A CONTRIBUTION TO POWDER COMPACTION THEORY BY THE PRESSING OF REGULAR ARRANGEMENTS OF SPHERES

BY D. TRAIN AND J. N. CARRINGTON*

From the Department of Pharmaceutics, School of Pharmacy, University of London, Brunswick Square, W.C.1

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Regular arrangements of annealed phosphor bronze spheres have been used to investigate the lubricating effect of graphite films located in various parts of the system being compressed in a cylindrical die. The relative importance of interparticulate lubrication and of die wall lubrication are discussed. The influence of the "angle of packing" on the pressing behaviour has been investigated using similar arrangements of spheres but varying the diameter of the upper layer. From consideration of these experiments, it would appear that die wall friction calculations for powders should include a factor for particle deformation and interparticulate frictional effects.

THE elucidation of mechanisms governing the compaction of powders in a die has been hampered by the practical difficulty of isolating a particular effect for detailed study. Some of the problems which require investigation are associated with the friction both at the die wall and between particles. It is of great practical interest to be able to assess whether the use of lubricants is advantageous or otherwise in various parts of a mass being compacted. Some general work has been reported[1–12]. Munzel

TABLE I

ANGLE OF PACKING AND RATIO OF DIE WALL TO APPLIED THRUST FOR VARIOUS BALL SYSTEMS

Lower ball diameter 0·794 cm.

Upper ball diameter d {in. / cm.	1/8 0·318	5/32 0·397	3/16 0·476	7/32 0·556	1/4 0·635	9/32 0·714	5/16 0·794
Angle of packing α degrees ..	55·7	50·4	46·2	42·8	39·3	37·5	35·3
$\tan \alpha$	1·465	1·220	1·044	0·925	0·836	0·765	0·708
F_d/F_a for linear portion of curves in Figures 5–7	—	0·124	0·094	0·096	0·084	0·068	0·064

with Kagi[13] and Seth[14] have classified substances used as lubricants for pharmaceutical tabletting into anti-frictional materials, acting at the die wall, and "glidants" which enhance the flow properties of a powder or granulation.

We have described experiments[12] on the compression of cylinders of various materials and single phosphor bronze spheres in an apparatus where the die can be moved relative to the material under compression whilst maintaining and measuring the axial forces exerted by the punches and by the die wall. This work suggested that, within the limit of the applied pressure used, the coefficient of friction at the die wall in a powder

* Present address: Macleans Ltd., Great West Road, Brentford, Middlesex

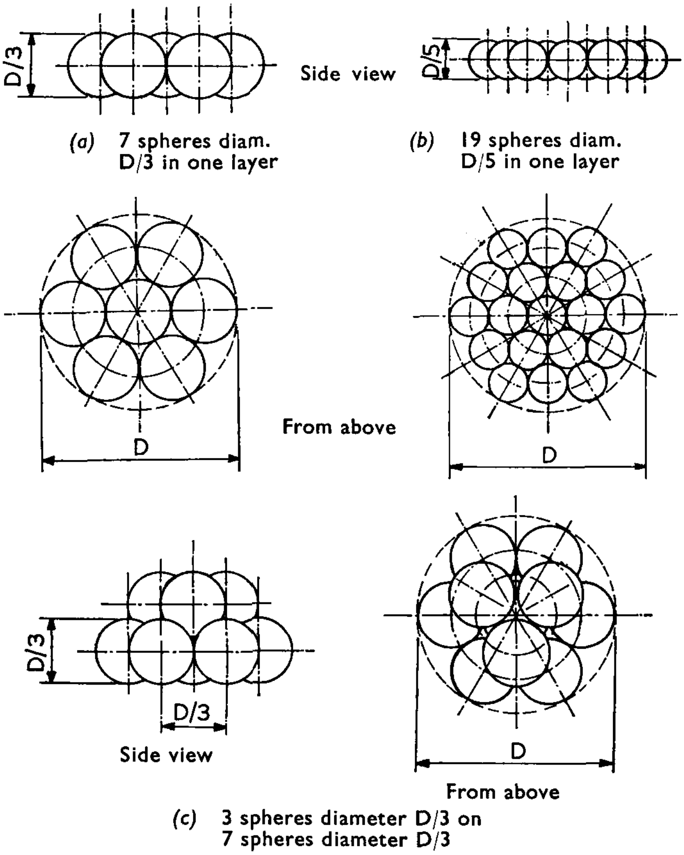

FIG. 1. Arrangement of spheres in a die, bore D.

compact may be constant. It is also nearly independent of the amount of movement, when this is produced at an approximately constant rate, at the interface between the compact and the die wall. But the work did not indicate the effects caused by interparticulate movement. The experiments now described were made to investigate these effects.

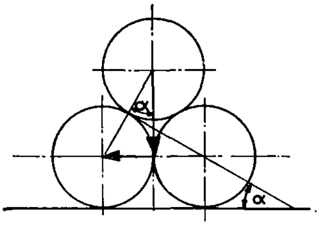

FIG. 2. Angle of packing = α.

Theoretical Considerations

A simplification of the complex physical condition produced by random interparticulate movement during compression may be made by using a system of spheres. The arrangements used are shown diagrammatically in Figure 1, *a* and *b* for single layers and *c* for a double layer.

With two layer systems there is an initial angle, α, between the horizontal and tangential planes of contact of the two balls in different layers (Fig. 2).

This angle is referred to below as the "angle of packing". Several workers[7,15,16] have assumed that the initial "angle of packing" of a powder is identical with the "angle of repose" of a heap of the same powder, but it has been shown[17] that an experimental value for the angle of repose may

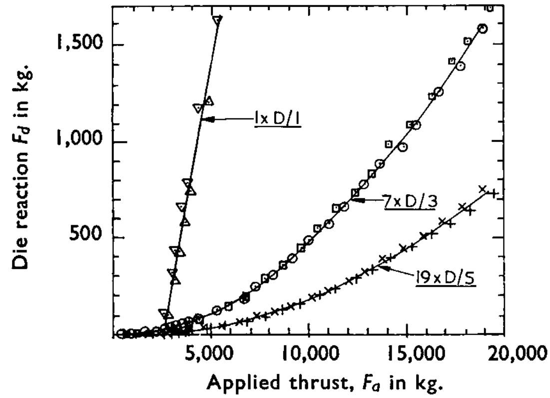

FIG. 3. Pressing single layer arrangements of unlubricated spheres in an unlubricated die of bore 2·38 cm.

△ Exp. I. ▽ Exp. II. System: 1 sphere diam. D/1.
⊙ Exp. III. ⊡ Exp. IV. System: 7 spheres diam. D/3.
+ Exp. V. × Exp. VI. System: 19 spheres diam. D/5.

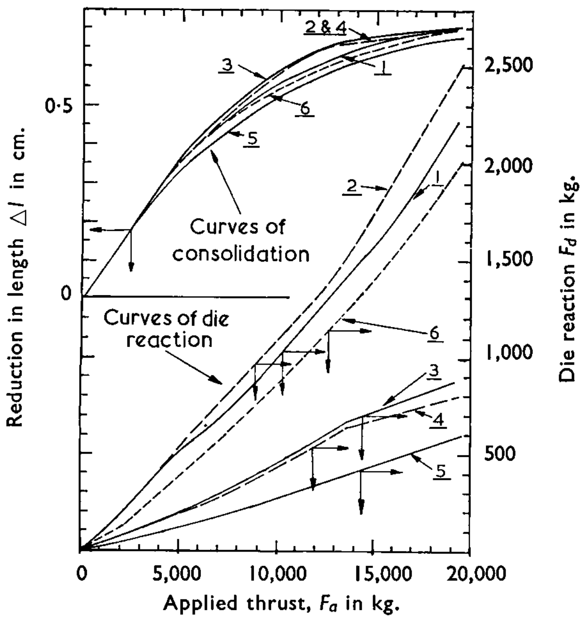

FIG. 4. Pressing double layer arrangements of spheres in a die of bore 2·38 cm. Graphite film on: 1, Punch surfaces. 2, Top layer. 3, All surfaces. 4, Bottom layer and die wall. 5, Die wall. 6, No graphite.

vary markedly with the method of measurement and that data based on angle of repose measurements must be used with caution. For the two layer arrangement shown in Figure 1*c*, it can be shown[18] that α may be varied by altering the diameter, *d*, of the three spheres in the upper layer (Table I).

TABLE II

SUMMARY OF LUBRICATION EFFECTS IN SIMPLE TWO LAYER ARRANGEMENT OF SPHERES

Curve No. on Figure 4	Location of graphite layer	Interface lubricated	Remarks
1	Punch surfaces	Punch surfaces in contact with balls	Die wall friction, F_d, was larger than for the unlubricated pressing. It would be expected that radial movement of the balls would be easier in this instance.
2	Upper layer of balls	Upper punch surface and internal contacts of balls	F_d larger than curve (1) particularly when the applied thrust, F_a, exceeded 5,000 kg., indicating that the effect of internal lubrication was significant above this level of thrust.
3	Both layers of balls, die wall and punch surfaces	Upper and lower punch surfaces, die wall and internal contacts of balls	F_d approximately half that observed for the unlubricated pressing, indicating that die wall lubrication has a sufficiently large influence to counteract punch surface and internal lubrication.
4	Lower layer of balls and die wall	Lower punch surface, die wall and internal contacts of balls	F_d smaller than when all interfaces were lubricated (curve 3), showing that the lubrication of the upper punch surface aids the force transmission in this system.
5	Die wall	Die wall in contact with balls	F_d smallest of all the experiments, since the punch surface and internal friction were high, favouring low radial force transmission, yet coefficient of die wall friction was low.

If interparticulate friction were absent in this system, the ratio of radial force, F_x to the axial force, F_a for practical values of *d* is

$$F_x/F_a = 2/3 \tan \alpha . \cos 30° \qquad (1)$$

It might be anticipated that the angle, α, would change during the pressing and that there would be some interparticulate friction. If the factor β is inserted to account for these phenomena,

$$\text{then, } F_x/F_a = 2/3\beta . \tan \alpha . \cos 30° \qquad (2)$$

but if F_d is the reaction at the die wall, then $F_d/F_x = \mu$, the coefficient of friction between the material and the wall,

$$\text{therefore } F_d/F_a = (2/3\mu . \beta \tan \alpha . \cos 30°) \qquad (3)$$

Symbols

D Die diameter.
d Diameter of upper layer of spheres.
F_a Applied axial thrust (or load).
F_d Die reaction in an axial direction.
F_x Radial thrust.
Δl Axial contraction of pressing due to applied thrust.
α Angle of packing.
β Factor connected with the internal characteristics of a multiparticulate system.
μ Coefficient of friction.

EXPERIMENTAL

All experiments were made using phosphor bronze balls of suitable diameter annealed, by heating to 600° for one hour, cooled and polished.

As a preliminary, balls in a single layer were pressed and the die reaction, F_d, was noted for different levels of applied thrust, F_a, of the top punch. The results are given in Figure 3.

Before varying the angle of packing, the effect was investigated of the location of a graphite layer on the packing system of seven D/3 spheres

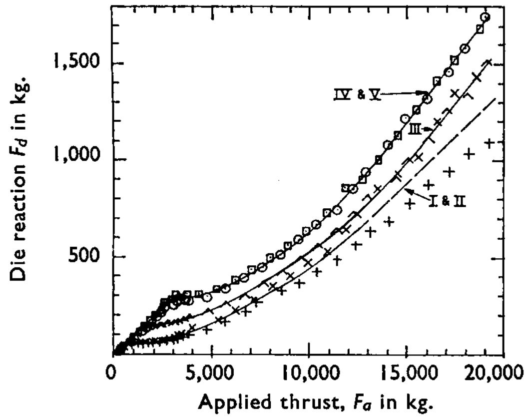

FIG. 5. 3 spheres diameter d, on 7 spheres diameter D/3 in a die diam. 2·38 cm. + Exp. I d = 0·3175 cm. × Exp. II d = 0·3175 cm. ∧ Exp. III d = 0·3969 cm. ⊙ Exp. IV d = 0·4763 cm. ⊡ Exp. V d = 0·4763 cm.

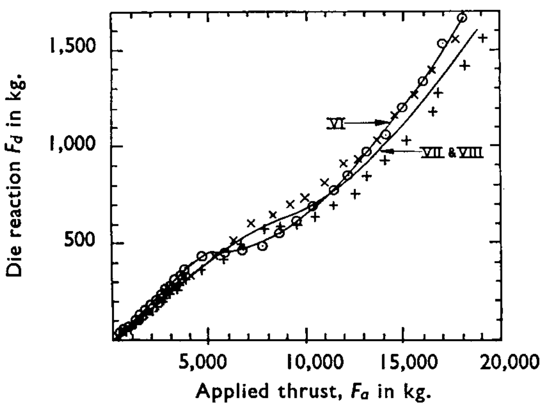

FIG. 6. 3 spheres diam. d on 7 spheres diam. D/3 (cont. from Fig. 5). ⊙ Exp. VI d = 0·5562 cm. + Exp. VII d = 0·6350 cm. × Exp. VIII d = 0·6350 cm.

surmounted by three D/3 spheres in the 2·38 cm. bore die (Fig. 1*c*). The experimental variation of die reaction, F_d, and the contraction, Δl, in compact length with applied thrust, F_a, is shown in Figure 4, whilst a qualitative survey of the effect of the location of the lubricant film is given in Table II.

The effect of variation of the "angle of packing", α, on the pressing-behaviour of the arrangement of spheres shown in Figure 1*c* was investigated by altering the diameter of the balls in the upper layer as indicated in Table I. The systems thus obtained were pressed as before, the balls and the die wall being polished and degreased, and without lubricant in any part of the system. Figures 5–7 show the experimental results.

Discussion

Single layer systems. It will be noted (Fig. 3) that the die reaction with a single ball is greater than with the other arrangements. Subsequent inspection of the compacts confirmed that the area of the zone of contact of the material pressed against the die wall was approximately proportional

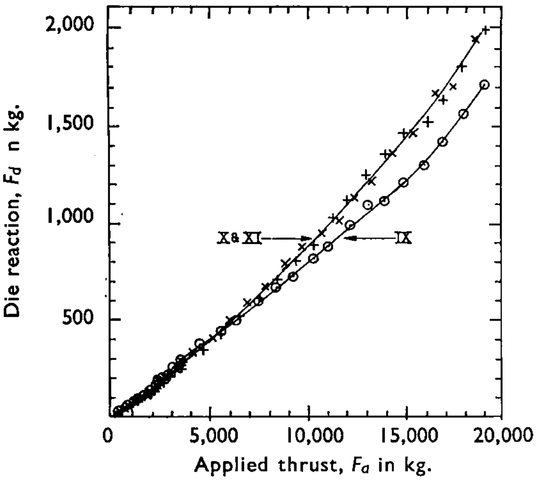

FIG. 7. 3 spheres, diameter d on 7 spheres, diameter D/3 (cont. from Fig. 6). D/3 = 0·7938 cm.

⊙ Exp. IX d = 0·7144 cm. + Exp. X d = 0·7938 cm. × Exp. XI d = 0·7938 cm.

to the magnitude of the die reaction. But it was realised that both size-effects and work-hardening properties of the material were modifying the reactions. The curves in Figure 3 can be considered as showing the order of magnitude of the die reaction and not a direct comparison between different arrangements of balls in a single layer.

Location of lubricant. The changing slopes of the curves (Fig. 4) indicate changes in the mode of force transmission through the system as F_a is increased. The magnitude of the die reaction depends upon two main factors, namely the internal-force-transmission-characteristics and the contact conditions at the interface between the balls and the die wall. Thus die reaction, F_d, is lowest in Curve 5, when there is a high coefficient of interparticulate friction and a low coefficient of die wall friction.

Examination of the curves of reduction in compact length, Δl, against applied thrust, F_a, in Figure 4, shows that consolidation was considerably increased in the mid-stage of the pressing by interparticulate lubrication and to a lesser extent by lubrication of the punch-compact interface. In both a marked flattening of the $\Delta l/F_a$ curve occurred at higher applied thrust levels, but when the maximum experimental applied thrust was reached, lubricated and unlubricated systems were all consolidated to the same amount $\pm$ 0·25 mm.

These experiments support the suggestion[15] that the effect on die wall friction of a change in the interparticulate coefficient of friction is small compared with changes in the coefficient of friction at the die-wall itself. An effect of the lubricant on the consolidation of the system was evident only at certain stages of the compaction process. This would account for the conflicting evidence on this point which has been reported in the literature[5–8].

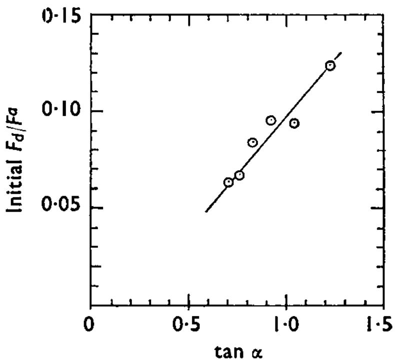

FIG. 8. Variation of F_d/F_a with tan α (please refer to text).

Double layer systems (*Figs.* 5–7). The effect of the diameter of the top layer is well marked, but the same general form of curve may be traced through all the pressings. The "angle of packing", α, would be expected to have the greatest effect on the die-wall friction at the beginning of the pressing. The slopes of the initial linear sections of the curves of die reaction, F_d, against applied thrust, F_a, shown in Figures 5–7 are recorded in Table I.

Figure 8 shows that, in this section, F_d/F_a equals 0·12 tan α and, substituting in equation (3), $2/3\,\mu.\beta \cos 30° = 0{\cdot}12$.

If the coefficient of friction, μ, is constant[12], it may therefore be stated that the factor, β, in the first stage of the pressing, is independent of the "angle of packing", α. It is likely that over a given range of applied stress, β depends upon those properties of the material that also control the so-called coefficient of interparticulate friction.

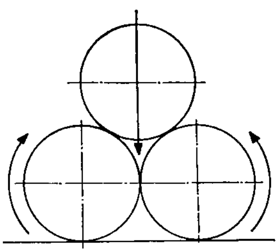

FIG. 9. Effect of interparticulate movement. Top ball moving downwards causing tendency for rolling in lower layer.

This factor, β, has been ignored in the past, and such an omission may account for the low value of the coefficient of friction, μ, at the die wall, calculated when pressing unlubricated copper powder[16].

At certain stages in some pressings, the die moved upwards, that is, in the opposite direction to the applied thrust, as the applied thrust F_a, was increased. After ejection of the pressing, marks on the balls in the lower layer suggested that each ball had been rotated owing to the insertion of the upper layer into the interstitial spaces of the lower layer, as shown in Figure 9. This action appeared to be governed by the ease with which the upper layer could be forced into the spaces and by the relationship between interparticulate and die wall friction.

A similar effect has previously been noted[8] when pressing powders. This phenomenon may be of importance in powder compaction and would bear further investigation.

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After Dr. Carrington presented the paper there was a DISCUSSION.