negligible compared with d/2 and I_{11} may be negligible compared with $Ad^2/4$. It would follow as an approximation that

$$I_{AA} \simeq \frac{Ad^2}{2} + \frac{bd^3}{12}$$

and for practical purposes this could be used as an effective approximation, in the form:

$$\sigma_t \simeq \frac{3}{2}\frac{Wl}{d^2}\left[\frac{d+2a}{6A+bd}\right] \quad .. \quad (17)$$

This simplification avoids the calculations of I_{11} and y_{1b} and provides a relatively simple approximate solution to what at first might appear to be a difficult problem. (It should be mentioned that the corresponding approximate tensile fracture stress (eqn 17) would err on the high side of the true value.)

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Punch tip geometry effects on powder compression

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Many workers have studied the compression process and found it to exhibit distinct phases (Seelig & Wulff 1946; Train 1956; Marshall 1970). During the major densification stage corresponding to particle deformation and/or fracture and recombination a linear relationship has been shown to exist between tablet relative volume and log compressional force (Walker 1923), and between tablet porosity and the reciprocal of log compressional force (Higuchi et al 1954). All these studies were carried out using flat faced punches. Aulton et al (1975) however, demonstrated a variation in surface hardness of tablets with alteration in punch face geometry.

To investigate the effect of punch shape on previously found relationships tablets were prepared using four different shaped punch faces namely flat faced, bevelled, concave and deep concave. The tablets were prepared from Avicel PH101 (F.M.C. Corpn. Marcus Hook, U.S.A.). This powder was granulated before compression using Avicel: water ratio of 5:2, mixed for 10 min in a Z blade mixer (Baker Perkins, Peterborough) passed through a 210 μm mesh on an oscillating granulator (Manesty Machines, Liverpool), dried to a final moisture content of 5% w/w and re-passed through a 210 μm mesh. The moisture content was determined using an Ohaus moisture balance. The prepared granules were mechanically sieved and the 105–108 μm fractions retained and stored in sealed jars until compressed.

Tablets were prepared using a 30 m.m i.d. punch and die set and a hydraulic press, at five levels of compressional force (F_A) 4·9 kN; 9·8 kN; 24·5 kN; 49·0 kN and 98·1 kN.

The thickness of each tablet was measured, immediately after ejection from the die, using a micrometer gauge, fixed rigidly on a metal stand, and capable of measuring ± 0·01 mm. The average height of four tablets was found and used in calculations of tablet relative volume (R.V) and tablet porosity (ϵ), these values being calculated assuming the punch tip profile to be identical with that of the tablet.

From Tables 1 and 2 it can be seen that for the flat faced punch the previously deduced relationships, namely $R.V \alpha \log_{10} F_A$ (Walker 1923) and reciprocal of $\log_{10} F_A \alpha \epsilon$ (Higuchi et al 1954) are also valid in this case. When considering the shaped tablets the same relation-

Table 1. Relationship between tablet relative volume and compressional force for all punch tip geometries.

Compression force (kN)	Relative volume (R.V.) Flat	Bevelled	Concave (a)	Concave (b)	Deep concave (c)	Deep concave (d)
4·9	2·06	2·08	2·48	2·51	2·91	2·56
9·8	1·76	1·79	2·219	2·10	2·61	2·08
24·5	1·39	1·35	1·60	1·68	2·11	1·68
49·0	1·23	1·25	1·54	1·49	1·74	1·57
98·1	1·07	1·11	1·30	1·28	1·54	1·42
Correlation coefficient $\log_{10}F_A$ vs R.V.	—1·0130	—0·999	—0·999	—1·011	—1·019	—0·988

Table 2. Relationship between total tablet porosity and compressional force for all punch tip geometries.

Compressive force (kN)	Total tablet porosity (ε)					
	Flat	Bevelled	Concave (a)	Concave (b)	Deep concave (c)	Deep concave (d)
4·9	51·5	52·0	59·7	60·2	65·6	60·9
9·8	43·1	44·2	54·8	52·4	61·7	51·9
24·5	28·2	25·7	37·5	40·5	52·6	40·5
49·0	18·7	20·2	35·1	32·9	42·5	36·3
98·1	6·3	10·0	23·1	21·9	35·1	29·6
Correlation coefficient $\log_{10}F_A$ vs ε	—1·016	—1·009	—1·008	—1·029	—1·014	—1·015

ships also hold regardless of the curvature of the punch face. However, as punch curvature increases there is a tendency to maintain tablet porosity to a greater extent so that zero porosity would theoretically be achieved at the following compressional forces: flat faced 167 kN; bevelled 206 kN; concave 550kN; deep concave 1·67 MN. The compressional force when using the flat faced punch was equivalent to a pressure of approximately 234 MNm^{-2}. Previous work using ungranulated Avicel PH101 gave theoretical zero porosity at a pressure of 300 MNm^{-2}, although the h/d ratio for each study differed markedly (Sixsmith 1977).

The effect of variation of h/d ratio was studied using concave and deep concave punches (Tablets 1 and 2, columns (a), (b), (c) and (d)) and found to have an effect on the volume-force relationship only in the case of those tablets prepared using deep concave punches where decreasing the h/d ratio by a factor of 2 caused an increase in the theoretical force to produce zero porosity from 1·67 MN to 2·55 MN. This effect is contrary to what one would expect as decrease in h/d ratio would decrease total die wall friction which should lead to a decrease in the resistance to compression.

This effect may be brought about because a large proportion of the total tablet volume is enclosed within the punch tip and decreasing the h/d ratio increases still further the proportion within the punch tip. Previous work, using flat faced punches, has shown that particles adjacent to the moving punch face are relatively protected during the compression process (Train 1956). It would be expected, therefore, that a similar situation would exist during the present investigation and the material enclosed within the moving punch tip would remain relatively protected until the main body of the tablet is compacted to a relatively low overall value of porosity. At this point the high density main body of the tablet may act as a secondary punch face causing compression of the material enclosed within the punch tip. As compressional force dies away exponentially from the point of compaction (Shaxby & Evans 1923) decrease in h/d ratio i.e. increasing the relative proportion and therefore relative height in the punch tip would require greater forces to be exerted to compact the material within the punch tip.

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