Tensile strength and compression of coated pharmaceutical powders

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A study has been made of the tensile strength and compression of loosely packed beds of lactose, sodium chloride and calcium phosphate powders after they had been coated with small amounts of stearic acid, polyethylene glycols and polyvinylpyrrolidones. The properties of the systems were measured over a range of temperatures. Only when the coatings were continuous and durable did they produce reductions in both tensile strength and resistance to compression. Marked changes occurred in tensile strength at temperatures 20 °– 40 °C below the conventional melting points of the coatings. The tensile strength results have been expressed in terms of the range and magnitude of the interparticle forces which depend on the surface free energy of the coated powders and on the Brinell hardness of the coating materials employed.

Pharmaceutical powders for the production of capsules or tablets are often coated with relatively small amounts of excipients. The coating may act as a binding agent, as a lubricant, as a wetting agent, or promote sustained release. Basically, it alters one or more of the various types of interaction forces operating between the powder particles (Kurup & Pilpel 1979). An overall estimate of the range and magnitude of these forces is provided by measurement of the tensile strength of a packed bed of the powder (Cheng 1968), it being assumed that the particles touch only at surface asperities, that there is a single functional relationship between the average force per unit area of contact and the average separation and that a law of corresponding states applies for all powders.

The interparticle forces depend on the size, packing, free energy (Johnson et al 1971), hardness and elasticity of the particles. For two purely elastic particles denoted 1 and 2 the cohesive strength $H_{(t)}$ is:

$$H_{(t)} = \frac{3\pi R_1 . R_2}{2(R_1 + R_2)} \sqrt{\gamma_{S1} . \gamma_{S2}} \quad \text{Joule m}^{-1} \quad (1)$$

(Derjaguin 1961). When they are plasto-elastic

$$H_{(t)} = \frac{3\pi R_1 . R_2}{2(R_1 + R_2)} \sqrt{\gamma_{S1} . \gamma_2} \cdot$$
$$\left(1 + \frac{3\pi Y}{X}\right) \cdot \sqrt{\gamma_{S1} . \gamma_{S2}} \quad \text{Joule m}^{-1} \quad (2)$$

(Krupp & Sperling 1967). R is the radius, γ_S is the free surface energy, Y is the yield pressure of the deformed layer and X is a numerical term which

depends on its area, shape and thickness. Hiestand (1978) believes that bond formation between particles is mainly due to plastic deformation but there may also be melting and resolidification of the surface asperities when powders are subjected to high compression (York & Pilpel 1972).

The present investigation extends previous work (Pilpel & Hepher 1977; Danjo & Otsuka 1978; Malamataris & Pilpel 1980) on the effects produced on the tensile strengths of powders by coating them with various excipients which will be expected to alter their hardness, elasticity, free energy and hence the fundamental forces that operate between the particles. Measurements have been carried out at temperatures between −10 ° and +80 °C.

MATERIALS AND METHODS

Materials

The materials used were: sodium chloride (B.P. grade from Evans Medical Ltd), calcium phosphate dihydrate, $CaHPO_4$ $2H_2O$, (N.F. 14 grade from Albright and Wilson Ltd), lactose (B.P. grade from Thornton and Ross Ltd), stearic acid I (B.P. grade 99% pure from BDH), stearic acid II (B.P. grade from Hopkin and Williams), polyethylene glycols, PEG, of mol. wt 1500 and 20 000 (both DAB 7 grade from Hoechst A. G., Frankfurt), polyvinylpyrrolidone, PVP, of mol. wt 10 000 and 40 000 (K-15 and K-30 from Aniline Film Company), diethyl ether, methanol and acetone (AR from Fisons Ltd).

Batches 250 g, of the 10–30 μm fractions of NaCl, $CaHPO_4$ and lactose powders which had been obtained with a Multiplex zig-zag classifier (Alpine, Augsburg, W. Germany) were passed through a

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33 μm sieve, dried in an oven for 48 h at 105 °C and were then coated as before (Malamataris & Pilpel 1980) with between 1·25 and 100·0 mol × 10^{-6} g^{-1} of stearic acid I, 0·012–1·5 mol × 10^{-6} g^{-1} of PEG (20 000), 0·006–0·75 mol × 10^{-6} g^{-1} of PVP (40 000) and with 100·0 mol × 10^{-6} g^{-1} of stearic acid II, 20·0 mol × 10^{-6} g^{-1} of PEG (1500) and 3·0 mol × 10^{-6} g^{-1} of PVP (10 000).

Hardness and elasticity testing

The Brinell hardness and Young's modulus of elasticity of the coating materials were calculated from microindentation measurements (Ridgway et al 1970) using a standard microindentation apparatus (Research Equipment Ltd, London).

The measurements were carried out on the stearic acid and the PEG in the form of cast films as previously reported (Pilpel & Britten 1979) and on the PVP in the form of thin (≈1 mm) discs 10·3 mm diam. which were prepared by hot compression for 2 min at 100 °C using a load of 100 N.

Surface free energy determination

The surface free energy of the coated powders, γ_S, was obtained from contact angle measurements with two test liquids, water which had been saturated with the appropriate powder and methylene iodide (Sigma, St Louis, U.S.A.).

The interfacial tension equation of Wu (1971):

$$\gamma_{LS} = \gamma_L + \gamma_S - \frac{4\,\gamma_L{}^d \cdot \gamma_S{}^d}{\gamma_L{}^d + \gamma_S{}^d} - \frac{4\,\gamma_L{}^P \cdot \gamma_S{}^P}{\gamma_L{}^P + \gamma_S{}^P} \quad (3)$$

and the Young–Dupré equation for the equilibrium contact angle θ of a liquid on a solid:

$$\gamma_S = \gamma_L \cos\theta + \gamma_{LS} \quad (4)$$

were employed for the calculation. γ_{LS} is the interfacial tension of the liquid L on the solid S, γ_L is the surface tension of the liquid which was measured by using a Du Noüy tensiometer (Cambridge Instrument Company, Ltd). $\gamma_L{}^d$, $\gamma_S{}^d$ are the non-polar (dispersion) and $\gamma_L{}^P$, $\gamma_S{}^P$ the polar components respectively of the surface tension (or surface free energy). $\gamma_L{}^d$ and $\gamma_L{}^P$ were determined by measuring contact angles against sheets of paraffin (Parafilm, American Can Company, Neenach, Wis.). The value of $\gamma_S{}^P$ for paraffin was taken as zero and that of $\gamma_S{}^d$ as 25·5 mN m^{-1} (Fowkes 1964; Zografi & Tam 1975). Table 1 lists numerical values of γ_L, $\gamma_L{}^P$ and $\gamma_L{}^d$ for each liquid used.

Tensile strength and resistance to compression tests

These were carried out simultaneously in a tensile tester as previous described (Malamataris & Pilpel

Table 1. Contact angle and surface tension terms for various liquids using paraffin at 20 °C.

Liquid	Surface tension γ_L (mN m^{-1})	Density of liquid $g\,cm^{-3}$	Contact angle for paraffin	$\gamma_L{}^d$ (mN m^{-1})	$\gamma_L{}^P$ (mN m^{-1})
Water	72·0	1·000	109°	23·2	48·8
Water (lactose)*	71·6	1·004	110°	21·9	49·7
Water ($CaHPO_4H_2O$)*	72·3	1·000	112°	20·3	52·0
Water (NaCl)*	76·3	1·203	117°	17·6	58·7
Methylene iodide	50·4	3·326	65°	50·4	0

* Saturated solution.

1980). Resistance to compression is defined as the stress required to consolidate the sample to a particular packing fraction, in the present work taken as 0·41 since this involved minimum extrapolation of the data.

RESULTS

The particle size parameters of the uncoated powders namely the mean effective diameter, $\bar{d}$, surface area, $\bar{s}$, and volume, $\bar{v}$, were determined by optical microscopy and use of equations derived by Cheng (1968). The values of $\bar{d}$ for the three powders were similar, between 8·0–8·4 μm; the corresponding values for $\bar{s}$ were between 161 and 184 $(\mu m)^2$ and for $\bar{v}$ between 1540 and 2400 $(\mu m)^3$. These values were not noticeably altered after the powders had been coated.

The Brinell hardness and modulus of elasticity of the coating materials, calculated from the micro-indentations, are given in Table 2. Table 3 lists values of the contact angles of saturated aqueous solutions of the powders and of methylene iodide on uncoated and coated powder substrates. It includes the values of surface free energy, γ_S.

The tensile strengths, T, and the applied consolidating stresses, P, for all the samples at all the temperatures investigated were found to fit the general equations:

$$\log T = A\,\rho_f + B \quad (5)$$

$$\text{and } P = A'\,\rho_f + B' \quad (6)$$

Where ρ_f = bulk density/particle density, with correlation coefficients >0·94 for at least six measurements over a range of packing fractions from 0·34 to 0·53 (cf. Farley & Valentin 1967; York 1973). The numerical values of A, B, and A', B', depended on the nature and amount of the coating employed and on the homologous temperature.*

* (Defined as the ratio of the temperature of measurement in degrees K to the melting point of the material.)

Table 2. Brinell hardness and modulus of elasticity of the coating materials at room temperature (Indentation and relaxation time 60 s).

Material and m.p. (K)	Brinell hardness (B_H) (Nm^{-2} × 10^{-6})	Modulus of elasticity (Nm^{-2} × 10^{-8})
Stearic acid I (343)	7·0	7·7
Stearic acid II (327)	5·2	3 6
PEG 1500 (317)	4·6	3·5
PEG 20 000 (331)	10·8	4·3
PVP 40 000 (509)	31·6	11·0

The tensile strengths of the powders coated with increasing amount of stearic acid I, PEG (20 000) and PVP (40 000) at the fixed packing fraction of 0·41 (selected because it involved minimum extrapolation of the rectilinear plots of log T vs ρ_f) were calculated from equation 5 and are plotted versus the coating content in Fig. 1 (a–c).

It is seen that the addition of PVP (40 000) produced a decrease while the addition of PEG (20 000) produced an increase in the tensile strength. The addition of stearic acid I to sodium chloride produced a continuous decrease in tensile strength, but when added to lactose and calcium phosphate it initially produced a slight increase followed by a decrease to a minimum and then another increase.

In order to relate the changes in tensile strength to the temperature-dependent properties of the coatings such as hardness, elasticity, surface energy and possible melting, the tensile strengths of the powders coated with approximately 3% w/w of the coating materials are plotted versus the homologous temperatures of the coatings in Fig. 2 (a–c). It is seen that

the tensile strengths increase up to a homologous temperature of about 0·9, then on Figs 2a and b pass through minima which are deepest for sodium chloride.

The tensile strengths of the powders before and after coating them were treated according to Cheng's (1968) method. Table 3 lists the values of 't_0' the range of the interparticle forces, of t the interparticle separation at the packing fraction of 0·41, and of 'ε_0' the energy or strength of the interparticle forces relative to the value for the particular uncoated substrate (i.e. lactose, CaHPO$_4$, 2H$_2$O or NaCl).

Dealing with the resistance of the samples to compression, the values of P required to achieve a ρ_f 0·41 were calculated from equation 6 and are plotted versus the coating content in Fig. 3 (a–c).

DISCUSSION

A common mechanism may be responsible for the similarities in the general patterns of the graphs which are seen most clearly by comparing Figs 1a and 3a and Figs 1c and 3c. The tensile strengths of the coated powders and their resistance to compression are ultimately determined by the range and magnitude of the physical-, Van der Waals'- and mechanical-frictional forces that act between the particles. In effect they are determined by the plasticity, mechanical strength and durability of the coatings. The friction observed between metallic surfaces when they are moved against each other under an applied pressure has been explained by postulating that elastic and plastic deformation takes place at the contact points between the surfaces
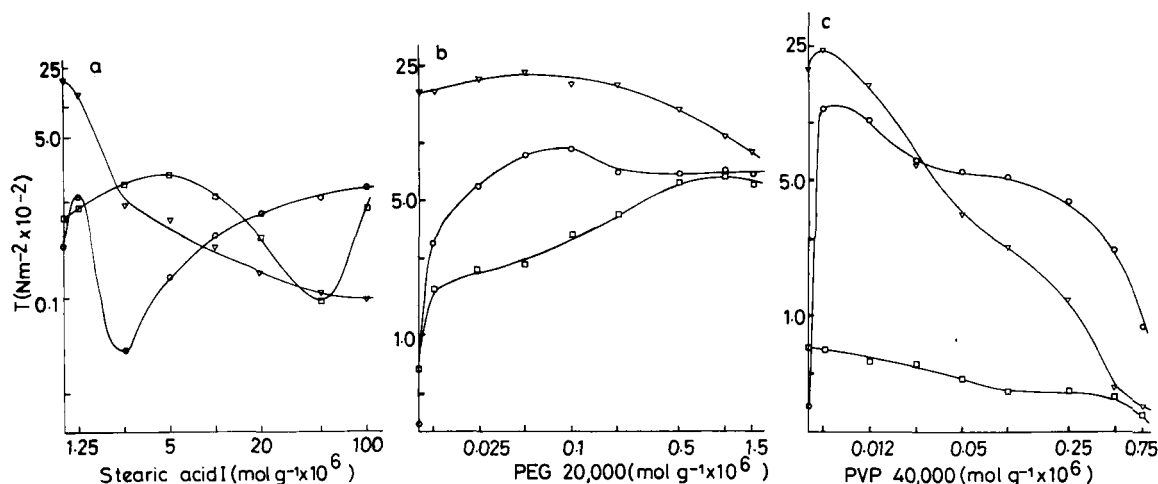

Fig. 1 (a–c). Tensile strengths at room temperature (20 °C) vs coating content at ρ_f 0·41 (○ lactose, ▽ NaCl, □ CaHPO$_4$ and coating: (a) stearic acid I, (b) PEG (20 000), (c) PVP (40 000).

Table 3. Contact angles and surface free energies and values of t_0, t and ε_0 at room temperature (20 °C).

Powder	Coating and content (mol g⁻¹ × 10⁶)	Contact angle		γ_s^d	γ_s^p	γ_s	t_0	t	ε_0
		Water	Methylene iodide	(mN m⁻¹)			μm	μm (at ρ_f 0·41)	
Lactose	None	29°	46°	37·1	32·8	69·9	0·7	1·0	1
	Stearic I (100·0)	60°	68°	26·4	22·3	48·7	0·7	0·7	5
	Stearic II (100·0)	59°	84°	19·2	25·6	44·8	0·5	0·4	3
	PEG 1500 (20·0)	23°	38°	40·7	33·8	74·5	1·0	0·7	40
	PEG 20 000 (1·5)	26°	40°	39·9	33·0	72·9	0·5	0·3	2
	PVP 40 000 (0·75)	21°	44°	38·0	35·5	73·5	0·5	0·5	0·8
CaHPO₄2H₂O	None	23°	51°	34·6	37·3	71·9	0·4	0·5	1
	Stearic I (100·0)	88°	118°	7·7	17·5	25·2	0·6	0·7	3
	Stearic II (100·0)	108°	124°	6·2	9·1	15·3	0·5	0·7	2
	PEG 1500 (20·0)	38°	42°	39·0	29·3	68·3	0·6	0·2	30
	PEG 20 000 (1·5)	37°	45°	37·5	30·3	67·8	0·9	0·4	60
	PVP 40 000 (0·75)	36°	37°	41·2	29·6	70·8	0·4	0·4	0·3
NaCl	None	28°	60°	34 6	41·3	75·9	0·8	0·3	1
	Stearic I (100·0)	48°	84°	19·2	36·9	56·1	0·2	0·6	<0·1
	Stearic II (100·0)	52°	105°	11·4	40·3	51·7	0·4	0·7	<0·1
	PEG 1500 (20·0)	31°	46°	37·1	39·1	76·2	1·1	0·3	3
	PEG 20 000 (1·5)	27°	49°	35·6	41·5	77·1	0·9	0·7	0·1
	PVP 40 000 (0·75	30°	40°	39·8	38·9	78·7	0·4	0·4	<0·1

(Bowden & Tabor 1957; Macfarlane & Tabor 1950). It seems probable that these mechanisms could be contributing to the changes in interparticle bonding strength and friction of the powder samples observed as the amount, the nature and the temperature of the coatings were altered. Addition of a plastic coating such as PEG causes a greater area of real contact to develop between the particles. This produces an increase in the cohesion between them and accounts for the rises in the curves in Figs 1b and 3b. Addition of a more elastic coating such as PVP produces the opposite effect of a decrease in the tensile strength and resistance to compression, Figs 1c and 3c. When stearic acid is coated on lactose or on calcium phosphate, though not on NaCl, the initial increase in both tensile strength and resistance to compression is similar to that reported with other fatty acid coatings on lactose (Malamataris & Pilpel 1980). The different behaviour of stearic acid on sodium chloride could be due to its intrinsically higher tensile strength than that of the other two substrates and to its strongly ionic surface to which stearic acid molecules would be expected to bond very firmly to form a hard and elastic coating.

The changes in tensile strength with temperature as seen in Fig. 2 (a–c) may also be ascribed to the development of bonds formed by plastic deformation of the coating which increase as the temperature is
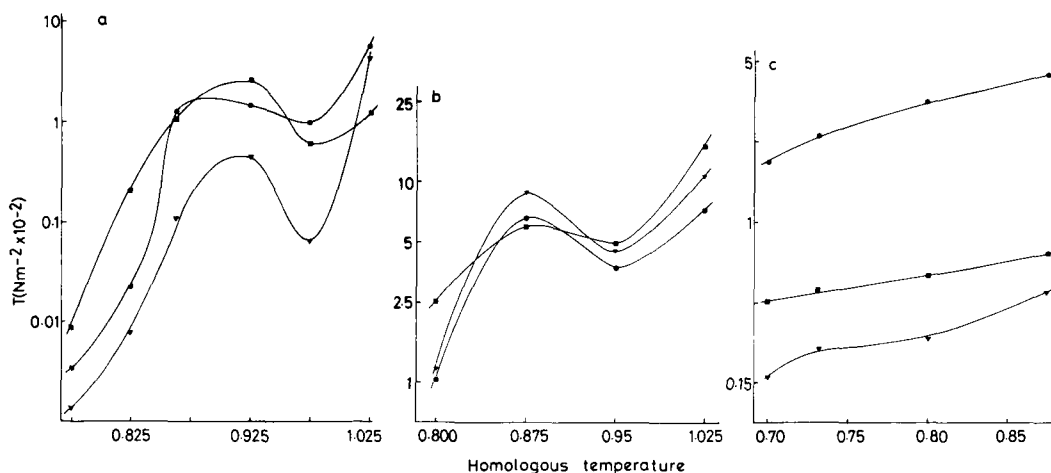

FIG. 2 (a–c). Tensile vs homologous temperature at ρ_f 0·41 of powders coated with: (a) 100·0 mol g⁻¹ × 10⁻⁶ stearic acid I, (b) 1·5 mol g⁻¹ × 10⁻⁶ PEG (20 000) and (c) 3·0 mol g⁻¹ × 10⁻⁶ PVP (10 000) (● lactose, ▼ NaCl and ■ CaHPO₄).
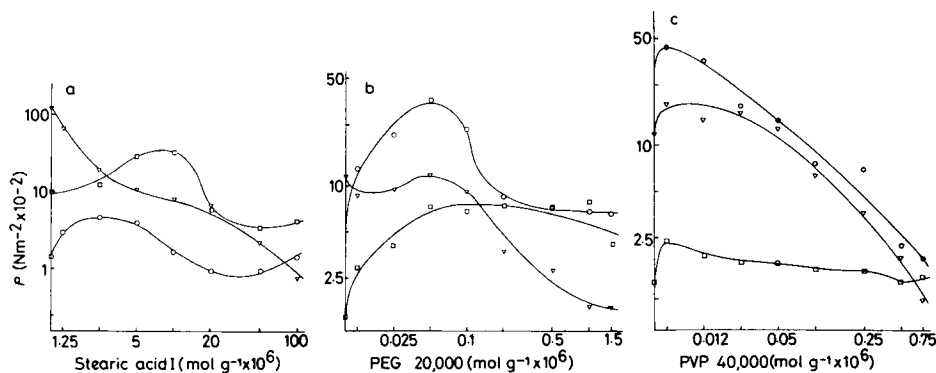
FIG. 3 (a–c). Applied stress required to achieve ρ_f 0·41 vs coating content at room temperature (Key as in Fig. 1 (a–c)).

increased up to the homologous temperature of 1·0. At homologous temperatures between 0·95 and 1·0 the coating begins to melt, the bonds weaken and the tensile strengths pass through minima. At higher homologous temperatures when the coating has liquified, capillary and surface tension forces develop, analogous in a way to those in moist powders. As a result, it may be justifiable to use the Pietsch & Rumpf (1967) and Cheng (1970) equations for moist powders for describing the strengths of the powders at these temperatures.
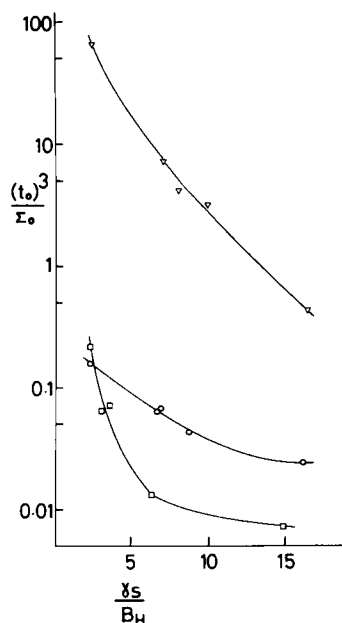

FIG. 4. $(t_o)^3/\varepsilon_o$ vs γ_S/B_H for coated powders, ○ lactose, ▽ NaCl and □ CaHPO$_4$. (Coatings and content: 100·0 mol g^{-1} × 10^{-6} stearic acid I and stearic acid II, 1·5 mol g^{-1} × 10^{-6} PEG (20 000), 20·0 mol g^{-1} × 10^{-6} PEG (1500) and 0·75 mol g^{-1} × 10^{-6} PVP (40 000).)

In addition to elastic and plastic deformations at the points of contact between particles, there may be actual melting at these points when high enough pressures are applied followed by re-solidification to form welded bonds (Jayasinghe et al 1969; York & Pilpel 1972). Tabor and his collaborators (Bowden & Tabor 1953/1964) were able to distinguish between melting and plastic flow on metal surfaces and on individual crystals using electron microscopy, but it is impossible to investigate bond formation in detail on powders consisting of irregularly shaped particles of varying homogeneity and inevitably covered by absorbed films of gas (Gane et al 1974). However, the mechanism of pressure melting (Jefferys 1935) could satisfactorily account for the maxima in Figs 2a and b occurring significantly below the homologous temperature of 1·0. In the absence of direct electron microscopic evidence in the present work, it is concluded that the results that have been obtained are consistent either with the hypothesis of plastic deformation or with the hypothesis of pressure melting at points of contact between particles.

We consider next the range 't$_o$' and the strength 'ε$_o$' of the interparticle forces responsible for the tensile strengths of the powders. Cheng's (1968) expression is:

$$\frac{\varepsilon_{o1}}{\varepsilon_{o2}} = \frac{(t_{o1})^3}{(t_{o2})^3} \cdot \frac{F_1}{F_2} \qquad (7)$$

where

$$F = \frac{T}{\frac{1}{2}\frac{\bar{S}}{\bar{v}} \cdot \rho_f} \cdot$$

Using the tensile strength results and plotting F on a logarithmic scale versus (t/t$_o$) graphs were obtained which were all approximately of the same shape and parallel to one another (Malamataris 1981) although

there was a certain amount of scatter which is considered to be unavoidable with most powders (Cheng 1968, 1970). This indicates that the same function ϕ relating F to (t/t_o) applies to all the powders that have been investigated—both uncoated and coated—and suggests that it may be possible to correlate the tensile strengths of the coated powders with the physicomechanical properties of the coating materials employed.* Considering equations 1, 2 and 7 and assuming that the yield pressure, Y, of the coatings is a function of the reciprocal of the Brinell hardness one should expect a correlation between the expressions $(t_o)^3/\varepsilon_o$ and γ_S/B_H since the sizes of the particles had not been noticeably altered by the presence of the coatings.

Fig. 4 shows plots of $(t_o)^3/\varepsilon_o$ vs γ_S/B_H derived from the values of B_H, γ_S, 't_o' and 'ε_o' given in Tables 2, 3. It is seen that in spite of the numerous simplifying assumptions made in the derivation of the above equations $(t_o)^3/\varepsilon_o$ is in all cases decreasing as γ_S/B_H is increased.

It may be concluded that the hardness of the coating material and the surface free energy of the coated powder are important variables in determining its tensile strength at any particular value of packing fraction.

Acknowledgements

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* It is seen from Table 3 that while coating lactose with stearic acid increases ε_o, coating NaCl with the same material reduces it. Again, coating lactose with PEG 1500 increases ε_o more than coating it with PEG 20000, but on $CaHPO_4 2H_2O$, the opposite occurs. These differences are presumably due to the differences in the surfaces of the substrate powders (polar or non-polar) and to differences in their abilities to absorb the different coating materials into the interiors of the particles.

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