisition and analysis were described by Oates & Mitchell (1990) and Dwivedi et al (1991). New software for the analysis of the decompression phase has now been developed. The results are saved as ASCII files and can be imported by various commercially available statistics and graphics software.

Determination of machine deformation

The compression phase of the compression cycle begins at the turret position where the powder bed first experiences force and ends when the punches are vertically aligned with an imaginary line connecting the axes of the upper and lower pressure rolls called the line of dead centre. This line is designated fr = 0 where fr refers to the position of the die table in fractions of a single revolution. The decompression phase begins at fr = 0 and ends when the applied vertical force, F, experienced by the tablet drops to zero.

The force applied by the press during the compression phase causes the punches and the press to deform. The sum of punch contractions and press deflection is the total machine deformation, D_m. At a fixed turret position, D_m is directly proportional to F (Oates & Mitchell 1989):

$$\Delta D_m = K_m^{-1} \cdot \Delta F \quad (1)$$

where ΔD_m = the change in machine deformation, K_m^{-1} = a constant of proportionality and ΔF = the change in the vertical force. The relationship between ΔD_m and ΔF was evaluated under static conditions using feeler gauges to vary the distance between the upper and lower punch faces at fr = 0 as described previously (Oates & Mitchell 1990) and K_m^{-1} estimated from the slope was found to be $2{\cdot}4 \times 10^{-6}$ cm N^{-1}.

Throughout the compression cycle, the upper and lower punch heads are pressed against their respective pressure rolls. The pressure rolls constrain the punches and, during powder compaction, force them together thereby decreasing the distance between the two punch faces. If the powder bed could be replaced by an incompressible solid, the distance between the punch faces would be constant throughout the compression cycle and must equal D_m at all turret positions. Hence, an F-fr curve for an incompressible solid would be proportional to the corresponding ΔD_m-fr curve according to equation 1.

Determination of tablet expansion

A series of F-fr curves was determined by compressing an 'incompressible' solid under running conditions. The ejection cam was removed and the thickness setting was fixed to give a distance of about 0·3 cm between the punch faces at fr = 0 in an empty die. The 'incompressible' solid consisted of a 1·269 cm diameter × 0·3 cm thick hardened steel tablet plus a small amount of Emcompress. The steel tablet was inserted into the die cavity and various weighed amounts of Emcompress were added to increase the peak force. After each addition, the steel-Emcompress 'tablet' was repeatedly compressed without ejection to minimize any Emcompress recovery. By increasing the mass of Emcompress from 80 to 430 mg in 10 mg increments, about 35 F-fr curves were recorded with peak forces ranging from 2 to 35 kN. A computer program converted the data from the decompression phase into an array of F-fr curves for evenly spaced values of F at fr = 0 ($F_{fr=0}$) ranging from 0 to 35 kN (Fig. 2). From this array, a F-fr decompression curve can be computed for any $F_{fr=0}$ in the range 0 to 35 kN.

Table 1. Literature values of Young's modulus.

Material	E (GPa) obtained by[a]				
	FT	SCCT	SCI	CT	TI/HA
Paracetamol			8·4[5]		
Adipic acid			3·7[5]		
Acetylsalicylic acid		8·8[9]			
180–250 μm				2·5[6]	
250–355 μm				2·3[6]	
Dicalcium phosphate dihydrate					
Emcompress	8·6[4,b]				7·0[10]
	182[10,c]				
	16[10,d]				
Hexamine		88[9]			
Lactose					
α-monohydrate					
(011) face			1·5[12]		
(110) face			0·84[12]		
anhydrous					53[10]
spray-dried	5·3[4,b]				
	14[10,c]				
	7·6[10,d]				
Mannitol					24[10]
Microcrystalline cellulose					
type unspecified	10–16[1]				
	9·7[10,c]				13[10]
	8·3[10,d]				
Avicel PH101	0·8–1·9[3]				
	6·3[4,b]				
	0·010[8]				
at 45% r.h.	9·0[2]				
at 75% r.h.	5·5[2]				
Avicel PH102	8·2[2]				
250–355 μm				4·7[6]	
Avicel PH 105	10[2]				
Emcocel (type unspecified)	9·4[2]				
Emcocel 90M	9·0[2]				
Unimac MG100	8·8[2]				
Unimac MG200	8·0[2]				
Powdered cellulose					
Elcema (type unspecified)	8·6[10,c]				
	6·7[10,d]				
Elcema P100	5·4[4,b]				
Paracetamol D.C.					5·7[10]
Potassium chloride			21–26[11]		
250–355 μm				9·2[6]	
Salicylamide		128[9]			
Sodium chloride	7·8[4]	186[9]	43[7]		
			36–37[11]		
Starch					
modified maize starch	6·1[10,c]				
	3·1[10,d]				
STA-Rx	1·4[4,b]				
Sucrose		216[9]			
(100) face			19[5]		
(001) face			73[5]		

1, Atkins & Mai (1985); 2, Bassam et al (1988); 3, Church & Kennerley (1982); 4, Church & Kennerley (1983); 5, Duncan-Hewitt (1988); 6, Kerridge & Newton (1986); 7, Lawn & Wilshaw (1975); 8, Mashadi & Newton (1987); 9, Ridgway et al (1969); 10, Roberts & Rowe (1987a); 11, Simmons & Wang (1971); 12, Wong & Aulton (1987). [a]FT = four-point flexure testing of large rectangular compacts; SCCT = single crystal compressive testing; SCI = single crystal indentation; CT = compressive testing of large cylindrical compacts; TI/HA = tablet indentation/Heckel analysis. [b]Values at relative density of 0·81. [c]Values reported by Church (1984) extrapolated to zero porosity using Spriggs' equation (Spriggs 1961). [d]Values reported by Church (1984) extrapolated to zero porosity using Wachtman's equation (Wachtman 1969).

A tablet which does not expand axially upon decompression would have an F-fr curve which coincides with the curve computed from the array at a matching $F_{fr=0}$. When a tablet expands axially it causes additional machine deformation, ΔD_m, which corresponds to the expansion of the tablet and results in a corresponding increase in force, ΔF. To determine ΔF, the F-fr curve derived from the array was subtracted from the F-fr curve of the test material. A ΔD_m-fr curve was obtained by converting ΔF to ΔD_m using equation 1. The range of turret positions over which ΔD_m is defined begins at fr = 0 and ends where the array curve drops to zero. The procedure for deriving ΔD_m from ΔF is illustrated in Fig. 3. Some representative plots of ΔD_m-fr for various materials are shown in Fig. 4. Any deformation and elastic recovery in the steel tablet will lead to errors in the estimation of ΔD_m. Errors in ΔD_m will increase with increases in

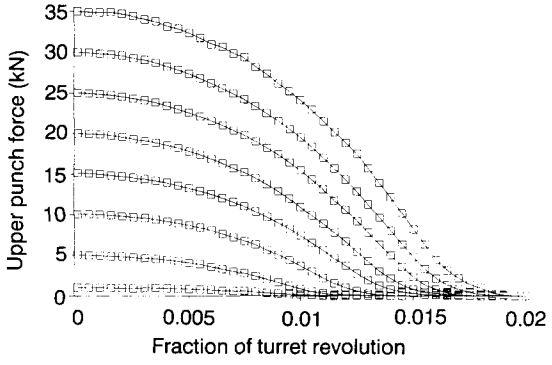

FIG. 2. An array of evenly spaced decompression curves for steel + Emcompress tablets. Decompression curves corresponding to any force at fr = 0 can be calculated by interpolation.

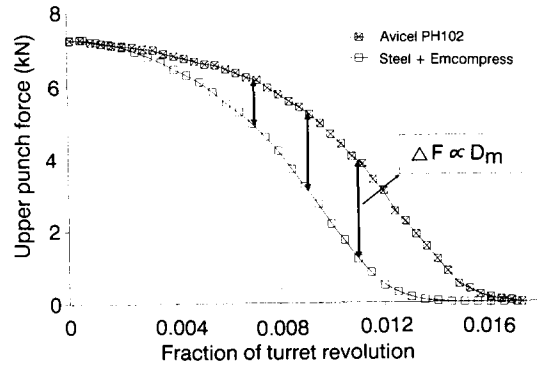

FIG. 3. Diagrammatic representation of calculation of tablet expansion. ΔF is the difference in force between the decompression curve of a test material and an array curve from Fig. 2, and is proportional to ΔD_m, the expansion of the test material.

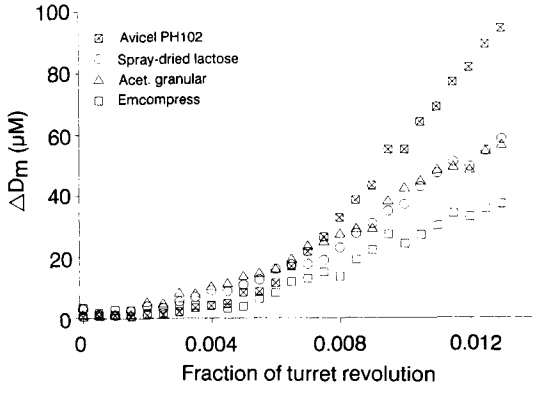

FIG. 4. Tablet expansion for various materials as a function of fraction of turret revolution during decompression.

compression force and will be greatest for tablets undergoing the least expansion during decompression. Thus, using an elastic modulus for steel of 200 GPa (Popov 1968), it can be calculated that the maximum error in estimates of ΔD_m was about 2·5% for Avicel PH102, which has a high elastic recovery on decompression, and about 5·0% for Emcompress, which has low elastic recovery.

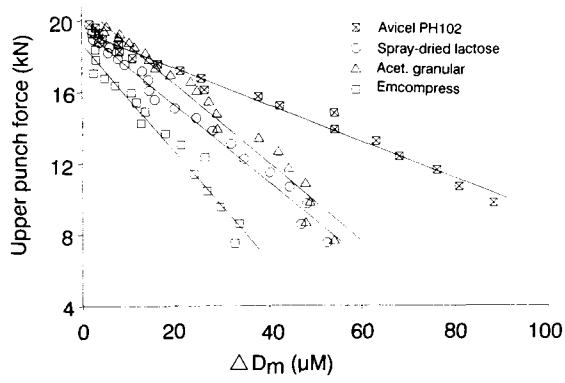

FIG. 5. Decrease in upper punch force during decompression. Each plot represents the expansion of a single tablet and the area from $\Delta D_m = 0$ to $\Delta D_{mF=0}$ gives the work of decompression.

Determination of work of decompression

The F-fr (Fig. 1) and ΔD_m-fr (Fig. 4) plots were combined to obtain plots of F-ΔD_m (Fig. 5). The F-ΔD_m curves were linear, with r^2 values usually above 0·95, and hence could be extrapolated to F = 0 to obtain a quantity called ΔD_m at F = 0 ($\Delta D_{mF=0}$). The area under the curve from $\Delta D_m = 0$ to $\Delta D_{mF=0}$ is the work done by the expanding tablet on the machine during decompression. The work of decompression, W_D, is the negative of this area, where the negative sign indicates that energy is being lost by the tablet during expansion. Fig. 6 gives the change in the work of decompression as the peak force is increased.

Determination of Young's modulus

Assuming tablet expansion during decompression is elastic, the force exerted on the upper punch can be expressed by the following form of Hooke's law:

$$\sigma = E_p \cdot \varepsilon \qquad (2)$$

where, σ = the axial stress given by F divided by the cross-sectional area of the punch face, E_p = a constant of proportionality at a given tablet porosity, and ε = axial strain which was obtained as follows.

Relative to compact thickness at the end of decompres-

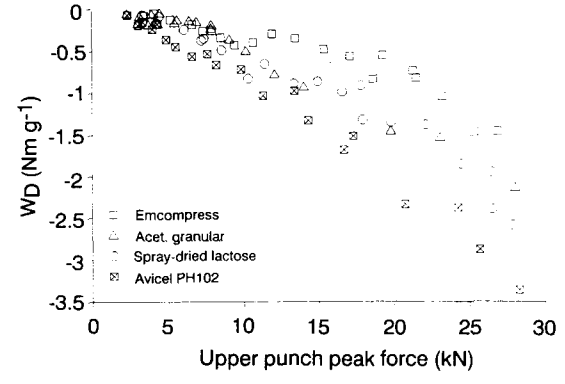

FIG. 6. Change in work of decompression with upper punch peak force. Each data point is obtained from the decompression analysis of a single tablet.

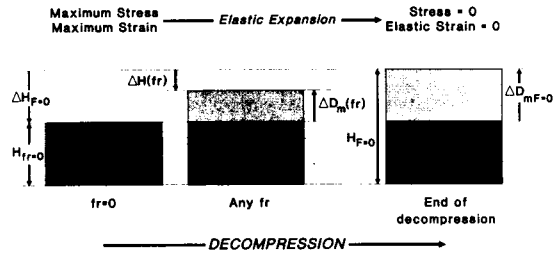

FIG. 7. Schematic representation of tablet expansion at various stages during decompression (drawing not to scale). The quantities shown are used to calculate the modulus E_p of tablets.

sion, $H_{F=0}$ (Fig. 7), the change in the thickness at any fraction during decompression, $\Delta H(fr)$, was given by:

$$\Delta H(fr) = \Delta D_{mF=0} - \Delta D_m(fr) \quad (3)$$

where the values of $\Delta D_m(fr)$ and $\Delta D_{mF=0}$ were obtained from Figs 4 and 5, respectively.

Tablet thickness at the end of decompression, $H_{F=0}$, was calculated from:

$$H_{F=0} = H_{fr=0} + \Delta D_{mF=0} \quad (4)$$

where, $H_{fr=0}$, the tablet thickness at $fr=0$, was given by,

$$H_{fr=0} = K^{-1} \cdot F_{fr=0} + 0{\cdot}314 \text{ cm} \quad (5)$$

The intercept of 0·314 cm is the distance between the punch faces in an empty die at $fr=0$ and was close to the machine thickness setting of about 0·3 cm. Equation 5 was derived from an independent experiment in which increasing weights of lead shot (#4, Winchester) were compressed by hand turning the press to give different values of $F_{fr=0}$. The thickness of ejected lead tablets was measured. Linear regression of this thickness against $F_{fr=0}$ ($r^2=0{\cdot}985$) gave $K^{-1}=2{\cdot}3\times10^{-6}$ cm N^{-1} which was close to the value of K_m^{-1} determined under static conditions using feeler gauges (Oates & Mitchell 1990). This indicates that the elastic recovery of compacts of lead shot was negligible upon decompression.

Combining equations 3 and 4 gave strain as a function of fraction, $\varepsilon(fr)$:

$$\varepsilon(fr) = \Delta H(fr)/H_{F=0} \quad (6)$$

Using equation 6, the plots of ΔD_m-fr were converted to plots of ε-fr. Dividing F by the cross-sectional area of the punch face converted the plots of F-fr to σ-fr. The σ-fr and ε-fr plots were then combined to obtain stress-strain (σ–ε) curves, the slopes of which gave E_p for a given tablet according to equation 2.

Determination of tablet porosity

Porosity, p, of a tablet within a die is given by:

$$p = 1 - \rho_r \quad (7)$$

where ρ_r = relative density calculated as mass per unit volume of a compact in the die divided by the true density of the compact material. Thus, knowing the mass, the true density and the in-die volume of the compact, its porosity can be calculated from equation 7. The true density was determined by helium-displacement pycnometry (Quantachrome Multipycnometer) using a 149·59 cm^3 sample cell. For flat-faced punches, the in-die volume equals the cross-sectional area of the die multiplied by the distance between the upper and lower punch faces. At the end of decompression this distance equals $H_{F=0}$, where $H_{F=0}$ was calculated from equations 4 and 5. Table 2 gives the true density of several pharmaceutical materials and their minimum porosity when compacted to about 30 kN.

Determination of tablet strength

The force of failure of the compressed tablets was determined using a CT-40 tablet strength tester (Systems Engineering) after storage at approximately 20°C and a r.h. of about 45% for 24 h.

Results and Discussion

Elastic expansion and work of decompression

Fig. 5 shows F-ΔD_m plots for a number of pharmaceutical materials. The linearity of these plots for all materials tested is strong evidence in support of the hypothesis that in-die tablet expansion during decompression is elastic. During decompression, force is registered only for as long as the expanding tablet is in contact with the receding upper punch face. Since tablet expansion may continue both during and after ejection from the die (Aulton et al 1973; York & Baily 1977), $\Delta D_{mF=0}$ obtained from Fig. 5 may not represent the total tablet expansion.

Representative ΔD_m-fr plots shown in Fig. 4 give a direct indication of tablet expansion during decompression. Such plots are useful for showing differences in the expansion of various materials, or formulations, after compression to the same peak force. Microcrystalline celluloses showed the greatest expansion during the decompression phase of the compression cycle, while brittle substances such as Emcompress and sucrose showed the least. A similar rank order was found in plots of W_D as a function of peak force, in which the greatest amount of work during decompression is done by the microcrystalline celluloses (e.g. Avicel PH102, Fig. 6).

Determination of Young's modulus

With increasing peak force, tablet porosity, p, decreases and as it approaches 0, E_p will approach the Young's modulus, E,

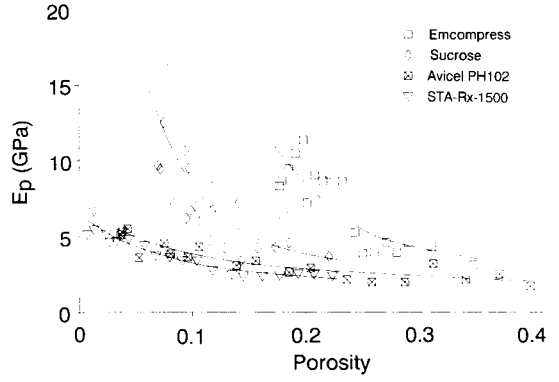

FIG. 8. Variation in modulus of elasticity of tablets with tablet porosity. Extrapolation to zero porosity gives the Young's modulus.

of the fully dense material. Some representative plots of E_p against p are shown in Fig. 8. Extrapolation of these plots to $p=0$ provides an estimate of E.

For low p values, E can be estimated from the least squares solution of the following linear equation (Wachtman 1969):

$$E_p = E + b \cdot p \quad (8)$$

Estimates of E are commonly obtained by least squares solutions of equation 9 which is based on an exponential relationship between E_p and p (Spriggs 1961):

$$\ln E_p = \ln E + b \cdot p. \quad (9)$$

The application of least squares solutions to nontransformed data requires the values of E_p corresponding to each p value to be normally distributed and randomly selected from such distributions. In addition, the distributions of E_p at each p value must have equal variances, i.e. the variances must be homoscedastic. While the least squares analysis is quite robust with respect to deviations from the requirements of normality and randomness, the variances must meet the requirement of homoscedasticity (Zar 1984). The latter requirement can be tested by plotting the residuals of a linear least squares model, e.g. equation 8, against p (Draper & Smith 1966; Zar 1984). A plot showing nearly the same value of residuals at all p values indicates homoscedasticity, and a simple linear relationship can be used. If the value of residuals increases with increasing values of p, the variances are heteroscedastic such that a logarithmic transformation in the form of equation 9 can be applied to make them homoscedastic (Carroll & Ruppert 1988). Residual plots for all materials tested in the present study were curved implying a curvilinear relationship between E_p and p. Linear regression on nontransformed or log-transformed data was therefore invalid. Since neither equation 8 nor equation 9 could be used, the E_p vs p plots were curve-fitted using polynomial regression. The degree of polynomial was selected on the basis of a *t*-test at a critical probability level of 0·05. For most materials a quadratic expression yielded a satisfactory fit.

The values of slope, b, obtained from linear regression are 'measures of the rate of change in the modulus relative to the change in porosity' and were related by Spriggs (1961) to the 'proportions of closed and open pores, or the proportions of continuous solid-phase structure and continuous pore-phase structure'. The need for polynomial regression in our work suggests that factors other than those mentioned by Spriggs (1961), are responsible for changes in E_p with p. These factors may include the effect of increasing load leading to differences in the preferred orientation of certain crystal faces during consolidation.

For easily deformable substances such as Avicel PH102 and STA-Rx-1500, the extrapolation to zero porosity using polynomial regression is short producing reliable E values (Fig. 8). Compacts made from brittle substances such as Emcompress and sucrose were much more porous than compacts made from Avicel PH102 and STA-Rx-1500, even after compression at high pressures, and showed a sharp inflection in E_p values. Therefore, the extrapolated estimates of E are less reliable. Nevertheless, Table 2 shows that the E values obtained from the Betapress are, in most cases, reasonably close to the range of published values (Table 1).

In addition to the problems with extrapolation, there are a number of other possible reasons why values of E_p determined under dynamic condition on the Betapress may differ from values determined using more conventional methods. The material used to determine E_p was not a single component since 0·5% magnesium stearate was included as a tablet lubricant. Inclusion of magnesium stearate was necessary because measurement of E_p using non-lubricated materials compressed in a die previously lubricated with a 5% solution of stearic acid in chloroform showed increased scatter compared with values obtained using the internal lubricant. Compressive and flexure tests are made on preformed, unconfined compacts. In contrast, the tableting process can be likened to the formation of a spring (or rather an assembly of springs with an associated viscous component) where the spring is formed during compaction and confined within the die cavity during the decompression analysis of elastic recovery. An elastic modulus implies that an equilibrium exists. Compressive and flexure tests are normally performed at low strain rates on pre-equilibrated compacts whereas on the Betapress, the modulus is determined at high strain rates on a non-equilibrated tablet. Total tablet recovery during unloading and postcompression includes both elastic and time-dependent viscoelastic components (Rippie & Danielson 1981). Although viscoelastic expansion can be a significant part of the total recovery (Celik & Travers 1985), its contribution would be negligible on the Betapress where the

Table 2. True density (ρ_t), minimum compact porosity[a] (p_{min}), and Young's modulus (E) of various pharmaceutical materials.

Material	ρ_t (g cm^{-3})[b]	p_{min}	E (GPa)
Acetylsalicylic acid	1·394	c	7·2 (1·9)[d]
Chlorpromazine hydrochloride	1·312	0·031	5·5 (1·4)
Emcompress	2·353	0·189	27 (5·4)
			8·2[e] (3·8)
Emdex	1·504	0·060	9·7 (3·7)
Ibuprofen (crystalline)	1·120	c	5·9 (1·7)
Ibuprofen (DCI-63)	1·233	c	6·0 (1·7)
Lactose			
α-monohydrate	1·538	0·107	36 (3·9)
spray-dried	1·538	0·091	17 (3·4)
Mannitol	1·490	0·080	25 (4·7)
Microcrystalline cellulose			
Avicel PH102	1·549	0·05	5·8 (1·1)
Emcocel	1·539	0·041	6·1 (1·0)
Paracetamol (crystalline)			
Acetaminophen Fine Powder	1·301	0·041	11 (1·9)[c]
Acetaminophen Powder	1·296	0·040	10 (3·4)
Acetaminophen Granular	1·294	0·070	9·7 (2·7)
Paracetamol (direct compression)			
Compap CG	1·299	0·053	8·5 (1·3)
Compap Coarse L	1·290	0·029	7·2 (1·5)
Compap Coarse 73 L	1·395	0·045	7·5 (0·9)
Compap L	1·306	0·063	8·0 (1·3)
Rhodapap DC-P3	1·295	0·064	6·8 (2·6)
Powdered cellulose (Elcema G250)	1·525	0·051	7·4 (0·4)
Potassium chloride	1·980	0·007	14 (6·9)
Sodium chloride	2·170	0·052	18 (6·9)
STA-Rx-1500	1·480	0·021	6·6 (0·8)
Sucrose (crystalline)	1·584	0·049	54 (6·1)
Sucrose (direct compression)			
Sugartab	1·560	0·047	20 (3·4)
Di-Pac	1·543	0·068	8·2 (1·8)

[a]Porosity at about 30 kN. [b]Coefficients of variation were less than 0·15% (n=8). [c]Minimum porosity less than zero. [d]Values in parentheses are 95% confidence intervals of the estimate of E. [e]E value at porosity=0·2 since extrapolation to zero porosity was unreliable.

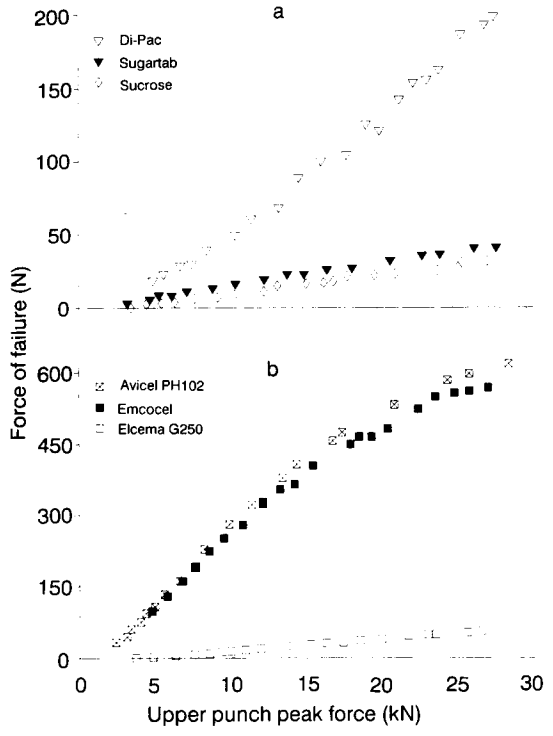

FIG. 9. Variation in force of failure of tablets with upper punch peak force for (a) sucrose and its direct compression forms, and (b) various celluloses.

decompression time was always less than 20 ms at a turret revolution time of 1 s. As stated above, the linearity of the F-ΔD_m plots also indicates that expansion in this time period was purely elastic.

Errors in the calculation of ΔD_m values due to expansion of the steel tablet lead to corresponding errors in the estimation of E. Thus the maximum error in E_p was about 4·5% for Avicel PH102 and about 3% for Emcompress. Extrapolation of E_p values, corrected for the expansion of the steel tablet, to $p=0$ gave E values which were within the 95% confidence intervals of the E values in Table 2.

For a given material compacted to a specific porosity, some of the scatter in the values of E_p can be attributed to the interrelated effects of crystal anisotropy and variation in powder orientation when filling the die cavity. This is reflected in the 95% confidence intervals reported in Table 2. The E values reported in this table are average Young's moduli for the various materials tested. The actual moduli for individual faces of the single crystals of these materials will differ due to crystal anisotropy. For instance, the E value of 54 GPa for sucrose is between the values of 19 GPa for the (100) surface and 73 GPa for the (001) surface found by single crystal microindentation work (Duncan-Hewitt 1988). It is also within the range of 48 to 97 GPa calculated from the initial linear portion of the stress-strain data for different crystallographic axes of a sucrose crystal obtained by a hydrostatic compression procedure (Bridgman 1949).

Effect of formulation and processing on Young's modulus

The E values of the processed forms of various excipients such as spray-dried lactose, Di-Pac, Sugartab and microcrystalline celluloses are lower than α-lactose monohydrate, sucrose and powdered cellulose (Elcema G250), respectively (Table 2). A lower E value means greater recovery during decompression on the Betapress. This suggests that tablets made from formulated or processed materials might be expected to possess a greater tendency to laminate or cap. In general, however, the tablets are stronger. Thus, tablets made from Di-Pac (Fig. 9a) and microcrystalline celluloses (Avicel PH102 and Emcocol, Fig. 9b) were much stronger than sucrose and powdered cellulose, respectively. Similarly, the direct compression forms of paracetamol gave much stronger tablets than crystalline paracetamol (Fig. 8 of Dwivedi et al (1991)), even though the E values are lower (Table 2).

The apparent paradox arising from the ability of the direct compression forms to produce stronger tablets, despite their greater elasticity, is explained by the tendency of these forms to deform by viscoplastic flow during compression, which leads to more extensive bond formation. An indication of the degree of viscoplastic deformation during compression is given by peak offset time, t_{off}, described previously by Oates & Mitchell (1989) and Dwivedi et al (1991). Thus, E values should be used in conjunction with t_{off} to characterize the behaviour of materials during high speed compression. An interesting situation is presented by crystalline ibuprofen and its direct compression formulation, DCI-63. The expansion of both materials is identical and as great as Avicel PH102. DCI-63 contains 63% ibuprofen, lubricant and other USP/NF grade excipients suggesting that the major component(s) of the excipients have similar elastic properties to ibuprofen. Compared with crystalline ibuprofen which cannot be compacted into tablets, DCI-63 shows an increase in the t_{off} (Dwivedi et al 1991) indicating that the excipients impart viscoplastic flow to the formulation and facilitate interparticulate bonding.

The analysis of machine recovery during decompression using the relationship between punch force and machine deformation provides a reliable estimate of the in-die tablet expansion and E_p. Together with the measurement of t_{off} and work of compression (Oates & Mitchell 1989), the calculation of tablet expansion, work of decompression and E_p, using the decompression analysis, could be useful in preformulation studies on new drugs and excipients, in the quality control of in-coming tableting materials, and for in-process validation of compaction.

The E values of pharmaceutical materials determined by compressive or flexure testing of compacts, tablet indentation, and single crystal microindentation require specialized equipment. The present method is a novel application of a high speed rotary press in that the Young's modulus, a fundamental material constant, is readily obtained under normal tableting conditions without the use of specialized equipment.

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