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Viscoelastic properties of some pharmaceutical powders compared using creep compliance, extended Heckel analysis and tablet strength measurements

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Summary

The viscoelastic properties of six pharmaceutical powders, which differ in the extent of fragmentation, plastic flow and elastic deformation during consolidation, were studied using various techniques applicable at different stages before, during and after the tableting process. The measured parameters included: the apparent viscosity and elastic compliance obtained from creep experiments; the yield value and elastic recovery derived from extended Heckel plots at the tableting stage; and the apparent failure viscosity and toughness of tablets calculated from deformation and failure measurements under diametral loading at the post-tableting stage. The usefulness of the viscoelastic properties as indicators of tabletability is considered and explained in the context of structural changes associated with the deformation and consolidation of particles under load.

Introduction

Time-dependent deformation of particulate materials under stress has a major influence on their tableting behaviour. Attempts to quantify such effects have included various techniques applied at different stages of the tableting operation before, during and after the actual compaction process. Thus tests have been performed on the starting materials, on the system undergoing consolidation, and on the finished tablets.

To characterise materials at the pre-tableting stage, indices of bonding, strain and brittle fracture have been proposed (Hiestand and Smith, 1984). Other workers have relied on properties such as the yield value (Heckel, 1961a,b; Hersey and Rees, 1970), the Brinell hardness (Ridgway et al., 1970, Holman and Leuenberger, 1988) the modulus of elasticity (Kerridge and Newton, 1986; Roberts et al., 1989), the critical stress intensity factor (Mashadi and Newton, 1988; Roberts and Rowe, 1989), the elastic compliance, the plastic compliance and the apparent viscosity (Tsardaka and Rees, 1989).

At the tableting stage, materials have been evaluated whilst undergoing dynamic compression, that is under conditions of changing stress.

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These studies have enabled determination of the work done on the lower punch during initial and repeated loading (De Blaey and Polderman, 1970, 1971), the residual die wall pressure and the Poisson's ratio obtained from radial vs axial pressure cycles (Long, 1960; Leigh et al., 1967; Obiorah, 1978). Materials in the compacted state whilst still under load have also been characterised using stress relaxation measurements at constant strain (David and Augsburger, 1977; Rees and Rue, 1978) and creep experiments at constant stress (Tsardaka and Rees, 1989) to quantify time-dependence. Heckel plots and extended Heckel plots, generated from dynamic compression and decompression data (Roberts and Rowe, 1985; Duberg and Nystrom, 1986) have not only provided yield values but also highlighted strain-rate sensitivity and given information on elastic recovery.

At the post-tableting stage, the viscoelastic properties of consolidated particulate materials have been assessed by non-destructive techniques (Radebaugh et al., 1989) and by examining the response of finished tablets to applied loads (Rees and Rue, 1978a,b; Patel and Staniforth, 1987).

The use of these various different techniques may create some potential confusion by generating several viscoelastic parameters, for a given particulate solid material, in various states of consolidation, and therefore having different, though obviously related, physical and geometric structure. In this study, therefore, we set out to obtain comparative experimental data by examining selected viscoelastic properties of six materials using three techniques which are applied at different stages of the tableting process. The parameters and techniques used to characterise the compressibility and elasticity were: (i) the apparent viscosity and elastic compliance obtained from creep experiments; (ii) the yield value and elastic recovery obtained from extended Heckel plots at the tableting stage; and (iii) the apparent failure viscosity and toughness of tablets obtained from deformation and failure measurements under diametral loading at the post-tableting stage.

The aim was to examine the relations between these properties and to assess their usefulness as indicators of tabletability.

Experimental

Materials

The six materials selected for this study cover a wide range of material properties, and differ in the extent to which they undergo fragmentation, plastic flow and elastic deformation during consolidation. Modified starch (Starch 1500, Colorcon Ltd, Orpington, U.K.), dibasic calcium phosphate dihydrate (Emcompress, E. Mendell Co, Carmel, NY, U.S.A.) and Paracetamol DC (Hoechst AG, Frankfurt, Germany) were chosen as materials that are generally considered to show satisfactory compaction properties and were used as received from the suppliers. Paracetamol crystalline powder (Cambrian Chemicals, U.K.) was chosen as an example of a material having poor compaction properties. Two batches of aspirin from different sources (ASA-A from Bayer AG, Leverkusen, Germany and ASA-B from Dott. Bonapace & Co, SRL, Milan, Italy) were chosen to represent a pharmaceutical substance that is commonly compressed into tablets. The crystalline paracetamol powder was classified using a zig-zag classifier (Multiplex-Alpine, Augsburg, Germany) to give three particle size fractions: finer than 15 μm, 15–45 μm and larger than 45 μm. Aspirin was used as received from the suppliers, and also after reducing the particle size to below 45 μm by grinding. The same lot of each material was used throughout the study.

Creep experiments

Powder samples, each sufficient to produce a tablet of 2.21 mm thickness at zero theoretical porosity, were accurately weighed to ± 0.1 mg and then stored for 7 days at 25°C/53% RH. Plots of creep compliance against time were obtained using a mechanical testing machine (T22K, J.J. Lloyd Instruments, Southampton, U.K.) fitted with a compression cage, constant stress module, two linear displacement transducers and a 12.7 mm flat-faced punch and die set. A range of constant loads was applied up to 18 kN, the platen rate being set to achieve two different controlled mean rates of load application of 4 and 16 kN min^{-1}. At each experimental condition, the number of replicate samples tested was

five in the case of Paracetamol DC, crystalline paracetamol and aspirin, and 10 in the case of Starch 1500 and Emcompress.

Using a graphics dump routine, the compliance data were plotted using a dot matrix printer. From the plots of compliance with respect to time, the viscoelastic parameters, such as the instantaneous and retarded elastic compliance and the apparent viscosity, were derived. Values of the ratio of elastic to plastic deformation were determined at time, t_i, the elastic retardation time (Malamataris et al., 1992); this is the time at which total creep compliance becomes equal to the equilibrium value of elastic compliance at infinite time. Fuller details of the equipment and procedure have been described elsewhere (Tsardaka, 1990; Malamataris et al., 1992).

Tableting experiments

Powder samples were weighed and conditioned as in the creep experiments. Each sample was transferred manually into the pre-lubricated 12.7 mm diameter die of an instrumented reciprocating single-punch tablet press (Manesty E2) and compressed at five, or more, different upper punch settings to achieve packing fractions in the range 0.80–0.95. Manual compression was employed to ensure maximum reproducibility in the weight of replicate tablets.

The force applied to the powder was recorded by a piezoelectric load cell and the upper punch movement was monitored by a 10 mm displacement transducer attached to the die table. The thickness of the powder bed during tableting was recorded every 1 ms with a correction for punch distortion. The analog signals were converted to digital form using a 12-bit A/D converter. The digital data were then stored on floppy disk for further processing. Tablet thickness, relative density D and $\ln(1/[1-D])$ values were calculated not only up to peak force but also during unloading. The yield value, P_y was determined as the reciprocal of the slope of $\ln(1/[1-D])$ vs compaction pressure, as the pressure increased in the range 40–100 MPa. Elastic recovery during force removal was expressed as the percentage increase in the tablet thickness compared with that at maximum punch displacement (Duberg and Nystrom, 1986).

10 tablets were compressed at each pressure setting. As in the case of creep experiments, after storage for 48 h (25°C, 53% RH), the dimensions (± 0.01 mm) and weight (± 0.1 mg) of the tablets were measured prior to tensile-failure testing.

Diametral tablet-loading experiments

The diametral breaking strength of the tablets was measured by placing them on edge and compressing them between the two platens of a tensile tester (type T22K, J.J. Lloyd Instruments, Southampton, U.K.). The rate of upper platen movement was 2 mm min^{-1}. The force applied to each tablet during the test, and the corresponding relative displacement of the platens (tablet deformation) were monitored continually. The area under the load-displacement curve was quantified to assess tablet toughness (Dieter, 1961; Rees and Rue, 1978a). The normalized work of failure (NWF) was calculated according to Eqn 1 (Rees et al., 1977):

$$\mathrm{NWF} = (2/\pi\phi T)\int_0^x F \cdot dx \qquad (1)$$

where ϕ is tablet diameter, T denotes tablet thickness, F is the force applied during diametral testing and x represents the tablet deformation.

Values of the toughness area-ratio (Moschos and Rees, 1986) were also determined to quantify the deviation from linearity of the load-displacement curves. This is calculated as the area under a hypothetical linear plot between applied force and platen displacement, divided by the corresponding area recorded during a tablet toughness test; the load and platen displacement at failure are taken as limiting coordinates in each case.

The results of diametral breaking strength were converted to tensile strength according to the relationship used by Rudnick et al. (1963) and the apparent tablet failure viscosity was obtained by dividing the tensile strength of the tablets by their strain rate. The strain was calculated as the diametral deformation undergone by a tablet during the diametral test divided by the tablet diam-

eter. The strain rate was determined knowing the time elapsed during the diametral test up to the point of failure.

Results and Discussion

Fig. 1 shows typical plots of total compliance, $J_{(t)}$ (curve A) and compliance due to elastic deformation (curve B) with respect to time, for four of the substances investigated, namely, Starch 1500, Emcompress, Paracetamol DC and one of the aspirin samples (ASA-A, size fraction $> 45\ \mu m$); each of these materials is capable of forming a satisfactory tablet. Curve B is derived from curve A by subtracting the plastic component of compliance, determined as the product of the slope (k_1) of the linear region and time (t). The apparent viscosity is given by the reciprocal slope ($1/k_1$). The instantaneous elastic compliance, J_o, is given by the intercept on the ordinate axis of the extrapolated initial part of the creep curve. The total elastic compliance at infinite time, J_i is given by the intercept, on the ordinate axis at zero creep time, of the extrapolated terminal linear region of the creep curve (A). The elastic retardation, t_i is given by the time when the total compliance $J_{(t)}$ becomes equal to J_i.

To compare the creep parameters of the different materials, the values at equivalent packing fraction, p_f were calculated by regression and interpolation of the data obtained by applying a range of loads at the two loading rates (4 and 16 kN min^{-1}). From the regression analyses of the creep results, it was found that for all the samples at both loading rates, the data fitted a general equation:

$$\log Y = A_i p_f + B_i \qquad (2)$$

where Y was either apparent viscosity ($1/k_1$) or instantaneous elastic modulus ($1/J_o$) or total elastic modulus ($1/J_i$). A highly significant correlation (correlation coefficient, $r > 0.95$) was found for at least five measurements over the range of packing fraction, p_f from 0.75 to 0.95. The packing fraction refers to the value at zero creep time when the constant load was first reached and the creep monitoring began. A_i and B_i are numerical terms which depended on the parameter concerned, the nature of the particulate material, the particle size and the loading rate employed. Results for $1/k_1$, J_o and J_i at certain p_f values, obtained from Eqn 2 by regression, are given in Table 1.

From Table 1, it is seen that for Emcompress

TABLE 1

Apparent viscosity $1/k_1$ (MPa s; $\times 10^9$), instantaneous elastic compliance, J_0 and total elastic compliance, J_i (MPa^{-1}; $\times 10^{-8}$) at selected values of packing fraction for powders tested at two different loading rates

Material	Packing fraction	Loading rate (kN min^{-1})					
		4			16		
		$1/k_1$	J_0	J_i	$1/k_1$	J_0	J_i
Starch 1500	0.85	0.4	1.3	49.2	0.5	9.8	67.6
Emcompress	0.85	17.6	0.3	0.7	19.8	0.1	0.6
Paracetamol DC	0.85	–	–	–	2.6	0.7	8.4
Paracetamol							
($> 45\ \mu m$)	0.85	20.4	0.1	1.2	28.8	0.3	0.9
(15–45 μm)	0.85	13.5	0.2	1.6	20.7	0.4	1.1
($< 15\ \mu m$)	0.85	9.9	0.4	2.4	10.1	0.5	2.7
Aspirin							
A ($> 45\ \mu m$)	0.95	0.7	2.5	23.1	0.8	1.7	22.2
A ($< 45\ \mu m$)	0.95	–	–	–	0.7	4.6	22.7
B ($> 45\ \mu m$)	0.95	1.4	2.2	14.5	1.7	2.4	11.9
B ($< 45\ \mu m$)	0.95	–	–	–	1.3	2.6	12.6

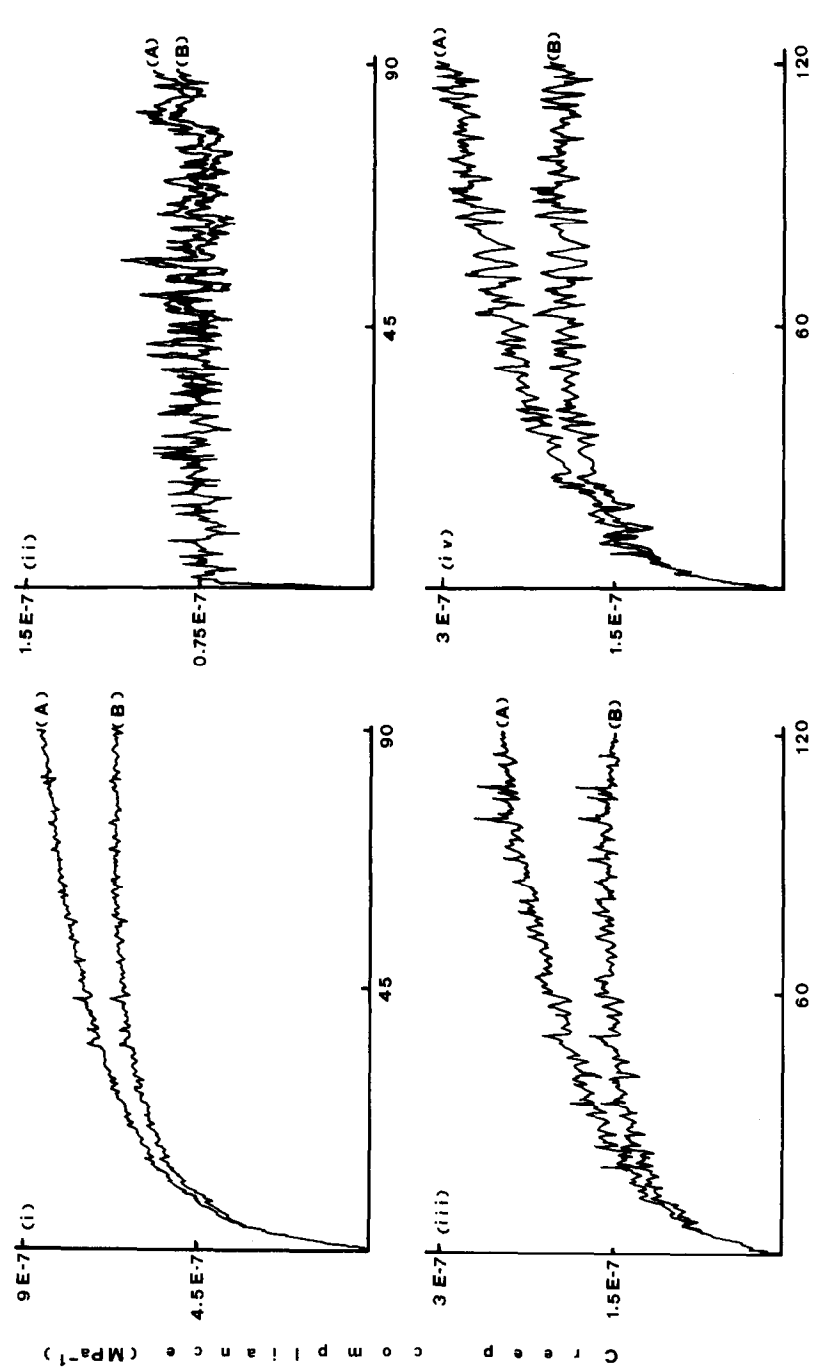

Fig. 1. Creep compliance curves at a loading rate of 16 kN min^{-1} for: (i) Starch 1500 at 8 kN constant load; (ii) Emcompress at 4 kN; (iii) Paracetamol DC at 8 kN and; (iv) aspirin (ASA-A, $> 45\mu m$) at 4 kN. In each case, curve A shows the total compliance and curve B the elastic compliance.

and crystalline paracetamol, the apparent viscosity ($1/k_1$) is greater and the elastic compliance parameters (J_o and J_i) are less than those for Paracetamol DC, aspirin and Starch 1500. By raising the loading rate, the apparent viscosity is increased for all the particulate materials investigated. For Starch 1500 both of the elastic compliance parameters (J_o and J_i) also increase significantly with loading rate. However, for Emcompress, crystalline paracetamol and aspirin, varying the loading rate has no systematic or major effect on the elastic compliance parameters; this may be partly because the elastic compliance values are relatively low or because elastic strain is relieved by particle fragmentation.

TABLE 2

Elastic retardation times, t_i and ratios of elastic / plastic compliance at time t_i for powders tested under different compression conditions

Material	Creep retardation time t_i (s)	Packing fraction p_f	Elastic/plastic compliance ratio (Loading rate (kN min^{-1}))	
			4	16
Starch 1500	27	0.80	6.2	11.0
Starch 1500		0.85	6.0	10.6
Starch 1500		0.90	5.6	10.4
Emcompress	7	0.80	37.6	23.0
Emcompress		0.85	19.1	13.2
Paracetamol DC	26	0.85	–	7.2
Paracetamol DC		0.90	–	6.6
Paracetamol				
(> 45 μm)	4.5	0.85	53.4	56.6
(> 45 μm)		0.90	45.4	38.9
(15–45 μm)	5	0.85	42.2	44.5
(15–45 μm)		0.90	33.1	37.2
(< 15 μm)	18	0.80	12.8	14.7
(< 15 μm)		0.85	12.2	14.1
Aspirin				
A (> 45 μm)	26	0.90	6.4	6.9
A (> 45 μm)		0.95	5.2	5.8
A (< 45 μm)	26	0.90	–	5.0
A (< 45 μm)		0.95	–	5.1
B (> 45 μm)	26	0.90	6.4	6.8
B (> 45 μm)		0.95	6.4	6.8
B (< 45 μm)	26	0.90	–	5.9
B (< 45 μm)		0.95	–	5.3

Replicate values of t_i derived from creep compliance plots varied by up to ±5% from the tabulated mean value.

As reported earlier (Tsardaka and Rees, 1989; Malamataris et al., 1992), in general with an increase in the apparent viscosity, there is a decrease in the elastic compliance. Emcompress, which is a brittle material, possesses a high apparent viscosity and low elastic compliance because much of the elastic strain is relieved by particle fracture. In contrast, a material such as Starch 1500, which can relieve elastic strain by undergoing plastic deformation, exhibits a low apparent viscosity and high elastic compliance. In the case of crystalline paracetamol, it is known that consolidation occurs to a large extent by elastic deformation, though extensive particle fragmentation has been demonstrated using surface-area measurement, by permeametry, as a function of compaction pressure (Alderborn et al., 1985). Aspirin particles also undergo extensive fragmentation but it is coupled with plastic deformation (Duberg and Nystrom, 1986). Table 1 shows that, for the different size fractions of crystalline paracetamol and aspirin, a reduction in the particle size leads to a decrease in the apparent viscosity and an increase in the elastic compliance (both J_o and J_i).

The reason for a reduction in apparent viscosity with a decrease in particle size is not immediately apparent given that smaller crystals generally are accepted to contain fewer dislocations and, therefore, to be more resistant to deformation. Certainly, if a crystal contains few flaws, elastic deformation is less likely to be relieved by brittle fracture; that would increase elastic compliance as the results in Table 1 show. Furthermore if, instead of brittle fracture, partial relief of elastic strain occurs by plastic flow, a decrease in apparent viscosity might be the result. Despite the larger number of interparticle contact points present, per unit volume of a compacted fine powder, provided the area of contact at each point is sufficiently small, the localised stress will be sufficiently high to ensure continuing plastic flow of material into the surrounding void space (Tsardaka and Rees, 1992).

The apparent viscosity and elastic compliance values should reflect the extent of elastic retardation; longer elastic, or creep retardation time should correspond to lower apparent viscosity

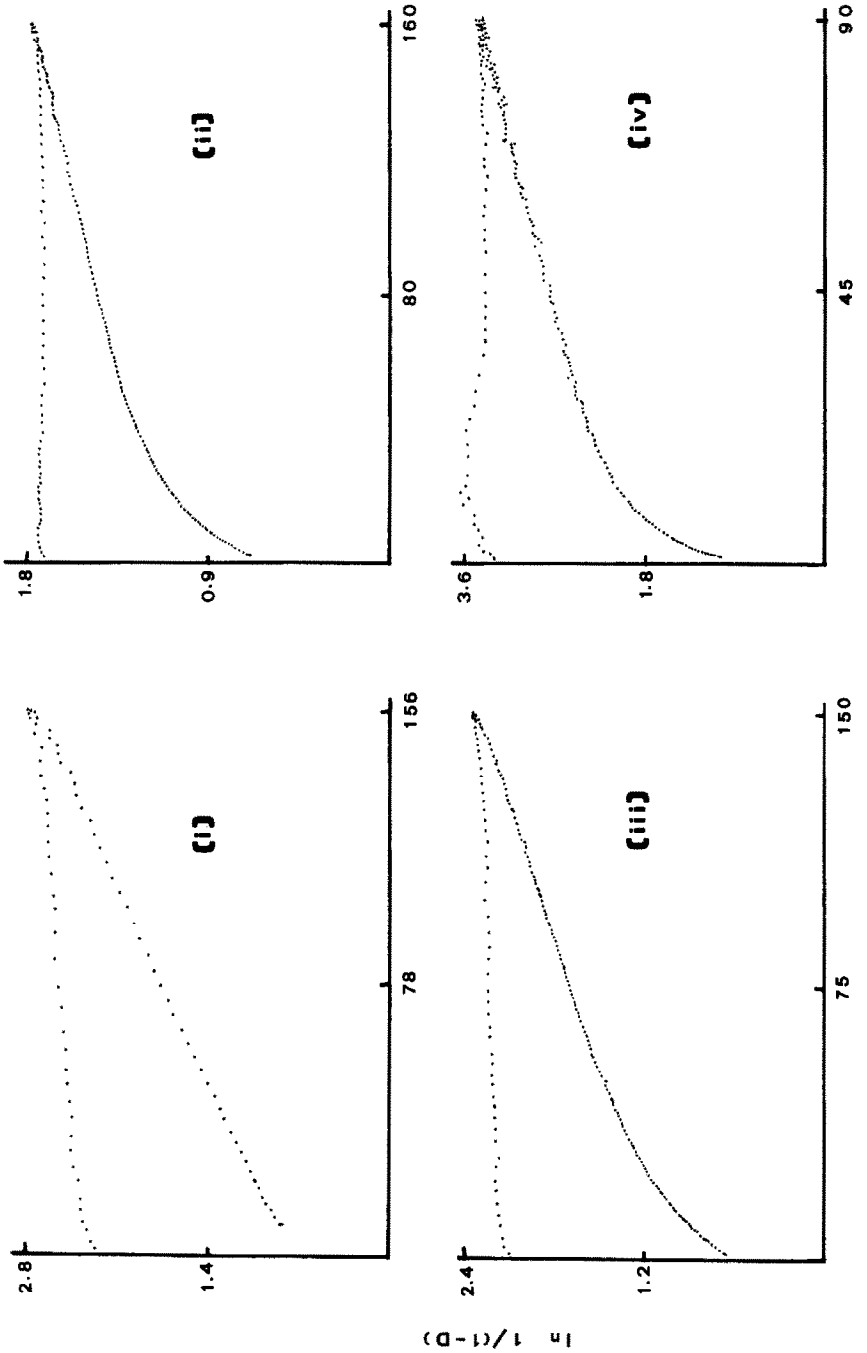

Fig. 2. Extended Heckel plots for: (i) Starch 1500, at 19.7 kN peak load ($p_f = 0.94$); (ii) Emcompress, at 20.1 kN ($p_f = 0.82$); (iii) Paracetamol DC, at 19.0 kN ($p_f = 0.90$); (iv) aspirin (ASA-A > 45μm), at 11.3 kN ($p_f = 0.97$).

and higher elastic compliance. The results for elastic retardation time, t_i, are given in Table 2. As expected, the values are not affected by the loading rate or the packing fraction but they are dependent on the nature of the solid material and its particle size. For this reason, and because of the other advantages reported previously (Malamataris et al., 1992), t_i was used as the time for quantifying the ratio of the reversible (elastic) to irreversible (plastic) compliance. These results are also given in Table 2. The values of compliance ratio are high for the crystalline paracetamol, especially for the coarsest material (> 45 μm), low for aspirin, and tend to decrease with a reduction in the particle size of both these powder materials. For Starch 1500 and Paracetamol DC, a change in the packing fraction has little if any effect on the elastic/plastic compliance ratio but for Emcompress, the coarser paracetamol and some aspirin samples, the values decrease markedly at higher packing fraction. This indicates that at a higher level of consolidation, even for the more brittle materials, the compliance ratio shifts towards an increased proportion of plastic flow. There is a large increase in the compliance ratio with loading rate for Starch 1500 compared with a small increase for aspirin, and, with one exception, for crystalline paracetamol. However, for Emcompress, there is a decrease in the compliance ratio at a higher loading rate.

The results for crystalline aspirin and paracetamol show that, in order to minimize the elastic/plastic compliance ratio, a small particle size is beneficial, coupled with a low loading rate and a high degree of consolidation. Such conditions would seem to reduce the fraction of compliance which is associated with recoverable elastic strain. This is particularly noticeable for paracetamol crystals in that the 'worst-case' ratio of 56.6 can be reduced to a value of only 12.2 by using the optimum conditions. However, in the case of Emcompress, there would seem to be possible advantages in using a high loading rate to achieve a comparable advantage. These observations indicate a need for further study of the relation between elastic/plastic compliance ratio and consolidation mechanisms.

Typical extended Heckel plots are given in Fig. 2 for the same four substances for which creep curves are shown in Fig. 1. The behaviour during compression and visco-elastic recovery of all the particulate materials investigated is quantified in Table 3 on the basis of the yield pressure, the elastic recovery during force removal and two work measurements, namely, the true work of compaction and the work of elastic deformation (expansion work). The results are expressed for

TABLE 3

Data derived by interpolation of the results from Heckel plots generated at a range of peak compression loads

Material	Packing fraction	True work (J)	Expansion work (J)	Yield pressure (MPa)	Elastic recovery (%)
Starch 1500	0.85	5.3	0.67	63.9	2.5
Emcompress	0.85	7.2	1.77	207.6	3.1
Paracetamol DC	0.85	5.5	0.28	117.9	1.3
Paracetamol					
(> 45 μm)	0.85	1.6	0.09	124.0	1.2
(15–45 μm)	0.85	2.5	0.29	142.5	2.5
(< 15 μm)	0.85	4.5	0.76	141.4	4.9
Aspirin					
ASA-A (> 45 μm)	0.95	1.0	0.03	59.0	0.4
ASA-A (< 45 μm)	0.95	1.3	0.06	76.0	0.5
ASA-B (> 45 μm)	0.95	1.0	0.04	54.4	0.4
ASA-B (< 45 μm)	0.95	1.5	0.05	95.3	0.5

selected values of packing fraction at peak compression load; these were obtained by interpolation using regression of experimental data produced at a range of compression loads. Standardizing the packing fraction enables comparison of visco-elastic parameters and other properties determined by various techniques. The fragmentation tendency of the materials under investigation can be quantified on the basis of the curvature of the Heckel plots when the applied pressure is relatively low; on the basis of deviation from a rectilinear relation, this is expressed inversely as the correlation coefficient, C_c (Duberg and Nystrom, 1986). The mean C_c values for 10 compressions were: Starch 1500, 0.999; Emcompress, 0.978; Paracetamol DC, 0.989; paracetamol (> 45 μm), 0.986; paracetamol (15–45 μm), 0.991; paracetamol (< 15 μm), 0.995; aspirin ASA-A (> 45 μm), 0.948; ASA-A (< 45 μm), 0.982; ASA-B (> 45 μm), 0.977; ASA-B (< 45 μm), 0.985. As expected, the coarser crystalline paracetamol and aspirin show evidence of more fragmentation than the fine particles. It is surprising, however, that only the coarsest crystalline paracetamol undergoes more fracture than Paracetamol DC according to these results.

From Table 3 it can be seen that the yield pressures, P_y, which reflect the resistance of particles to deformation are in decreasing order for Emcompress > crystalline paracetamol > Paracetamol DC > aspirin (< 45 μm) > Starch 1500 > aspirin (> 45 μm). Also, the P_y values are in reverse order to those for elastic compliance at infinite time, J_i, from creep experiments (Table 1). A comparison between two related parameters, $1/k_1$ from creep experiments and P_y from Heckel plots, is shown in Fig. 3. From Fig. 3 and the results in Tables 1 and 3, it is seen that a change in particle size has more effect on the apparent viscosity of crystalline paracetamol than on the yield pressure, while the opposite is true for aspirin. This difference may constitute evidence that in the case of paracetamol, the minimal amount of plastic deformation occurs after brittle fracture of the particles whereas, for aspirin, plastic deformation also takes place before fragmentation under the conditions of compression rate and pressure employed. Hess (1978)

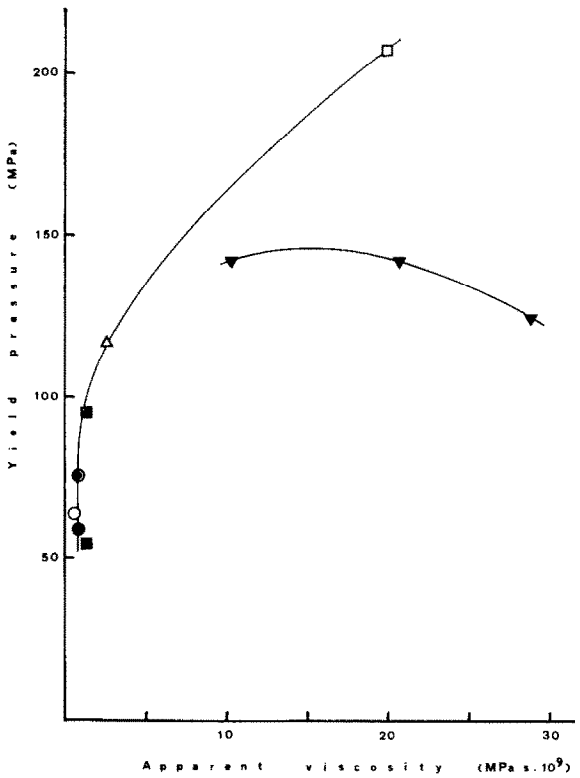

Fig. 3. Yield pressures from Heckel data for various particulate materials plotted against apparent viscosities measured in creep experiments after loading at 16 kN min^{-1}. (○) Starch 1500; (□) Emcompress; (△) Paracetamol DC; (▼) crystalline paracetamol; (●) aspirin ASA-A (> 45 μm); (⊙) aspirin ASA-A (< 45 μm); (■) aspirin ASA-B (> 45 μm); (⊡) aspirin ASA-B (< 45 μm).

showed that stepwise displacement occurs along slip planes within aspirin crystals, which may lead to a stepwise plastic flow and a change in the yield pressure.

From the results in Table 3, the elastic recovery of different materials during decompression is related to the expansion work with the exception of crystalline paracetamol; even for crystalline paracetamol a similar type of relation is observed for the three different size fractions. There is also some rank order agreement between the yield pressure and the true work of compression (Table 3); although aspirin and crystalline paracetamol do not conform with the other materials, the particle size fractions of aspirin do follow the same trend. For crystalline paracetamol, the yield

pressure is high compared with Paracetamol DC or Starch 1500, but the true work of compaction, especially of the coarsest size fraction of crystalline paracetamol, is relatively low. This is probably due to extensive fracture of the coarser paracetamol crystals once the yield pressure is exceeded. Especially in the case of the coarsest size fraction (> 45 μm) these properties, coupled with its exceptionally high apparent viscosity (Table 1) would explain the problems of achieving adequate interparticle bonding in crystalline paracetamol to form coherent tablets.

There is a total lack of correlation between the elasticity parameters for different materials derived from creep experiments and from Heckel-plots. A number of factors may be responsible. First, the continuing plastic deformation which occurs during decompression in a tablet press cannot be taken into account. Second, there are errors associated with the determination of tablet thickness when the force rapidly approaches zero since the values are recorded only every millisecond. Furthermore, the absence of a simple correlation may be due to differences in the elastic behaviour of materials subjected to static load conditions in a creep test and under dynamic loading when a Heckel plot is generated in a tablet press.

An important general observation from the findings reported in Table 3 is that smaller particles require more work and, with one exception (paracetamol < 15 μm) exhibit a higher yield pressure. They also undergo more elastic recovery and exhibit higher expansion work. This is a consequence of the lower incidence of dislocations than in larger crystals, as referred to earlier.

Typical plots of applied load as a function of platen displacement during diametral testing of tablets, a measure of tablet deformation, are shown in Fig. 4 for two materials which differ markedly in toughness. The mechanical properties derived from the diametral loading and tensile failure experiments for each of the materials investigated are summarized in Table 4. They relate to specified values of packing fraction to allow comparison with the creep data and Heckel parameters. No results are quoted for crystalline paracetamol because, following the compaction cycle, powder was ejected from the die cavity. Paracetamol DC produced the tablets of greatest strength and highest apparent failure viscosity. However, they had a lower toughness and normalized work of failure than Starch 1500 tablets. The tablets of Emcompress had a tensile strength and an apparent failure viscosity comparable with those of Paracetamol DC and Starch 1500 but the toughness and normalized work of failure were lower. All of the aspirin samples produced tablets of inferior mechanical properties to the other materials subjected to mechanical testing. The finer particle size fractions of aspirin from both sources gave tablets having somewhat improved strength, toughness and failure viscosity.

There is apparently no simple interdepen-

TABLE 4

Mechanical properties of tablets, at selected values of packing fraction, derived from diametral loading and tensile failure experiments

Material	Packing fraction	Tensile strength (MPa)	Toughness area ratio	Apparent failure viscosity (MPa s)	Normalised work of failure ($J\ m^{-2}$)
Starch 1500	0.85	2.12	1.00	11.04	232.9
Emcompress	0.85	1.99	0.82	13.87	108.6
Paracetamol DC	0.85	2.58	0.92	15.17	217.6
Aspirin					
ASA-A (> 45 μm)	0.95	0.28	0.42	1.19	23.2
ASA-A (< 45 μm)	0.95	0.73	0.67	3.56	61.7
ASA-B (> 45 μm)	0.95	0.38	0.51	1.62	24.2
ASA-B (< 45 μm)	0.95	0.73	0.73	3.24	55.2

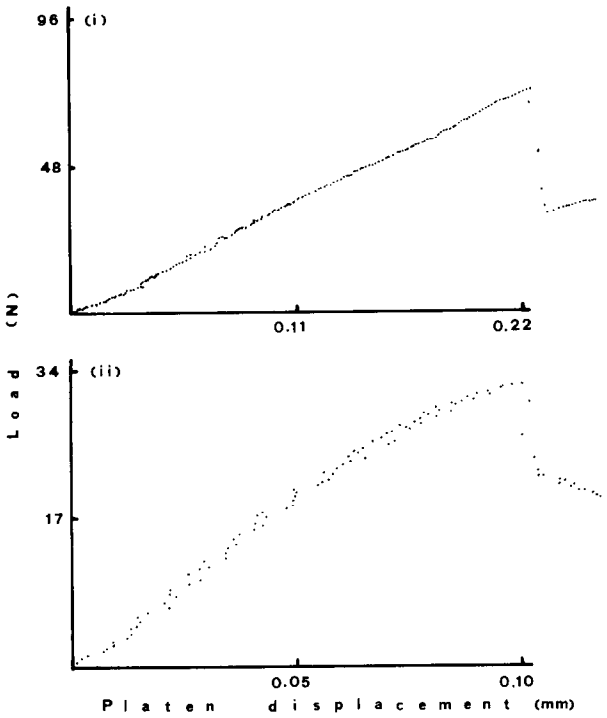

Fig. 4. Plots of applied load versus platen displacement during diametral loading of tablets of (i) Starch 1500 and (ii) aspirin (ASA-A, $> 45\ \mu m$).

dence between the different mechanical properties measured (Table 4) though all four parameters clearly were able to distinguish the inferior properties of the aspirin samples from the Starch 1500, Emcompress and Paracetamol DC. Some general rank correlation was evident between tensile strength and apparent failure viscosity. Likewise, as might be expected, toughness and normalised work of failure (NWF) showed a similar ranking of compacts though NWF appeared to offer greater discrimination than toughness per se. No apparent correlation could be identified between properties measured in diametral loading experiments, such as apparent failure viscosity, and those recorded in the creep experiments, such as apparent viscosity, or in the tableting experiments, such as true work of compaction.

The inability of crystalline paracetamol to form tablets calls for further comment. Relatively low values were recorded for the elastic recovery and expansion work of the coarsest crystalline paracetamol (Table 3). Similarly, low values were found for the elastic compliances (Table 1). This may seem surprising, particularly in comparison with the results for Paracetamol DC which produced tablets having good mechanical properties. The explanation is that even very minimal elastic strain recovery of a compact in which interparticle contact areas are small will result in bond failure and loss of strength. Although a reduction in particle size of the crystalline paracetamol to $< 15\ \mu m$ led to an improvement in properties such as apparent viscosity (Table 1), this was apparently not sufficient to counteract a corresponding adverse increase in elastic compliance which was associated with a marked increase in elastic strain recovery of tablets (Table 3).

The results in Table 2 show that the ratio of elastic/plastic compliance at the creep retardation time, t_i diminished as particle size decreased. Furthermore, the results for aspirin showed an increase in the tensile strength of tablets with a reduction in the particle size (Table 4). It was decided therefore to see whether any inverse correlation could be found between tablet tensile strength and the elastic/plastic compliance ratio at time t_i. The results are presented graphically in Fig. 5 for different consolidation states (packing fraction) of the powders. Clearly, the mechanisms responsible for tensile strength and viscoelasticity will alter with p_f due to deformation and fracture of particles. In accordance with fracture mechanics, a true solid ($p_f = 1.0$) appears to break in tension as a result of the propagation of minute cracks within it (Ouchiyama et al., 1987). Other workers (Chan et al., 1983; Bangudu and Pilpel, 1984) have found that for lower packing fractions of less than about 0.85, depending on the material, tensile strength data could reasonably be expressed by Cheng's equation which takes into account particle size and consolidation state, as well as a quantity that depends on the hardness, yield strength, plastoelasticity, brittle fracture and toughness of the material. From Fig. 5 there appears to be an inverse relation between tensile strength and the elastic/plastic deformation ratio at time t_i.

In the case of Starch 1500, Emcompress and Paracetamol DC, the solid lines in Fig. 5 show a

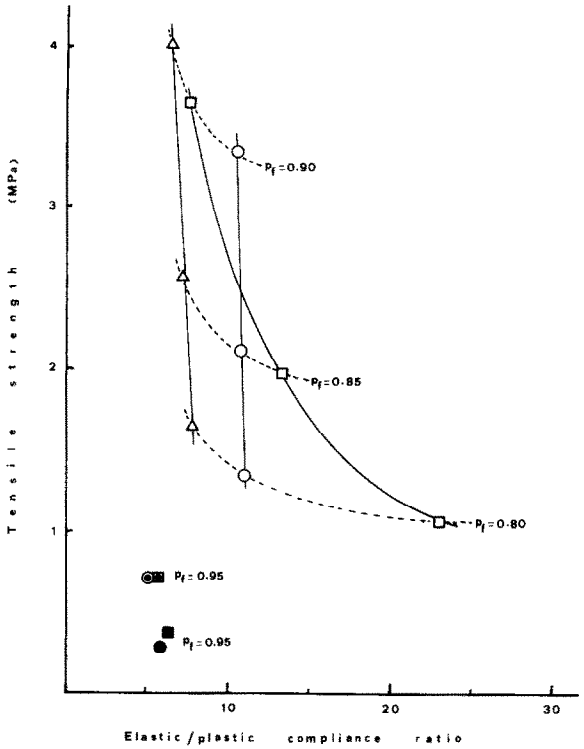

Fig. 5. Tablet tensile strength at defined packing fraction plotted against corresponding values of the elastic/plastic compliance ratio determined at the creep retardation time, t_i. Creep loading rate: 16 kN min^{-1}. (○) Starch 1500; (□) Emcompress; (△) Paracetamol DC; (▼) crystalline paracetamol; (●) aspirin ASA-A (> 45 μm); (⊙) aspirin ASA-A (< 45 μm); (■) aspirin ASA-B (> 45 μm); (⊡) aspirin ASA-B (< 45 μm).

marked decrease in tensile strength as the compliance ratio increases; the three co-ordinates for each individual material were obtained by altering the packing fraction. The observed effects can be explained on the basis that tensile strength and plastic compliance are indicators of the strength of bonds formed between the particles within a compact. Clearly though, other factors also play a part, such as closer proximity of particles as the material consolidates at lower porosity.

There is a similar though less pronounced decrease in tablet tensile strength with increasing compliance ratio shown by the dotted line relations in Fig. 5; these relations, for the same three materials, show the effect of a change in material properties at a given value of packing fraction. Materials which consolidate by different mechanisms when a compressive load is applied will achieve different bulk particle configurations and different interparticle contact geometries. Nevertheless, the results for Starch 1500, Emcompress and Paracetamol DC indicate that, at a given packing fraction, a lower compliance ratio is associated with a higher tablet strength.

The results for aspirin in Fig. 5 do not support this generalisation, however; the tensile strength values are considerably less than would be expected from the results for other materials obtained at lower levels of p_f. Nevertheless, they provide some indication that, for both grades of aspirin, a reduction in particle size decreases the compliance ratio and thereby increases the tablet strength. Indeed, the steepness of the curves presented for Starch 1500 and Paracetamol DC, together with the results for the two aspirin samples, suggest that small changes in the compliance ratio may have a major beneficial effect on tablet strength.

We conclude that no single viscoelastic property suffices as an indicator of tabletability. When interpreting the meaning of a given viscoelastic parameter, one needs to take into account additional information derived from studies on the particulate solid prior to tableting, as well as measurements during tablet compaction and on the finished tablets.

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