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International Journal of Pharmaceutics 141 (1996) 101–108

international journal of pharmaceutics

Apparent compressive elastic modulus and strength isotropy of compacts formed from binary powder mixes[1]

S. Malamataris[a,*], Th. Hatjichristos[a], J.E. Rees[b]

[a] *Laboratory of Pharmaceutical Technology, School of Pharmacy, Aristotle University of Thessaloniki, Thessaloniki 54006, Greece*
[b] *School of Pharmacy and Pharmacology, University of Bath, Claverton Down, Bath, Avon BA2 7AY, UK*

Received 17 July 1995; revised 28 May 1996; accepted 31 May 1996

Abstract

An apparent compressive Young's modulus of elasticity of cylindrical tablets, produced from binary powder mixtures compressed at two tableting rates, was compared with the tensile strength isotropy expressed as the ratio of axial to radial tensile strength. The binary powder mixtures comprised materials which differ in yield pressure and in the extent of elastic deformation, plastic flow and fragmentation during their consolidation. A log-linear correlation was found between the apparent Young's modulus of elasticity of the tablets and the tensile strength isotropy, indicating that they were similarly related to the composition of the tablets. However, some differences in the effect of compression rate were evident. Thus, apparent Young's modulus varied with compression rate, depending on the principal consolidation mechanism of the component materials. In contrast, the tensile strength isotropy was virtually unaffected by an increase in the compression rate except for mixtures of paracetamol with Avicel which showed a slight decrease in isotropy. The tensile strength isotropy — a measure of the interparticle bonding isotropy — of the tablets could be improved by increasing the apparent Young's modulus, through the incorporation of a component, the particles of which undergo fragmentation or possess a high yield pressure.

Keywords: Tablets; Apparent compressive Young's modulus of elasticity; Tensile strength isotropy; Powder mixtures; Compression rate

1. Introduction

Isotropy is an attribute of a material having a specific characteristic that is constant irrespective of the plane or orientation considered, i.e. the

* Corresponding author.

[1] Paper presented in part at the 1st World Meeting on Pharmaceutics, Biopharmaceutics and Pharmaceutical Technology, Budapest, 1995.

PII S0378-5173(96)04621-2

property does not vary depending on the direction in which that property is measured. Deviation from isotropy is described as anisotropy.

Uni-axial compaction of pharmaceutical powder formulations between two punches in the die of a tableting press usually results in anisotropic particle deformation during compression, followed by anisotropic recovery during decompression. The resulting compacts contain flaws, in the form of pores of variable size, shape and orientation, and exhibit anisotropy with respect to interparticle bonding and associated mechanical attributes. These effects are accompanied by the relief of elastic strain in particles under load, either as a result of fragmentation or plastic deformation, which further influences the mechanical properties of the tablets that are produced. Plastic deformation should facilitate the formation of extended areas of interparticle bonding but will result in greater anisotropy of flaw orientation as a result of the axial yielding of particles. Fragmentation should increase both the number of interparticle contact points and bonds as well as the flaw isotropy. Elastic strain recovery should result in a weakening of interparticle bonds but also at least in partial recovery of flaw isotropy. The extent of anisotropy therefore is a function of the physical and physicomechanical characteristics of the components of the tablets and depends on the compaction conditions.

In the present study, an apparent compressive Young's modulus of elasticity of cylindrical tablets, produced from binary powder mixtures compressed at two tableting rates, is compared with the tensile strength isotropy expressed as the ratio of axial to radial tensile strength, a ratio that provides a measure of the interparticle bonding isotropy.

Through the use of binary mixtures, comprising materials which differ in their principal consolidation mechanisms, we set out to quantify the effect of mutual replacement of elastic, plastic and fragmenting components on isotropicity, elastic modulus and the relation between these two parameters. Such information could enable investigators to predict how certain components affect the elastic modulus of a tablet, and might thereby help formulators in the choice of formulation additives, in the design of new excipients and in the selection of manufacturing conditions.

2. Materials and methods

2.1. Materials

Three particulate materials were used: microcrystalline cellulose (Avicel PH 101, R.T. Vanderbilt, Norwalk, CT, USA) representing a plastically deforming material of low yield pressure; paracetamol crystalline powder (Cambrian Chemicals, UK) as a fragmenting material of intermediate yield pressure, and; dicalcium phosphate dihydrate (Emcompress, Edward Mendell, New York, USA) as a fragmenting material of high yield pressure.

2.2. Preparation of tablets

Using a Turbula mixer (WAB, type 2C, Switzerland), 500 g batches of binary mixes containing Avicel (A), paracetamol (P) and Emcompress (E) were prepared at three true-volume ratios (1:2, 1:1 and 2:1). Magnesium stearate (1.5% by weight in true solid volume) was incorporated as a lubricant and blended for 15 min. These powder mixes were formed into tablets on a Kilian (type KIS, Köln-Niehl, Germany) single-punch tablet press, using 13 mm-diameter flat-faced punches. Tablets were compressed at two tableting rates (20 and 60 tablets min^{-1}), and at different consolidation levels within the packing fraction range $p_f = 0.75–0.90$, by changing the setting of the punches. For each powder mix, the die fill weight was adjusted by trial and error so that, irrespective of materials and compaction conditions employed, the final thickness of all the tablets that were analyzed was within the range 3.75 ± 0.50 mm. The tablets were stored in well-closed glass jars for 1 week before measuring the following mechanical properties.

2.3. Axial/radial tensile strength ratio

The diametral breaking strength of tablets was determined by placing them on edge between par-

allel steel platens, and loading them using a compression cage in conjunction with a mechanical testing machine (Type T30K, Lloyd Instruments, Southampton, UK) operated at a crosshead rate of 1 mm min^{-1}. All the tablets tested in this manner underwent tensile failure allowing the data to be converted to radial tensile strength according to the relationship used by Rudnick et al. (1963).

The axial tensile strength of tablets was measured as described by Nyström et al. (1978). Tablets were fixed between a pair of parallel faces using cyanoacrylate adhesive and strained in tension on the mechanical testing machine at 1 mm min^{-1} until they failed. Certain modes of failure were not considered as axial tensile fracture, i.e. if fracture of a tablet occurred at a position near to the point of attachment, or if gradual failure occurred starting from one side edge of the tablet and extending through the centre. Under the test conditions employed, approximately 20% of the measurements were therefore rejected as non-valid due to failure occurring other than in tension.

All the results of radial and axial tensile strength presented are mean values for five replicate samples.

2.4. Apparent compressive Young's modulus

A modification of the technique described by Paddon and Wilson (1976) and by Kerridge and Newton (1986) was employed. The procedure involved placing five tablets face-to-face and loading the composite structure axially between the parallel platens of the compression cage of the Lloyd testing machine which was connected to a chart recorder. An approximate value for the mean compressive strength of three replicate five-tablet specimens was first determined by applying an axial load at 0.5 mm min^{-1} until failure occurred, and plotting the load vs time. This was not intended to give an accurate measurement of compressive strength but enabled selection of a suitable loading range for the subsequent measurement of Young's modulus. The measurements of apparent Young's modulus also were performed at a crosshead rate of 0.5 mm min^{-1}. To ensure that the elastic limit was not exceeded, a loading range of 1/10–1/2 of the compressive strength of replicate samples from the same batch of tablets was selected. The strain was measured with an accuracy of ± 0.3 μm using an external linear displacement transducer GTX 2500/RDP 1981 and a transducer indicator–conditioner RDP E309 (RDP Electronics, Wolverhampton, UK). Before the slope of the load-deformation curve was recorded, four loading–unloading cycles were completed; this was to avoid possible strain errors caused by incomplete contact between the five tablets under test. That, in turn, should have reduced the errors in load measurement due to friction between the tablets, though, as in conventional compressive tests, the effects of friction between the specimen and the platen could not be avoided. The reduced crosshead rate of 0.5 mm min^{-1} was necessary to improve precision of measurement over the limited load range of the elastic region. Young's modulus, E was calculated as follows, to include a correction for deformation of the test rig:

$$E = L/[A(X - C)] \quad (1)$$

where, L is the combined length (i.e. 'thickness') of the five tablets, X is the reciprocal slope of the plot of tablet deformation vs load, C is the machine constant (determined by loading the machine without a specimen) and A is the cross-sectional area of the tablet face.

Changes in the diameter of the 5-tablet specimen during loading were not taken into account in the measurements. Furthermore, a number of other potential sources of measurement errors, outlined above, could not be excluded though they were controlled by standardising the test methodology. For those reasons, the reported values of Young's modulus are described as 'apparent' Young's modulus. The mean value was calculated for five replicate tests on each specimen of tablets.

3. Results and discussion

Typical force-time plots obtained by loading 5-tablet specimens until they failed, are shown in Fig. 1a–f. Each tablet in the specimen comprised

of a binary mixture having a true volume ratio of 2:1 or 1:2. During the compressive strength determinations the five tablets of the specimen underwent apparently simultaneous failure and the mode of fracture was, in most cases, a combination of compressive and shear failure. The shapes of the plots obtained for tablets of all the binary mixtures investigated, reflect the characteristics described by Newton et al. (1993) and can be classified into three types:

(1) the plots for tablets containing a high proportion of Avicel, A_2, show a levelling-out of the force before the peak and then an initial slight decrease after the peak, Fig. 1a,b, probably due to extensive plastic deformation before final failure of the tablet;
(2) the plots for tablets containing a high proportion of Emcompress, E_2, show a sharp-edged peak due to a sudden decrease in force after the maximum, Fig. 1c,d; and
(3) the plots for mixtures containing a high proportion of paracetamol, P_2, are sawtooth, or jagged, at the force maxima, showing that failure proceeds in stages, Fig. 1e,f.

The abrupt decrease in the compressive force, in the case of tablets containing a high proportion of Emcompress (Fig. 1c,d), corresponded to sudden catastrophic crack propagation, whereas the slow decrease in the compressive force, in the case of tablets containing mainly Avicel (Fig. 1a,b), is typical of stable crack growth (Ouchiyama et al., 1987).

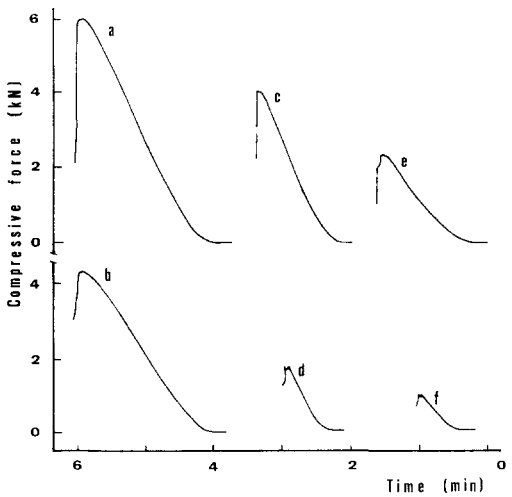

Fig. 1. Force-time plots of compressive strength determinations for tablets of binary mixtures, at the upper and lower true volume ratios. Packing fraction, $p_f \approx 0.85$. Tableting rate: 60 min^{-1}. (Key: (a) A_2E_1; (b) P_1A_2; (c) A_1E_2; (d) E_2P_1; (e) P_2A_1 and (f) E_1P_2).

Table 1 presents the experimental values of packing fraction, tensile strength (radial and axial) and apparent elastic modulus for each binary mixture compacted to an upper and lower level of consolidation at two tableting rates. No simple or general effect of tableting rate on the packing fraction of tablets was observed. It was decided therefore, to examine a possible relation between the strength characteristics, the apparent elastic modulus of the tablets and the packing fraction, p_f rather than to seek any general dependence on tableting rate.

The p_f of many of the samples tested was relatively lowranging from 0.744 to 0.908. Extrapolation to $p_f = 1$, therefore, was considered inappropriate as a means for normalising and comparing the tensile strength parameters and the apparent elastic moduli for the different binary mixtures. Instead, the values at a given packing fraction ($p_f = 0.85$) were calculated by regression of each set of data obtained at the different compression conditions (i.e. packing fraction and rate).

The tensile strength values (radial and axial) at p_f 0.85 were obtained from the equation:

$$\log y = A_i p_f + B_i \quad (2)$$

where y is tensile strength. A_i and B_i are numerical terms which depend on the nature of the components, the tableting rate and whether the computed tensile strength is axial or radial.To calculate apparent elastic moduli at $p_f = 0.85$, linear regression analyses were undertaken using two equations:

- the empirical relation employed by Spriggs (1961),

$$\log E = \log E_0 - b(1 - p_f) \quad (3)$$

where E is the apparent Young's modulus of the specimen, E_0 is the value at zero porosity ($p_f = 1$) and b is a constant, and

Table 1
Experimental values of the mechanical properties of each binary mixture compacted to an upper and lower level of consolidation at two tableting rates

Mixture	Tableting rate (min^{-1})	Packing fraction	Tensile strength		Strength isotropy ratio	Apparent Young's modulus (GPa)
			Radial (MPa)	Axial (MPa)		
P_2A_1	(20)	0.859	1.03	0.24	0.23	1.05
		0.897	1.46	0.22	0.15	1.33
	(60)	0.865	1.00	0.17	0.17	1.13
		0.893	1.26	0.18	0.14	1.23
P_1A_1	(20)	0.758	0.64	0.13	0.21	0.59
		0.905	2.54	0.49	0.19	1.34
	(60)	0.778	0.81	0.18	0.22	0.68
		0.885	1.87	0.27	0.14	1.30
P_1A_2	(20)	0.755	1.29	0.26	0.20	0.62
		0.908	3.70	0.56	0.15	1.53
	(60)	0.755	1.28	0.32	0.25	0.63
		0.892	3.06	0.24	0.08	1.40
E_1P_2	(20)	0.820	0.24	0.10	0.42	1.33
		0.867	0.48	0.11	0.23	1.73
	(60)	0.828	0.22	0.10	0.45	1.10
		0.840	0.40	0.14	0.35	1.53
E_1P_1	(20)	0.851	0.69	0.26	0.38	2.76
		0.880	1.36	0.30	0.22	3.32
	(60)	0.857	0.78	0.27	0.34	3.17
		0.882	1.07	0.19	0.17	2.89
E_2P_1	(20)	0.847	1.08	0.54	0.50	6.45
		0.892	1.96	0.64	0.33	6.27
	(60)	0.840	1.22	0.70	0.57	8.05
		0.894	1.90	0.80	0.42	7.80
A_1E_2	(20)	0.750	0.90	0.35	0.39	1.67
		0.846	2.26	0.95	0.42	5.33
	(60)	0.751	0.81	0.32	0.40	1.71
		0.845	2.20	0.93	0.42	3.84
A_1E_1	(20)	0.770	1.20	0.33	0.27	1.22
		0.897	4.28	1.07	0.25	2.25
	(60)	0.768	1.25	0.36	0.29	1.17
		0.895	4.22	1.20	0.28	3.42
A_2E_1	(20)	0.744	1.28	0.27	0.21	0.73
		0.850	3.11	0.60	0.19	1.47
	(60)	0.754	1.14	0.22	0.19	0.76
		0.844	2.77	0.63	0.24	1.71

- the equation recommended by Wachtman (1969) for systems of low porosity, which is based on fundamental fluid mechanics of a heterogeneous system.

$$E = E_0[1 - a(1 - p_f)] \quad (4)$$

The constant a is related to the shape of the pores within a compacted specimen and ranges theoretically from 2 for spheroidal pores to 3 for cylindrical and 4 for ellipsoidal pores (Roberts and Rowe, 1987).

The values of a for the binary mixtures examined in the present study ranged from 2.2 to 4.9. These are similar to figures of 2.97 to 4.15 quoted for a number of direct compression diluents by Roberts and Rowe (1987). Table 2 lists the

Table 2
Calculated values of the mechanical properties, at $p_f = 0{,}85$, for binary mixtures compacted at two tableting rates. Each value was obtained by regression analysis of experimental data presented in Table 1

Mixture	Tableting rate (min^{-1})	Tensile strength		Strength isotropy	Apparent Young's modulus (GPa)	
		Radial (MPa)	Axial (MPa)		(Eq. 3)	(Eq. 4)
P_2A_1	(20)	0.99	0.20	0.20	0.99	0.97
	(60)	0.90	0.17	0.19	1.23	1.44
P_1A_2	(20)	2.70	0.40	0.14	0.97	1.06
	(60)	2.46	0.28	0.11	1.05	1.10
E_1P_2	(20)	0.37	0.11	0.29	1.38	1.41
	(60)	0.50	0.15	0.30	1.94	1.82
E_2P_1	(20)	1.16	0.65	0.56	6.13	6.15
	(60)	1.26	0.71	0.56	7.28	7.37
A_1E_2	(20)	2.23	0.97	0.43	4.89	4.93
	(60)	2.22	0.96	0.43	3.92	3.81
A_2E_1	(20)	2.99	0.68	0.23	1.65	1.64
	(60)	2.88	0.66	0.23	1.54	1.50

strength parameters and elastic moduli obtained by regression analysis at $p_f = 0.85$ for the tablets of each binary mixture at the upper and lower true-volume ratios of 2:1 and 1:2.

For each binary mixture, the results for apparent Young's moduli (Table 2), calculated using the Spriggs equation (Eq. (3)) and Wachtman equation (Eq. (4)) are closely comparable. There are some marked differences in apparent elastic moduli for tablets of different composition and, to a lesser extent, for tablets of the same binary mixture prepared at different compression rates. In general, a large proportion of Emcompress, E_2, gives higher values of apparent elastic modulus, whereas Avicel, A_2, shows lower values. The effect of tableting rate varies, depending on the composition of the binary mixture. The apparent elastic modulus increases with tableting rate for the mixtures containing paracetamol, this effect being most marked for the binary mixtures with Emcompress. For mixtures of Avicel and Emcompress, the higher tableting rate gives lower values of elastic modulus.

Regarding the tensile strength parameters in Table 2 it can be seen that the different components contribute to tensile strength as follows: for radial strength, $A > E > P$; whereas for axial strength, $E > A > P$. Thus, the combination E_2P_1 gives a higher axial and a lower radial tensile strength than the corresponding mixture of paracetamol with Avicel, P_1A_2. Elastic and plastic deformation and fragmentation of powder particles during tableting will affect the load distribution, the number and strength of interparticle bonds and the structure of flaws (i.e. their size, shape and orientation) in the tablets in different ways. The high elastic strain, and subsequent large strain recovery, of paracetamol contribute to weaker interparticle bonding and a lower tensile strength. However, in the context of tensile strength isotropy, particle fragmentation of paracetamol and of Emcompress evens out the load distribution and improves the strength isotropy in comparison with Avicel. Although plastic deformation of Avicel results in extended areas of interparticle bonding and increases the radial tensile strength, it also reduces isotropy in interparticle bonding. Some inverse evidence that plastic flow may adversely affect strength isotropy is given by the relatively high isotropy values of up to 0.56 shown (Table 2) by tablets containing Emcompress — a material with a yield pressure that is even higher than that of paracetamol (Malamataris and Rees, 1993). This suggests that fragmentation with minimum associated plastic flow is needed to minimise anisotropy.

The tensile strength isotropy values (Table 2) are not affected by compression rate except for the mixture of paracetamol and Avicel, P_1A_2 which shows a slight decrease. However, the composition of the mixtures has a marked effect on the isotropy. In general, the changes in tensile strength isotropy, due to the composition of the mixture, seem to parallel those for apparent Young's modulus (Table 2). The combination E_2P_1 gives the highest values for both properties whereas the combinations of paracetamol with Avicel give the lowest values. Fig. 2 shows the relation between tensile strength isotropy and the logarithm of apparent Young's modulus, at $p_f = 0.85$. The data points are the calculated values for all 9 binary mixes each tableted at two rates.

The correlation between the apparent Young's modulus of elasticity of the tablets and the tensile strength isotropy, Fig. 2, can most likely be rationalised by a consideration of flaw anisotropy, and particularly the flaw orientation, in a tablet. The flaw orientation and associated anisotropy depend mainly on the extent to which powder particles deform during tableting. A rigid compact of high modulus undergoes minimal elastic deformation and therefore minimal recovery or plastic relief. In contrast, a compact of low modulus undergoes large elastic deformation and therefore considerable recovery or plastic relief. Since fracture, during a strength determination, is associated principally with the phenomenon of crack propagation, the flaw structure of the tablet affects its fracture propensity and therefore has a major influence on the tensile strength isotropy. Conversely, the apparent elastic modulus is mainly associated with the solid structure and the material rigidity; flaws, therefore, do not have the same influence on elastic modulus as on tensile strength. In any case, the apparent elastic modulus is measured in only one direction, that is, in the same direction as the applied uni-axial compaction force in the tableting press. However, the flaw structure of the tablet, established during compaction, will be influenced by the elastic modulus of the component solid particles. Extensive deformation of particles possessing a low elastic modulus, or exhibiting plastic flow, will tend to produce a compact having a less isotropic flaw structure and therefore will reduce the strength isotropy.

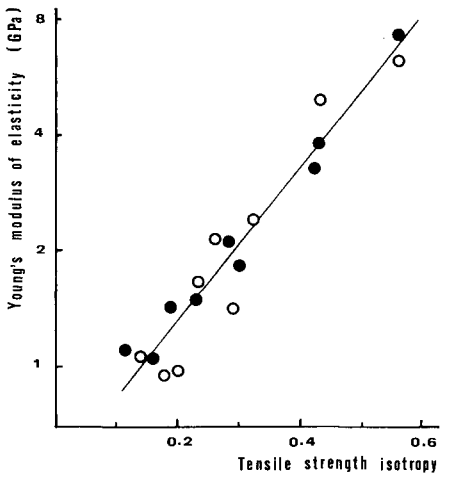

Fig. 2. Relation between the apparent Young's modulus of elasticity (logarithmic scale) and the tensile strength isotropy at a fixed p_f (0.85) for compacts of binary mixtures prepared at two tableting rates: (○) 20 and (●) 60 tablets per min.

Differences in the effect of tableting rate on the elastic modulus may be explained on the basis of plastic deformation and/or fracture of particles under the influence of an applied load. When brittle elastic materials such as Emcompress and paracetamol are compacted, the amount of particle fragmentation increases with loading rate; the residual elastic strain (compliance), therefore, is reduced and the Young's modulus increases. In contrast, the amount of plastic deformation of Avicel is reduced at a higher tableting rate, because plastic flow, in response to an applied load, is time-dependent. The elastic strain (compliance) in tablets containing Avicel therefore increases and the Young's modulus is reduced. Such effects are analogous to those reported previously in relation to creep analyses on compacts of Emcompress and Starch 1500 (Malamataris et al., 1993) and could account for the apparent complex effect of tableting rate on Young's modulus observed in the present study.

The effect of mutual replacement of elastic, plastic and fragmenting powder components, can be summarised in general qualitative terms as follows. Replacing an elastic and fragmenting ma-

terial like paracetamol by a plastic material such as Avicel decreases both the strength isotropy and the apparent elastic modulus. In contrast, replacing paracetamol by a material like Emcompress, which fragments but also has a higher yield pressure, increases both the strength isotropy and the apparent elastic modulus. The strength isotropy and the apparent elastic modulus of a compact are also increased by replacing the plastic Avicel with fragmenting Emcompress.

4. Conclusion

A log-linear correlation was found between the apparent Young's modulus of elasticity and the tensile strength isotropy for the compacted binary systems considered in this study. These properties therefore showed a similar dependence on the composition of the tablets. The apparent Young's modulus exhibited small changes with compression rate, depending on the consolidation mechanisms of the component materials. In contrast, the tensile strength isotropy was virtually unaffected by compression rate. The tensile strength isotropy, which provides some indication of the interparticle bonding isotropy and the flaw isotropy, of tableted powder formulations may be improved by increasing the apparent Young's modulus of the tablet, through the incorporation of a component, the particles of which undergo fragmentation or possess a high yield pressure.

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