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Uniaxial strain rate effects in pharmaceutical powders during cold compaction

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The results of uniaxial compression tests on some pharmaceutical powders subjected to strain rates of between 10^{-3} and $10^{5}\ s^{-1}$ are given. The tests fall into three main categories: low-strain-rate tests (10^{-3}–$10\ s^{-1}$) performed on a servohydraulic variable speed-compression machine at constant compression rate; medium-strain-rate tests (10^{2}–$10^{3}\ s^{-1}$) carried out on a drop hammer; and high strain rate tests (10^{3}–$10^{5}\ s^{-1}$) performed on a high-pressure air projectile launcher compaction apparatus. Axial and radial pressures, as well as displacement–time measurements, are made. Powders tested include: Dipac sugar; sodium chloride; potassium bromide; lactose; paracetamol d.c.; avicel; calcium phosphate; and copper sulphate. The influence of compression rate on the form of the characteristic pressure–density and radial–axial pressure relationships during uniaxial straining is presented. The investigation showed that the general tendency for all powders tested, except for paracetamol d.c., is to exhibit increased compaction pressure with strain rate up to $10^{5}\ s^{-1}$. Due to morphological and compositional effects, paracetamol d.c. softens with the rate of straining up to about $10^{2}\ s^{-1}$ and at higher rates it behaves like other powders. Also the mean radial pressure at the die wall (obtained by a pin-type transducer) shows that the friction conditions are variable during the process, and their effect tends to decrease as the speed of compaction increases, resulting in more uniform density compacts. Finally, by observing the decay of both axial and radial pressures with time under constant volume conditions, a reasonably linear behaviour is obtained for all materials tested, particularly the axial relaxation curves, over the period recorded.

1. Introduction

The compaction process has important uses in the fields of powder metallurgy, ceramics, polymers and pharmaceutical industry. Although there has been some earlier work, notably by Walker [1], it was not until the upsurge of interest in powder metallurgy in the late 1930s, that the mechanics of the compaction process began to receive widespread attention. The work during this period was concentrated in two main areas: (i) attempts to obtain a relationship between the applied pressure and the corresponding change in volume [2–4]; and (ii) efforts to analyse the processes occurring within the compact during compression and to investigate the resulting changes in density and hardness on a microscopic basis [5–8].

In the 1950s, where the process is used to form solid but easily dissolvable "tablets" from pharmaceutical preparations, the particular problems of the pharmaceutical industry began to receive attention [9]. The ability to control the post-compaction properties, particularly those produced at high rates, increasingly become one of the primary aims of the pharmaceutical industry, whereas increasing the tablet-production rate is hampered by the inability of a large family of powders to compact into resilient tablets. Fracture or "capping" of compacts during load removal or ejection is also a well known problem in the industry, and any effort to overcome it requires fundamental understanding of the process mechanics. Any improvement in the mechanical properties of tablets, produced at high rates, is expected to save the cost of additional tableting machines and reduce loss in manufacture.

Much effort has been expended over the last few decades to identify the significant parameters which govern the compaction process. However, many aspects are still obscure. One very important aspect, which to date has not been carefully or systematically investigated, is the influence of axial and radial stresses and their individual rates of loading and unloading on the mechanical properties of the formed tablet. To the author's knowledge, very few attempts to take the effect of the pressing speed into account have been reported: among these are the works of Fell and Newton [10] and David and Augsburger [11].

Extensive data has been published for tests performed on either conventional testing machines or actual industrial tableting machines. Such machines engender variable strain rates during the process. Consequently, it is difficult directly to compare the results of the different materials, particularly those

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which exhibit strong sensitivity to strain rate. Thus it is not surprising to see a varying degree of discrepancy between results of different investigators, as reported by Krycer and others [12], particularly when considering strain-rate-sensitive formulations.

The importance of compression rate during the compaction process and the testing of tablet strength, have been highlighted by Rees and Rue [13] and later by Barton [14] and Es-Saheb [15]. Also, as a result of the work of Amidon *et al.* [16], it has become increasingly apparent that rates of axial and radial pressure removal have a paramount influence on the instantaneous stress distribution in both the perform and the die. The resilience of the formed tablet is expected to be heavily dependent on the stress-distribution history during the whole compression cycle. Careful studies of the rate effect on the process are essential in order to complete the total picture of material behaviour. In addition, knowledge of rate-dependent behaviour over a wide range of strain rates is necessary in formulating constitutive relations as well as in determining the predominant mechanisms responsible for material behaviour.

In this paper, a summary of an extensive research programme on the influence of axial compression rate on the compaction characteristics of pharmaceutical powders is presented. The results for some of the powders tested in the strain rate range 10^{-3}–$10^{5}\ s^{-1}$ are also included.

2. Experimental procedure

The test programme was carried out for eight materials provided by ICI Pharmaceuticals Ltd (UK): sodium chloride; potassium bromide; copper sulphate; calcium phosphate; lactose and avicel in their normal laboratory form; and ordinary sugar and paracetamol, both specially formulated for direct compression without granulation and hence referred to in the paper by the trade names of "dipac sugar" and "paracetamol d.c.", respectively.

Three different systems (rigs) were employed to cover a strain rate range of 10^{-3}–$10^{5}\ s^{-1}$. Tablets from all eight powders were formed on these rigs to cover the low, medium and high axial strain rates.

2.1. Low strain rates (13^{-3} to $10\ s^{-1}$)

For the low axial strain rates, a Keelavite variable speed hydraulic machine (tableting machine simulator) was used. The simulator consists of two independently operated, servo-controlled, hydraulic actuators which can move standard pharmaceutical punches within a die at velocities up to $400\ mm\ s^{-1}$, to a positional accuracy of 5 μm. In addition, the simulator can follow a force-time profile with the same relative accuracy up to a maximum compressive force of 55 kN. The two actuators have separate control systems which can be independently programmed. The required upper and lower punch displacement–time profiles are converted to digital form using an ultrasonic graph plotter, or a mini-computer (Commadore, model 3032). The two profiles are stored separately then fed out simultaneously to the two actuators at a rate of between 0.001 and 30 Hz, which gives a range of cycle times of 33.3 (10^{-3})–(10^{3}) s. Each actuator is instrumented with a precision load cell and displacement transducer which serves two purposes: (i) to feed back force and positional data to the control system; and (ii) to provide a permanent record of the force and displacement histories of each punch. For this latter purpose, the outputs from the transducers are relayed to galvanometers in a multi-channel UV recorder. They may also be monitored on peak-picking digital voltmeters, as well as on the fitted microcomputer. The tests carried out on the simulator were at constant compression rate $\dot{\gamma}$ (i.e. keeping the punch velocity, v, in proportion to the current height, H, of the compact) in accordance with the following equation

$$\dot{\gamma} = (d\gamma/dt) = (1/H)(dH/dt) = v/H$$

assuming a uniform cross-sectional area of a cylindrical tablet specimen. Hence it was possible to separate the influence of strain from that of strain rate.

2.2. Medium strain rates (10^{2} to $10^{3}\ s^{-1}$)

For medium strain rates the experimental drop hammer is used. The drop hammer was originally built to provide the kinetic energy of a free falling tup mass for deforming various materials at medium strain rates (at velocities of up to $7\ m\ s^{-1}$). In order to use this apparatus for powder compaction a special rig or "sub-press" to house the die and punches, as well as to transmit the compaction load and guide the punches, is constructed. The sub-press also incorporates a capacitance transducer to measure the axial displacement. Fig. 1 shows the complete assembly drawing of the sub-press used. Tablets from all the powder samples were formed by letting steel tup mass of 14 kg impinge axially upon the sub-press at various impact velocities ranging from 1.0 to $5.0\ m\ s^{-1}$. In this situation a constant compression rate is not possible because the impact velocity reduces to zero at the end of compression. However, an average or mean compression rate was used which is defined as the final degree of compaction divided by the total duration. The axial pressure and displacement as well as the mean radial pressure on the die wall were measured and displayed on two Gould digital oscilloscopes. The tup mass initial impact velocity was measured in each case, using two steel wires 200 mm apart, connected to a Racal-type SA-535 microsecond counter through a simple electric circuit.

The specially designed radial pressure transducer was housed in a purpose-built hardened steel die. The transducer was made out of a 3.2-mm silver steel pin, on the circumference of which two strain gauges (Tinsley Telcon type 2/120/EC) were attached diametrically opposite so that any bending effects were eliminated. The transducer was pre-calibrated so that strain values were readily converted to pressure.

2.3. High strain rates (10^{3}–$10^{5}\ s^{-1}$)

For high strain rates, a specially designed projectile

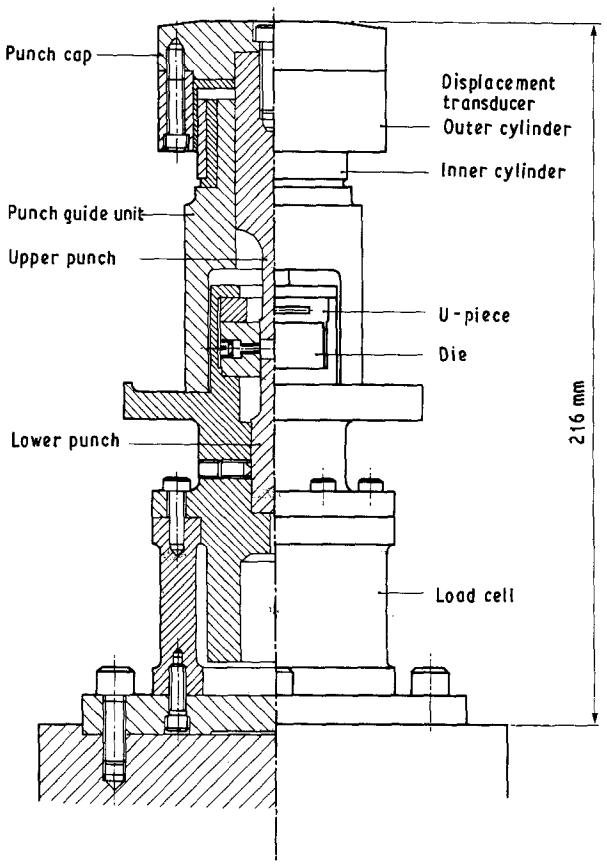

Figure 1 Drop-hammer sub-press assembly.

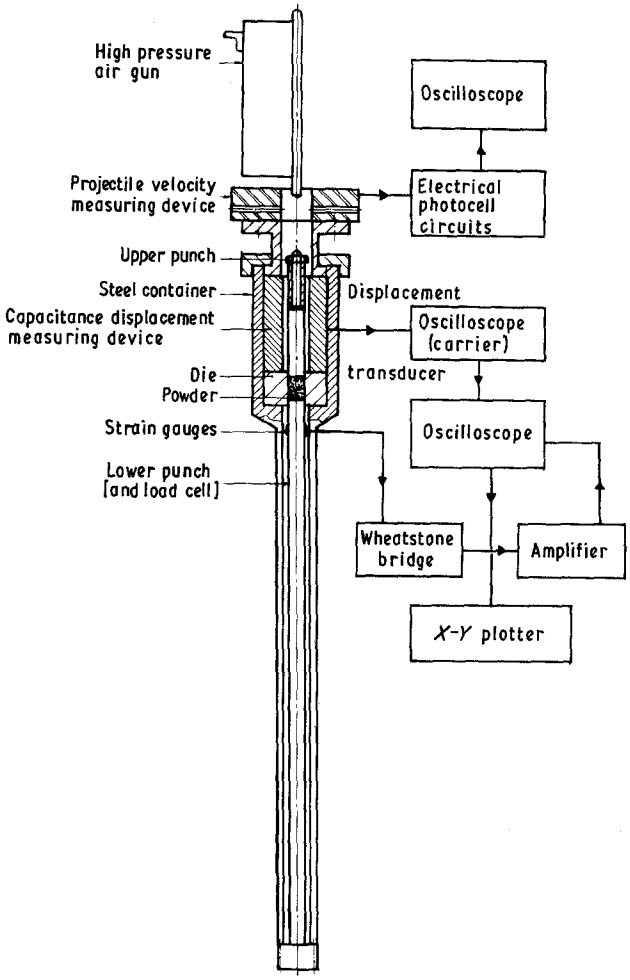

Figure 2 Schematic diagram for the high-speed powder compacting apparatus and associated equipment.

launcher was used. It consisted basically of long hardened silver steel cylindrical lower punch (914.4 mm long × 9.525 mm diameter) instrumented with two strain gauges (Tinsely Telcon type 7/120/EC) mounted diametrically opposite, to be used as load cell utilizing the stress-wave technique, for measuring the transmitted axial compaction loads. The 10-mm-diameter steel die of 30 mm maximum depth of fill, together with the capacitance transducer body and the upper punch used to measure the axial displacement of the powder, were housed in a cylindrical steel structure as shown in Fig. 2.

The displacement transducer was of the variable capacitance type. It consists of two concentric cylinders which serve as the plates of the capacitor, the outer cylinder being fixed to the guide unit and the inner one is the steel upper punch itself. Thus by monitoring the relative movement of the guide unit and the punch, the change in volume of the powder was measured. But in order to avoid buckling in the upper punch due to the different dynamic compaction loads likely to be encountered in the process, two upper punch units (of 130 and 75 mm long × 9.53 mm diameter) were employed, together with two matching guide capacitance units of 100 and 50 mm long, respectively.

A high-pressure air gun (up to 27.58 MPa) was used to fire projectiles of polythene bullets (30 mm long × 9.35 mm diameter, up to velocities of 430 m s^{-1}), and lead bullets (20 mm long × 9.35 mm diameter, up to velocities of ~ 140–190 m s^{-1}) on the upper punch to provide the compaction loads required. The impact speed of the projectiles on the upper punch was measured in each test by using two pairs of electric-photocells 25 mm apart, connected to a storage oscilloscope through a special electric circuit. Using this apparatus, tablets from all powders were formed uniaxially at various high strain rates. The axial transmitted load and displacement signals were acquired by Gould digital storage oscilloscopes and later processed.

For each material and at each speed of pressing, the compaction test was repeated at least three times to check for consistency. The results of these tests are presented later in this paper. For further details on equipment, measuring methods and behaviour of other powders, as well as the effect of lubricants such as magnesium stearate on the process [15].

3. Results

The measurements in each test were processed for graphical presentation. The axial load is converted to axial pressure, the punch displacement to axial strain ε_x (degree of compaction) and axial strain rate, $\dot{\varepsilon}_x$, and the radial pin readings to radial pressure.

In the low-strain-rate range for each test, the axial pressure degree of compaction, C, was first derived as follows. From the UV recorder traces obtained and by using the proper calibration factors, which had been previously obtained for load cells and displacement

transducers, it was possible directly to convert the results obtained into axial pressure, radial pressure and axial displacement. However, at each rate, a mean curve was chosen as being representative. These representative curves were plotted on common axes for each material.

For the medium and high rate tests, the average strain rate was obtained from the displacement–time trace and the corresponding axial pressure from the axial load–time trace. This was thought to be a more convenient method for comparing different processes. Typical traces of axial displacement, axial pressure and radial pressure against time graphs for the drop hammer tests are shown in Fig. 3. Similarly, results for the high rate tests are obtained from the air gun apparatus and typical traces for dipac sugar powder, are shown in Fig. 4.

Interesting typical plots giving the variation of the axial pressure (stress) against axial strain (degree of compaction) and the average radial pressure with the axial pressure at various strain rates (speeds) obtained from the simulator (low strain rates) and drop hammer (medium strain rates) tests are shown in Figs 5–7 for sodium chloride, paracetamol d.c., and lactose powders, respectively. Each curve is evaluated from a large number of experimental points obtained from more than one test.

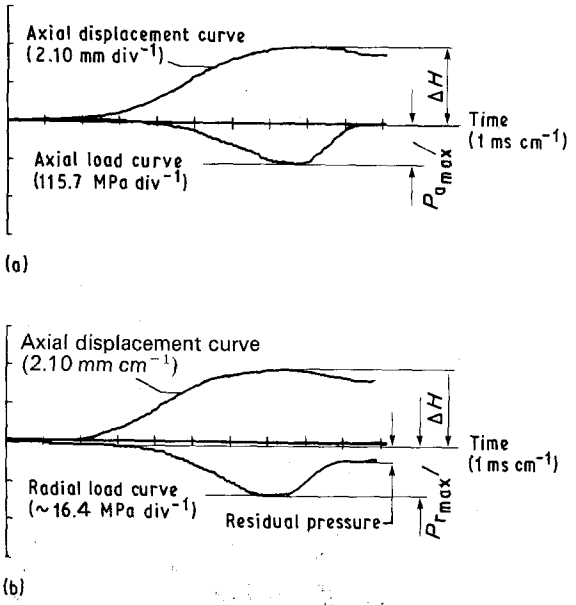

Figure 3 Oscilloscope traces for lactose powder compacted at medium strain rate range. (a) Axial displacement and pressure; (b) axial displacement and radial pressure.

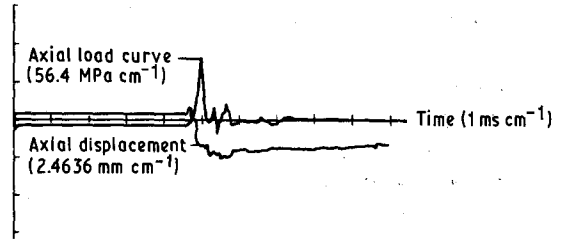

Figure 4 Oscilloscope traces for dipac sugar powder compacted at high strain rate range: axial displacement and axial pressure.

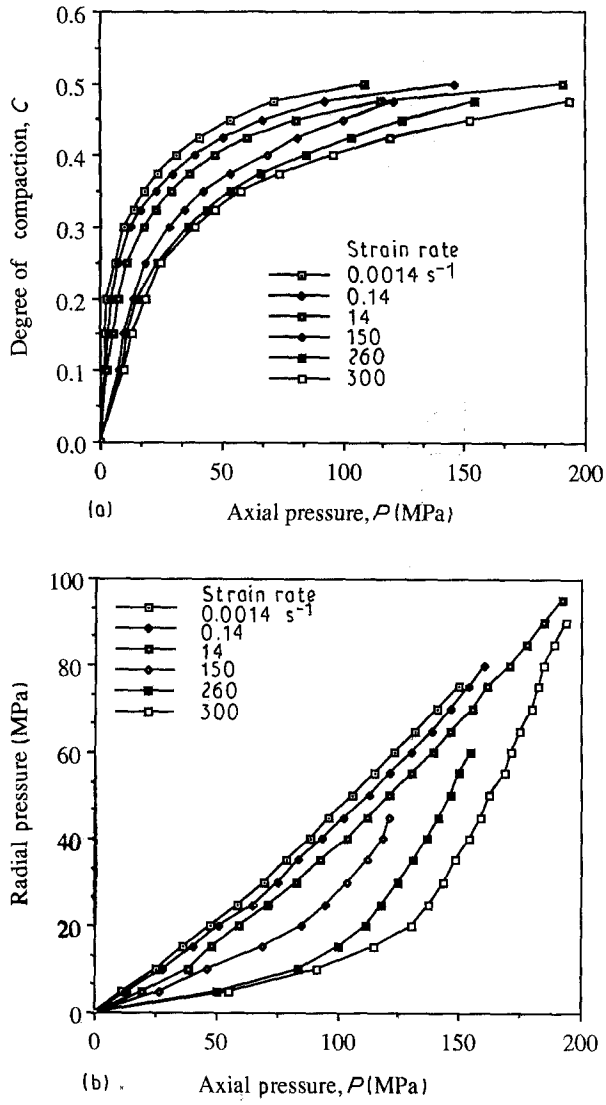

Figure 5 Axial pressure–degree of compaction and axial pressure–radial pressure curves for sodium chloride powder at various strain rates.

Another very important feature of these pharmaceutical materials is their creep and relaxation characteristics. Typical axial and radial pressure relaxation diagrams, obtained under constant volume conditions, for dipac sugar, sodium chloride, potassium bromide and paracetamol d.c. are shown in Fig. 8.

It is, however, interesting to examine the axial pressure variation with axial strain rate for the eight materials considered over the whole range of strain rate. These are given in Fig. 9, all at an axial strain of 40% (i.e. at 40% compaction).

4. Discussion

4.1. Strain rate and relaxation effects

In general, the pharmaceutical materials considered exhibit sensitivity to the rate of loading. In the advent of high speed tableting machines, it becomes essential to recognize the degree of sensitivity.

For all powders, from axial pressure–degree of compaction curves shown in Figs 5–7, it can be seen that after the initial low-pressure compacting stage, (i.e. rearrangement and packing stage [6]), where it is

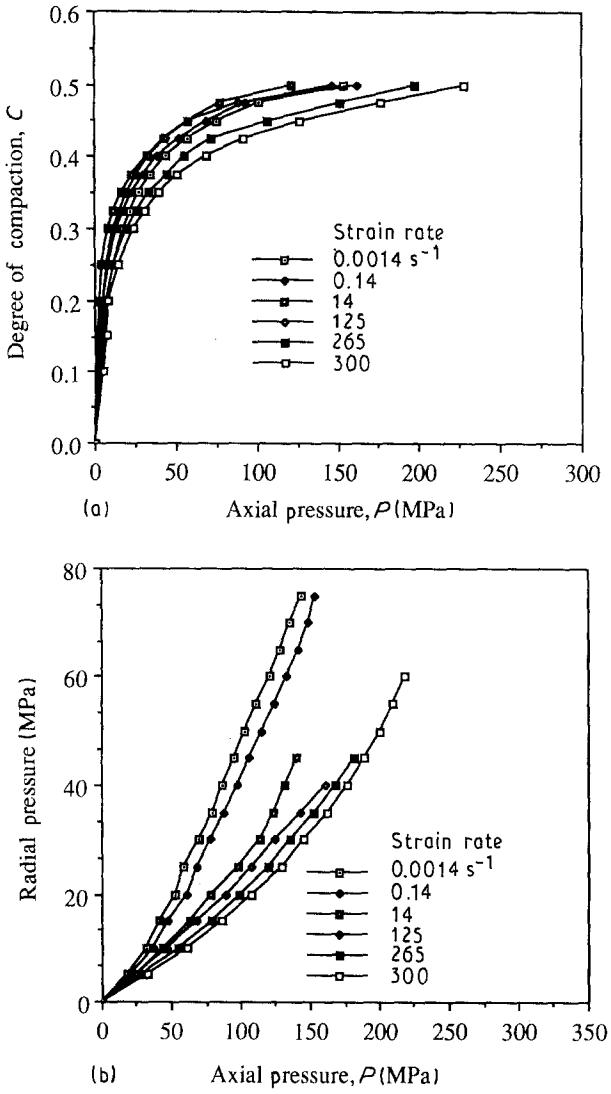

Figure 6 Axial pressure–degree of compaction and axial pressure–radial pressure curves for paracetamol d.c. powder at various strain rates.

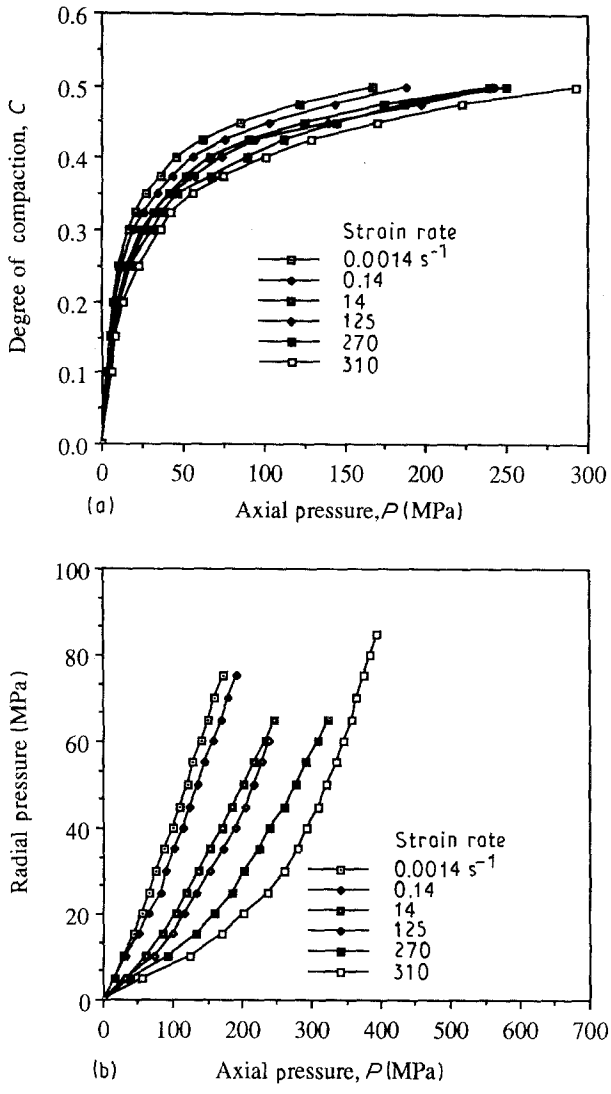

Figure 7 Axial pressure–degree of compaction and axial pressure–radial pressure curves for lactose powder at various strain rates.

impossible to differentiate between the curves, considerable variation exists between the low constant compression rate curves and the higher rate curves. Particularly for sodium chloride and avicel (the most ductile of the materials tested), the maximum pressure recorded for a rate of 0.0014 s^{-1} is ~ 28 and 39%, respectively, less than that at rate of 14 s^{-1}. This is the direction of variation that would be expected from the consideration of the high degree of relaxation associated with the plastic deformation that occurs in most pharmaceutical materials, as displayed in Fig. 8. It is clear from these curves that the relaxation of the axial pressure is higher (i.e. faster) than the radial pressure. For example, it is found that the axial pressure exerted by the punches on a well-compacted sample of sodium chloride decayed by about 10% within a minute of terminating the punch movement, compared to about 4% decay in the radial pressure for the same time. It is important here, to mention that the assessment of the material relaxation characteristics is essential to avoid 'capping' (which is the name given to the phenomenon of lamination of the compact on ejection from the die), and producing resilient compacts, particularly at higher rates of compaction.

The conclusion drawn from this is that, in a low compression rate test, (which in this case takes place over an 8-min period), the internal time-dependent mechanisms which cause relaxation become significant in determining the form of the pressure–degree of compaction curve for this material. In other words, alongside the increase in pressure due to the resistance of the powder to the imposed reduction of volume, there is also a tendency for the pressure to decrease with time.

This explanation is upheld when considering the rest of the materials curves at medium and high rates. These are relatively close, but again it seems that less pressure is required at the lower rates. It should be remembered that the compression rates are not in a simple arithmetical progression. Therefore the time periods over which the medium and fast rate cycles occur are probably too short for relaxation to have a significant effect, hence the relative closeness of these curves.

For lactose, dipac sugar, calcium phosphate, and copper sulphate, (see Fig. 7), it is noticed that, although in all cases the overall direction of variation is the same as for sodium chloride and avicel, the

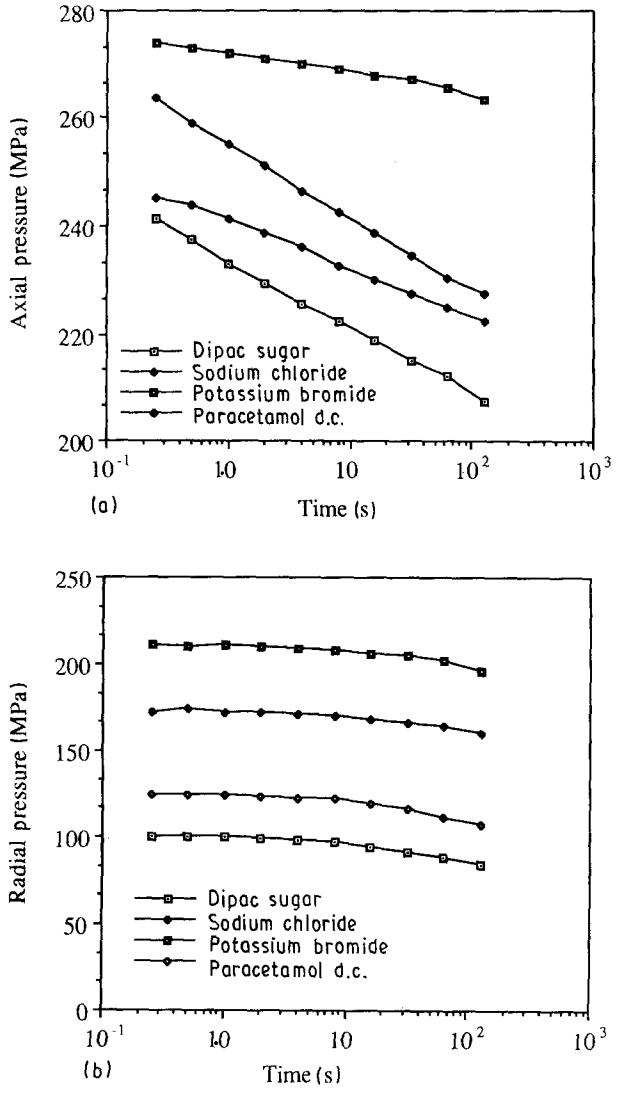

Figure 8 Typical axial and radial pressure relaxation curves for some pharmaceutical powders.

difference between the slow rate curves and the other ones are much less, in particular those curves for copper sulphate and calcium phosphate (i.e. those least sensitive to strain rate). This is despite the fact that most materials display a significant rate of relaxation (as e.g. dipac sugar, lactose and potassium bromide) (see Fig. 8). Therefore it is suggested that, there must be some other mechanism working to oppose the effects of relaxation and that this must be more pronounced for these materials than for the sodium chloride and avicel.

In this mechanism, after the general rearrangement and packing down of particles which occurs during the first stages of compaction, a basic, still very porous structure is formed. As the applied pressure is increased further, the bearing stress between the contacting area of adjacent particles will rise and may become sufficiently high to cause the plastic deformation or melting of particle asperities necessary to produce bonding. It seems reasonable to suppose that the strength of any bonding between particles at this stage is dependent on the amount of plastic deformation taking place. A bond due to a large plastic deformation area is likely to be more resistant to fracture than one with a small area. However, plasticity is a time-dependent phenomenon or, in other words, the amount of plastic flow increases with time under a given set of stress conditions. It is therefore suggested that, at a high compression rate, there is likely to be less deformation of particle asperities than at a lower rate. Hence any bonds that are formed will be less effective and more likely to be fractured under the action of shear stresses within the compact. The net result is that, instead of retaining the original structure, particles will tend to continue to roll one over another to fill any remaining voids, thus making the compact appear less resistant to the applied pressure. Another possible factor is that the tendency for brittle fracture of particle asperities may increase with speed of loading. Here it is also possible that stress waves generated from the punch tips have some effects, particularly at very high punch speeds. The result is that particles are broken down into smaller units and, due to the closer packing that can be achieved, the compact will again appear less resistant to applied compaction pressure. Obviously these arguments depend on the properties of the material under consideration, its coherent and plastic behaviour, its morphology and composition, and its tendency for brittle fracture. Thus the effects of these factors will vary from material to material.

This can be seen from the results obtained for paracetamol d.c. (Fig. 6). Again the curves are close, but in this case the order of variation is reversed, with the material actually appearing less resistant to applied compaction pressure as the rate increases. Because paracetamol d.c. is a mixture of gelatin and paracetamol, the morphology and composition of the paracetamol d.c. granules, as well as its structure, are believed to be responsible for its peculiar behaviour under varying rates of compression. To verify and examine this behaviour, a few more fractions of pure paracetamol and gelatin were tested. In each case, however, the direction of variation was found to be the same as the rest of the main powders tested earlier (i.e. increasing resistance to compaction as the speed is increasing). As a result of this, two principal deformation mechanisms are suggested to explain the paracetamol d.c. behaviour.

4.2. Deformation mechanisms

In the first mechanism of deformation and as a result of Seager's [17, 18] work on paracetamol d.c. where the powder granules are believed to be hollow shells, the main compaction resistance offered by the material is believed to be due first to the granules' collapse, and then to the combined action of the actual stiffening resistance due to deformation of the collapsed granules and the softening resistance due to trapped air, which its softening effect increases as the speed of compaction is increased.

In the second suggested mechanism of deformation, it is believed that the trapped air effect is not a major factor in this peculiar behaviour. The trapped air effect does not show at all when compacting other materials under the same conditions of compaction, even for lactose which is prepared by the same technique as

paracetamol d.c. (spray drying technique). Also, a close examination of the loose broken shells (granules) of paracetamol d.c. under the electron-scanning microscope shows that these granules are not absolutely hollow. Actually, they are constructed of varying densities of nested particles of paracetamol cemented with varying percentages of solid gelatin. In some cases it is well above the 3% stated in the specifications. Therefore the explanation advanced for this mechanism, which is also believed to be true for all the powders tested as well, and has been reported by Al-Hassani and Es-Saheb [19], is detailed below.

As reported by Seeling and Wulff [6], the compaction process of powders consists of three stages, the second of which is elastic deformation followed by both plastic deformation (a measure of ductility) and fragmentation of particulates (a measure of brittleness). The amount of plastic deformation and fragmentation involved in the process is believed to be dependent on the compaction speed as well as the mechanical properties of the powder under consideration. However, at low speeds enough time is available for the particles to deform plastically rather than fracture, and hence the dominant compaction mechanism at this range of speeds is plastic deformation. At higher speeds, the dominant compaction mechanism is believed to be fragmentation.

Paracetamol d.c. is made of a mixture of two materials, gelatin and pure paracetamol, with different mechanical properties: hence at low speeds of compaction gelatin will deform plastically first (being the softer component in the mixture) allowing the harder paracetamol flakes to sink and be embodied into the plastically deforming gelatin to reinforce the structure and to increase resistance to any further compaction. As the speed of compaction increases, the chances of plastic deformation of the particles become less and fragmentation becomes increasingly the dominant deformation mechanism, and hence lower resistance to compaction is offered. However, the differential effect of these two deformation mechanisms involved in compacting paracetamol d.c., (i.e. both plastic deformation and fragmentation of both mixture components), seen over this low range of speeds, seems to decrease as the speed of compaction is increased. This is clearly shown in the higher speed tests (see Fig. 9) when paracetamol d.c. adjusts its behaviour at these speeds of compaction and follows the same pattern as the rest of powders (i.e. increases resistance to compaction as the speed increases).

As discussed above, the combined effects of all deformation mechanisms involved in the process of compaction are very much affected by the speed of compaction, particularly the ductile and brittle behaviours of the powder, and consequently the form of the compaction curve. This is clearly shown in the axial pressure–axial strain rate plots of Fig. 9, where three distinct regions representing the main ranges of strain rates covered (low, medium and high) can be identified. This indicates that different compaction and deformation mechanisms are dominant in each of these regions. All these plots show a linear relation between the axial pressure and the axial compression

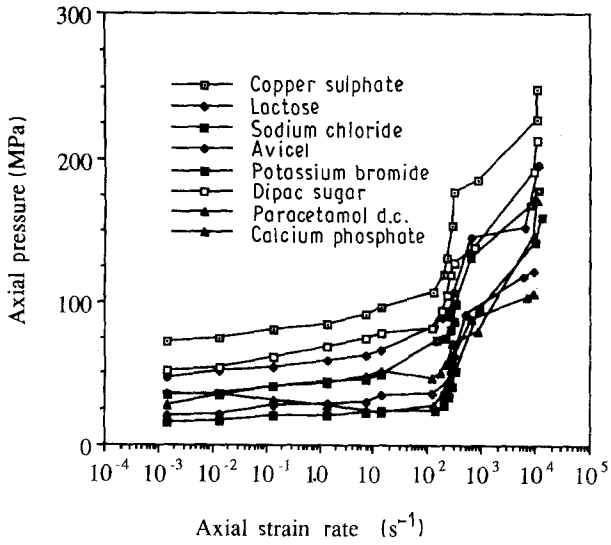

Figure 9 Axial pressure variation with axial compression rates for all powders tested, at constant axial degree of compaction of 40%.

rates, at the constant levels of axial strain (40%), almost over the whole range of low speeds. However at medium and high strain rates and strains, non-linear behaviour is noticed. This is believed to be due to the increasing brittle behaviour of the various materials at these ranges of speeds and strains, as well as the main effect of strain rate and cold working of the compacts. Under these conditions the materials show increased resistance to deformation and hence higher compaction pressures are expected. But this differs from powder to powder, depending on its mechanical properties and behaviour under the various loading conditions.

Ideally a constitutive equation which allows for strain rate should be fitted to the results. But this would require rigorous and complicated mathematical considerations. It is difficult as it is, without the influence of strain rate, to incorporate large strain in the non-associative plasticity theory. However a comprehensive finite element analysis for triaxial loading of these powders and some theoretical analysis are given by Loo [20] and Al-Khattat [21], respectively.

4.3. Radial pressure transducer

As far as the radial pressure transducer used is concerned, in general this performed well and gave consistent results. However, on comparing the transducer with other means of measuring the radial pressure, the following points may be made. The use of strain gauges on a "cut-away portion" of the die [22, 23] appears reasonable, but the reduced die-wall thickness will affect the results obtained. Likewise, a Perspex die, used in conjunction with photo-elastic techniques [24] will alter the behaviour of the die due to the lower stiffness of Perspex. Commercially manufactured diaphram-type strain gauges on the end of a screw, as used by Hiestand and others [25], would seem to be one of the best ways of obtaining accurate local values of radial pressure. However, considering the nature of the work carried out here, the radial pressure transducer is more suitable and is relatively simpler, and is inexpensive.

4.4. Axial–radial pressure curves

For the axial pressure–radial pressure curves (Figs 5 to 7) some general remarks are necessary. Carless and Leigh [23] obtained what are essentially very similar results, but for cyclic compression–decompression tests at one speed of compaction only, although the method of measurement of the die-wall pressure was quite different. They managed to approximate their curves by a series of straight lines and identified the points of transition from one slope to another, as corresponding to a condition of yield for the material. They also compared their results with the theoretical curves of several ideal solid bodies and were thus able to make several useful conclusions. This approach is questionable, because in several respects a powder compact is quite different from a solid body. The most important of these is that, because of the large proportional changes in volume which take place with a powder compact, friction at the die wall cannot be ignored. The effect of this is to bring about an extremely non-uniform distribution of stress, and therefore density within the compact, as documented by Train [9], Crawford [26], Loo [20] and recently by Es-Saheb and others [27]. Thus changes in the behaviour of the material are not expected to occur simultaneously throughout the compact, and to talk, therefore, of a yield point for the compact as a whole would seem to be erroneous. For this reason, no attempt is made here to approximate the results by straight lines, especially as it is possible in all cases to fit a reasonably good smooth curve through most of the experimental points.

However, from these compression curves obtained at the various testing speeds of compaction, a few important conclusions can be drawn. All pharmaceutical powders tested exhibit a non-linear behaviour between the axial and radial pressures in compression over the whole ranges of speed and pressure tested. The curves in all cases tend to become more non-linear as the speed of compaction is increased. This is probably due to the combined effect of the changing internal and external friction condition between the powder particles and the powder and the die wall, as well as the mechanisms of deformation involved in the process, particularly the plastic deformation and plastic flow, which are affected by the speed of compaction. The relative values of radial pressure to the axial pressure are noticed to decrease as the speed of compaction is increased.

Furthermore, going back to the changing processes which occur during compression, the extents of the different deformation mechanisms involved in the process are affected by the magnitude of the applied pressure and speed of compaction, as well as other important parameters e.g. material mechanical properties, particle size, etc. which determine the amount of bonding and hence the strength of the compact. However, the mechanisms governing powder bonding illustrate that increased compression pressure is required to form strong compacts, but this action exacerbates the problem associated with decompression, particularly at high speeds, which can lead to capping and lamination of the formed compact. This also explains why most materials tested, except avicel, exhibit "end capping" at high tableting speeds. This phenomenon is usually associated with brittle materials such as ceramics as reported by Thompson [28].

5. Conclusions

All the materials tested exhibit compression rate effects to some extent. The general tendency in all the powders tested, except paracetamol d.c. is to exhibit increased resistance to compaction with strain rates up to $10^5\ s^{-1}$. For paracetamol d.c. the mechanism of compaction is different due to its morphology and composition: it softens with the rate of strain up to about $10^2\ s^{-1}$, when it starts behaving like other powders. Both ductile and brittle behaviours occur in powder compaction, and the relationship between them during the compaction process is continuously changing. As the strain rate increases, the brittle behaviour dominates the process and tablet 'capping' becomes more prominent.

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