ANGLE OF REPOSE AS FUNCTION OF THE PHYSICAL PROPERTIES AND THE PARTICLE-SIZE OF THE MATERIALS

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A correlation $\tan \theta_{s,d} = K \varepsilon [dp(1-\varepsilon)^3]^{0.11}$ where $\tan \theta$ is the tangent of the angle of repose θ (static or dynamic), K is a constant, dp is the mean sieve particle-size and ε is the voidage fraction, is presented. Compared with other correlations, its application is simple and the results are accurate within a maximum error of $\pm 3\%$. It has also been shown that the tangent of the dynamic-angle is 1.126 times the static-angle over a specific gravity range of 1.3903—.300.

Introduction

The work on the angle of repose dates back to French General Morin who while working on trenches first realised its importance. Rankine[1] later reproduced different values of the angle without giving the method of their determination. Since then much work on the variables such as the moisture, the particle-size, the physical properties and the methods of determination affecting the angle of repose, has been carried out.

Train[2] has classified these methods as follows: (1) The fixed-funnel and the free standing cone. (2) The fixed-diameter cone and the funnel. (3) The tilting-box. (4) The rotating cylinder. (5) Free standing cone method as defined by Brown and Richards.[3] Whatever is the method, it will be noted that there are always two angles of repose, one is called the static while the other is known as the dynamic angle. Franklin and Johanson and later Fowler and Wyatt[4,5] have reported that the dynamic angle is 3 to 10 degrees smaller in value than the static angle of repose. According to the present work, it has been observed (discussed later) that the dynamic angle is greater than the static-angle by a few degrees.

The angle of repose also known as angle of friction, is a function of the physical properties and the characteristics of the granular materials used. Fowler and Chodziesner[6] have expressed the angle as follows:

$$\mu = \tan \theta = a/f^2 + b\,(R/d_{av}) - c.P_t + d \qquad (1)$$

This relationship though takes into account nearly all the known properties of the material, does not indicate whether the angle θ is static or dynamic? Moreover, before making any use of the correlation, it is necessary to determine the shape-factor with the help of a modified Lea and Nurse apparatus[7] and later making use of Carman's equation.[8] This would mean a sufficiently lengthy method for finding out the angle of repose.

In connection with the study on mixed particle-size powders, Nakajima and coworkers[9] have suggested the following equation for the sliding angle:

$$\theta = a'\,(S + b'/a')\,(d + a''/a) + b'' - \frac{a''b'}{a'} \qquad (2)$$

where θ = Sliding angle in degrees. S='Standard-deviations' of the mixed powders. d = Mean particle-diameter of the mixed particles. a, a′, a″, b′ and b″ are constants.

This equation is once again not very convenient to apply, as the values of the constants depending on the material will have to be determined before it could be of some practical utility.

The determination of the particle-size other than the sieve method is cumbersome and time consuming and so is the determination of shape factor and the surface roughness. There are a number of methods now available for finding out the particle-size of which the sieve method is the most convenient and rapid. Particle diameter may also be determined under microscope by a method outlined by Heywood.[10]

Shape factors or coefficients may be determined using either Lea and Nurse apparatus (permeability method) and later Carman's equation. The following relationship as proposed by Heywood[10] may also be used for the same purpose:

$$f = 1.57 + Q\,(ke/m)^{4/3}\,\frac{(n+1)}{n} \qquad (3)$$

Surface roughness which is defined as the average depth between the particles constituting the surface, may be determined in the usual manner.

It will therefore, be seen that the determination of the mean particle-size, the shape-factor and finally the surface roughness of the particles, involve lengthy procedures. But at the same time, it may be pointed out that no simple methods (save for particle-size determination) other than those described above, are available for finding out these values.

As already stated, the bulk-density is a manifestation of the particle-size, its shape and the surface roughness. Use has been made of this fact in the present work and consequently a simple correlation between the angle of repose, the true and the bulk-density and the particle-size is presented. The relationship as expressed below can be applied conveniently without the knowledge of the particle shape or its surface roughness. The overall average deviation as shown in Table 5 is about ± 3 percent.

$$\mu = \tan \theta = K \varepsilon \left[dp \, (1-\varepsilon)^3 \right]^{0.11} \qquad (4)$$

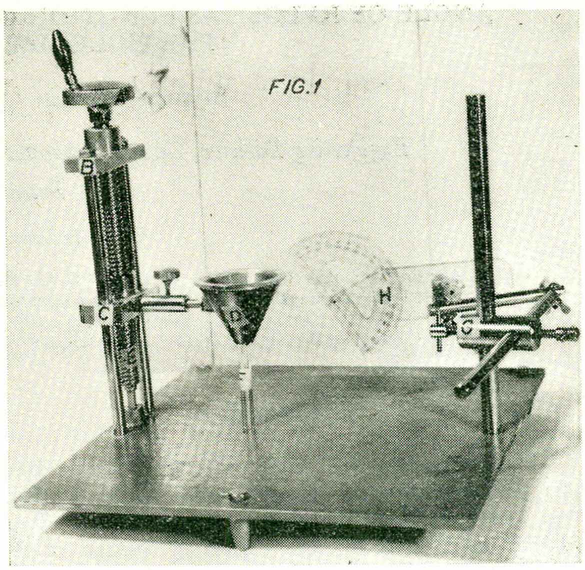

Fig. 1.

Apparatus and Experimental Procedure

The apparatus used for determining the angle of repose is shown in Fig. 1. On one side of the platform, a vertical rod supporting the arrangement (G) for holding the divider (H), moveable in the vertical as well as horizontal planes, is mounted. On the other side, a metal cone (D) mounted on a screw, moveable in a vertical plane, is provided. With the help of a glass funnel (F), small heap of the granular material is formed by gradually raising the funnel in such a manner that the distance between the tip of the funnel and the granular heap, is kept minimum. Higher distances will result in greater impact and consequently frequent collapse or deformation of the heap.

During the heap formation, it was observed that a stage is reached when further addition of the material results in the collapse of the heap, making it settle to a stable position. There will thus be two angles, the first one where the granular cone is in an 'unstable' state, the angle subtended by the inclind with the horizontal-plane is named as dynamic-angle and the angle in its 'stable' state is called static-angle of repose. Similarly in the case of rotating-cylinder method, the granular material constantly rises to a maximum angle called the dynamic-angle and then slides down the inclind surface. As soon as the rotation is stopped, the inclind plane of the granular bed slumps and settles down to a lower angle i.e. the static angle of repose. It will therefore be seen that according to the present definition the dynamic angle will always be greater than the static angle of repose. This is contrary to what has been stated by Franklin and Fowler.[4,5]

Materials

Both vesicular and non-vesicular materials namely coal, coke, sand, felspar and iron-ore (for specific-gravity see Table 1), over a wide particle-size range (−10+12), (−16+18), (−22+25), (−30+36), (−44+52), (−60+72), (−85+100), (−120+150), (−150+170) and (−170+200) mesh B. S. S. were used.

Results and Discussion

1. *Bulk-Density as Function of Particle-Diameter.*—Bulk-density of the different materials as function of particle-size was determined by the method according to A.S.T.M. Standards.[12] The different values of the bulk-density in relation to the particle-size are given in Table 1 which shows that in case of coal, sand and felspar, the bulk-density rises with the increase in the particle-size. The rise for sand and felspar is more prominent over the size range 0.270 to 1.071×10^{-3} while for coal the relationship between the two variables is almost linear. The behaviour of vesicular materials namely coke and iron-ore, is identical i.e. first there is rise in bulk density over the particle-size range 0.270 to 0.542×10^{-3} and afterwards as the particle-size increases from 0.542 to 5.05×10^{-3} ft., it gradually falls off.

TABLE 1.—BULK DENSITY AS A FUNCTION OF PARTICLE-SIZE.

No.	Particle size dp. (ft).		Bulk Density lbs./C. Ft. Coal (1.390)	Coke (1.510)	Sand (2.680)	Felspar (3.015)	Iron-ore (3.300)
1.	5.050 × 10⁻³	(−10 + 12)	46.10	36.70	92.4	94.80	87.75
2.	3.038 × ,,	(−16 + 18)	43.80	39.53	91.7	90.30	86.30
3.	2.150 × ,,	(−22 + 25)	—	39.80	91.4	86.85	85.65
4.	1.508 × ,,	(−30 + 36)	38.90	40.66	90.0	84.53	86.40
5.	1.071 × ,,	(−44 + 52)	—	42.80	90.4	83.20	90.70
6.	0.754 × ,,	(−60 + 72)	38.30	43.95	87.2	80.85	87.20
7.	0.542 × ,,	(−85 + 100)	36.90	44.92	79.3	79.30	89.23
8.	0.375 × ,,	(−120 + 150)	35.70	44.40	75.8	75.90	88.42
9.	0.317 × ,,	(−150 + 170)	33.63	44.05	71.7	74.90	86.34
10.	0.270 × ,,	(−170 + 200)	33.30	44.00	70.0	74.30	84.63

Bracketted figures show specific gravity and mesh B. S. S.

It will be seen that both the vesicular and the non-vesicular materials show similar behaviour over smaller particle-sizes i.e. from 0.270 to 0.754×10^{-3} but behave opposite to each other for the particle-size range 0.754 to 5.05×10^{-3}. It may therefore follow that the bulk-density is not the function of particle-size alone but also appears to be effected by the other characteristics such as the shape and the surface roughness of the particles or it may be said that all the characteristics such as particle-size, the shape factor and the surface roughness combine together to determine the bulk-density.

2. *Angle of Repose as Function of Particle-Diameter.*— Both the dynamic as well as the static angle of repose were determined by the procedure described above. The results of the different materials and the particle-diameters are given in Table 2 which shows that first the value of the

TABLE 2.— ANGLE OF REPOSE AS FUNCTION OF PARTICLE-SIZE AND VOID.

No.	Particle size dp. ft.	Coal tan θ_s	Coal tan θ_d	Coal Voidage ε	Coke tan θ_s	Coke tan θ_d	Coke Voidage ε	Sand tan θ_s	Sand tan θ_d	Sand Voidage ε	Felspar tan θ_s	Felspar tan θ_d	Felspar Voidage ε	Iron-Ore tan θ_s	Iron-Ore tan θ_d	Iron-Ore Voidage ε
1.	5.050×10^{-3}	0.833	0.983	0.469	0.955	1.069	0.609	0.810	0.910	0.445	0.885	1.004	0.501	0.962	1.072	0.574
2.	3.038 × ,,	0.801	0.946	0.495	0.923	1.025	0.581	0.774	0.879	0.449	0.851	0.972	0.524	0.900	1.007	0.581
3.	2.150 × ,,	—	—	—	0.869	0.979	0.577	0.755	0.841	0.450	0.830	0.942	0.542	0.851	0.959	0.584
4.	1.508 × ,,	0.773	0.900	0.552	0.846	0.946	0.569	0.737	0.819	0.460	0.813	0.916	0.554	0.827	0.932	0.581
5.	1.071 × ,,	—	—	—	0.810	0.907	0.546	0.711	0.795	0.457	0.785	0.893	0.562	0.774	0.879	0.560
6.	0.754 × ,,	0.735	0.866	0.558	0.786	0.877	0.535	0.700	0.780	0.477	0.740	0.857	0.574	0.752	0.848	0.577
7.	0.542 × ,,	0.721	0.836	0.575	0.759	0.849	0.524	0.725	0.821	0.510	0.749	0.851	0.582	0.744	0.803	0.568
8.	0.375 × ,,	0.721	0.810	0.589	0.756	0.839	0.529	0.762	0.841	0.547	0.743	0.853	0.600	0.744	0.816	0.571
9.	0.317 × ,,	0.722	0.809	0.613	0.754	0.849	0.533	0.776	0.840	0.566	0.741	0.859	0.604	0.748	0.816	0.581
10.	0.270 × ,,	0.721	0.810	0.619	0.756	0.849	0.533	0.781	0.850	0.580	0.754	0.851	0.608	0.740	0.819	0.589

$\tan\theta_s$ or $\tan\theta_d$ falls or rises over the particle-diameter 0.270-0.542×10-3 and thereafter it rises in proportion to the particle-diameter. In between these two parts there appears to exist a 'transition-region' over the particle-size 0.542 and 0.754×10-3 after which the behaviour of all the materials is identical. Log-log plots (Figs. 2 and 3), show existence of a linear relationship between $\tan\theta$ and the particle-diameter dp. The straight line-relationship after the particle-diameter 0.542×10-3 may be expressed as follows:

$$\tan\theta_{s,d} = K\,(dp)^n \qquad (5)$$

The values of the constants K and n in equation 5, for the different materials are given in Table 3.

3. *Angle of Repose as Function of Voidage Fraction.*—On the basis of Table 2, when $\tan\theta_s$ is plotted against the voidage ε, the types of the curves obtained are shown in Fig. 4. The behaviour of the materials differs from each other, depending upon the particle-size, its shape and surface-roughness. In case of coal for example, the angle of repose is inversely proportional to the voidage i.e. the angle of repose increases as the voidage decreases. A similar behaviour is shown by the felspar. Coke and iron-ore both being vesicular materials show indentical results over the particle-diameters 0.270 to 0.542×10⁻³ i.e. there is a fall in the voidage without any rise in the angle of repose or that the angle is independent of the voidage. Above 0.542×10-3, the rise in the value of tan θ for coke is proportional to the voidage. In case of iron-ore, $\tan\theta_s$ is independent of the voidage over the particle-diameter range 0.270 to 0.542×10-3 but thereafter it rises to its maximum and becomes almost independent of the voidage. For sand, the value of $\tan\theta_s$ first falls, but later rises with fall in the voidage. Thus it will be seen that the angle of

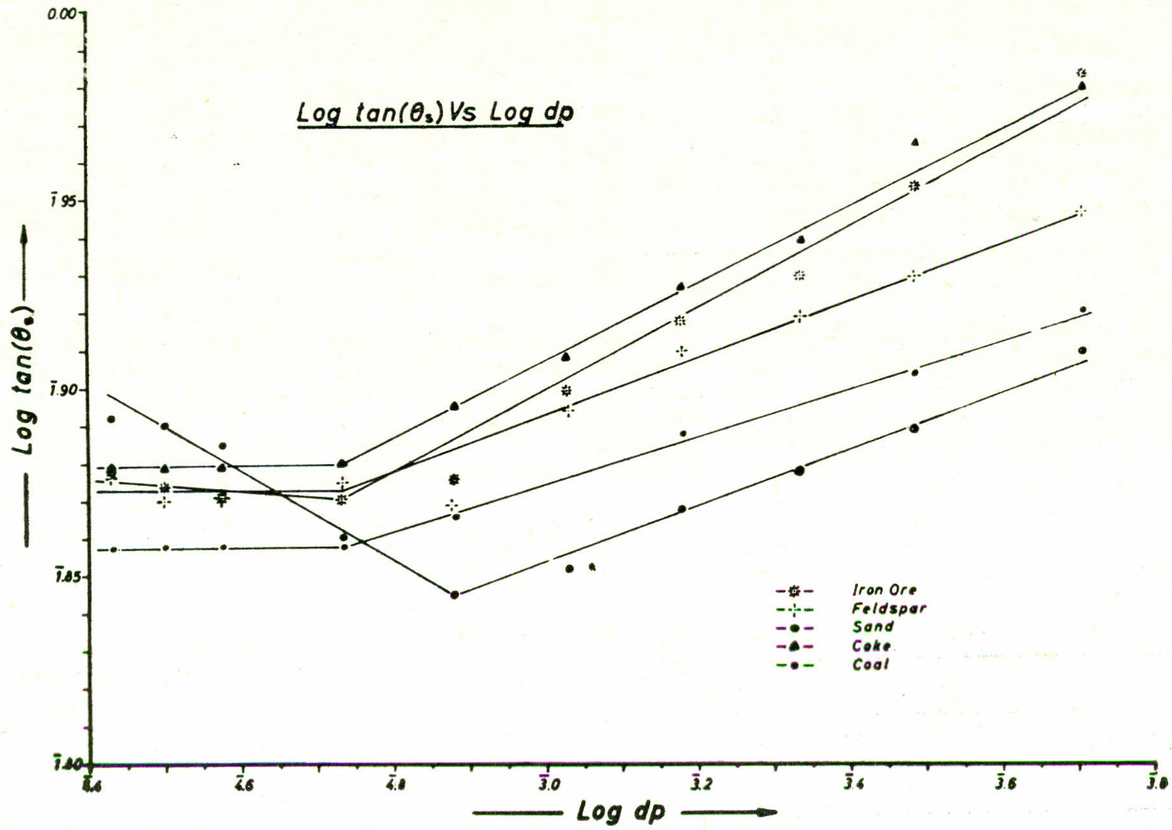

Fig. 2.

repose is not a smooth function of the voidage and varies from material to material. Almost similar behaviour is observed in case of the dynamic angle of repose.

1 and 4) the particle-diameter, a set of straight lines as shown in Fig. 5 and 6 is obtained. Straight lines for coal, sand and felspar have almost the same slope while that of coke and iron-ore

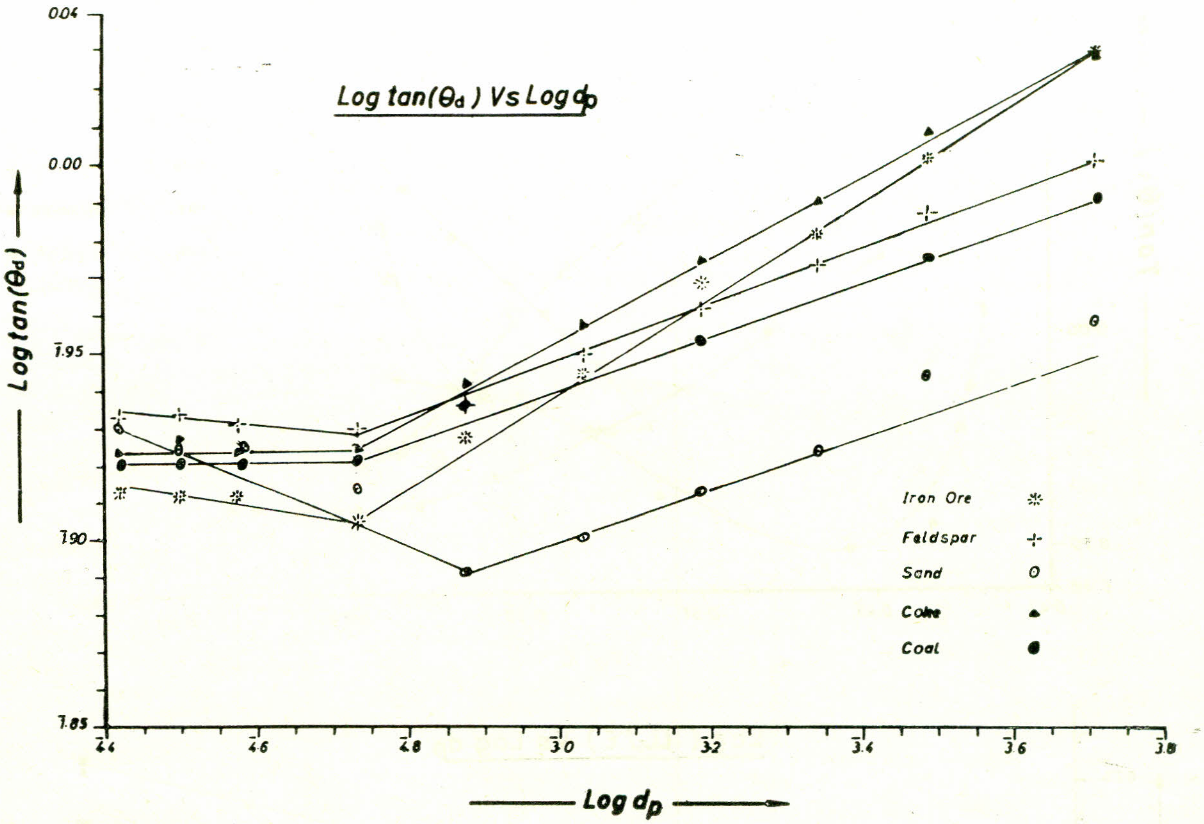

Fig. 3.

The Correlation.—Referring to Figs.2 and 3, it will be seen that log. $(\tan\theta_s)$ and log. $(\tan\theta_d)$ either before or after the 'transition-region' is a linear function of the log dp. It was also observed that the straight lines for the vesicular materials are close while those of the non-vesicular materials lie apart from each other and are not in the order of the specific-gravities of the materials used. No correlation could be worked out on the basis of these figures.

As already discussed the particle-diameter, the shape-factor and the surface-roughness, are all manifest in bulk-density and ultimately the voidage which in its own turn is related to $\tan_s$ and $\tan\theta_d$. Introducing the voidage it was found when log. $\tan\theta_{s,d}/\varepsilon$ is plotted against (see Tables

TABLE 3.—VALUES OF THE CONSTANTS K AND n FOR DIFFERENT MATERIALS.

No.	Material	Dynamic K	Dynamic n	Static K	Static n
1.	Coal	1.445	0.073	1.167	0.064
2.	Coke	1.904	0.109	1.659	0.104
3.	Sand	1.305	0.072	1.194	0.073
4.	Felspar	1.581	0.084	1.345	0.079
5.	Iron-ore	2.133	0.130	2.247	0.117

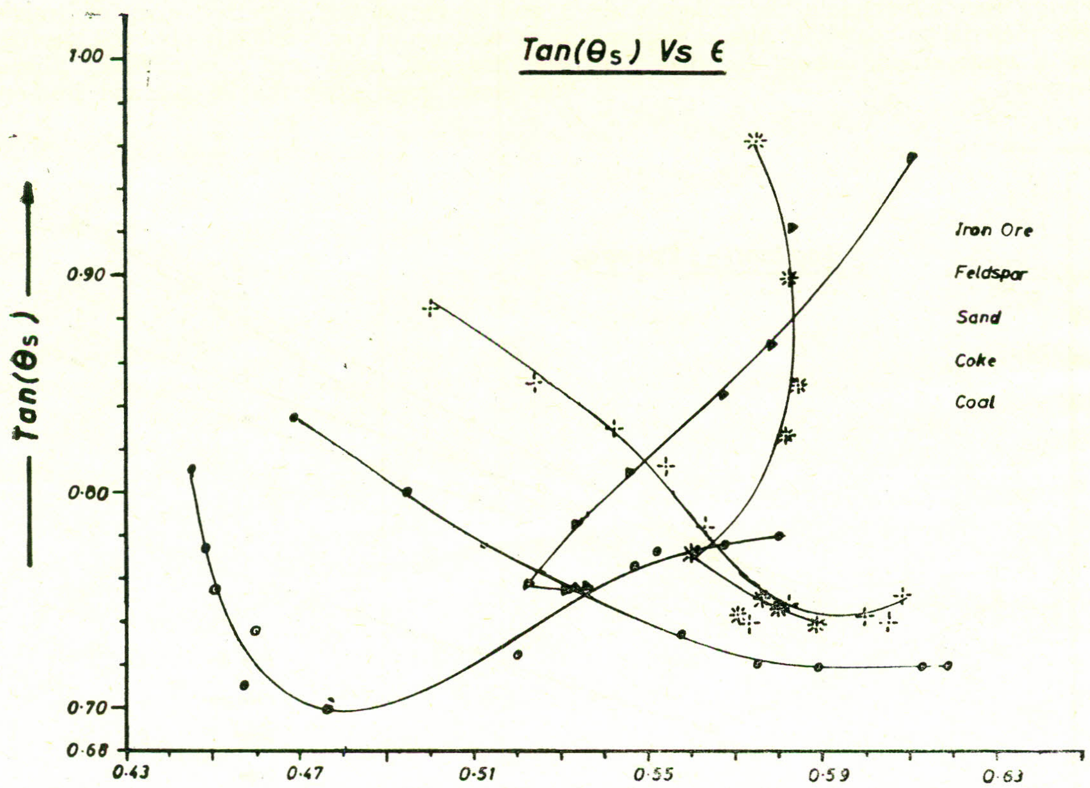
Tan(θs) Vs ϵ
Tan(θs)
1·00
0·90
0·80
0·70
0·68
0·43
0·47
0·51
0·55
0·59
0·63
Iron Ore
Feldspar
Sand
Coke
Coal

Fig. 4.

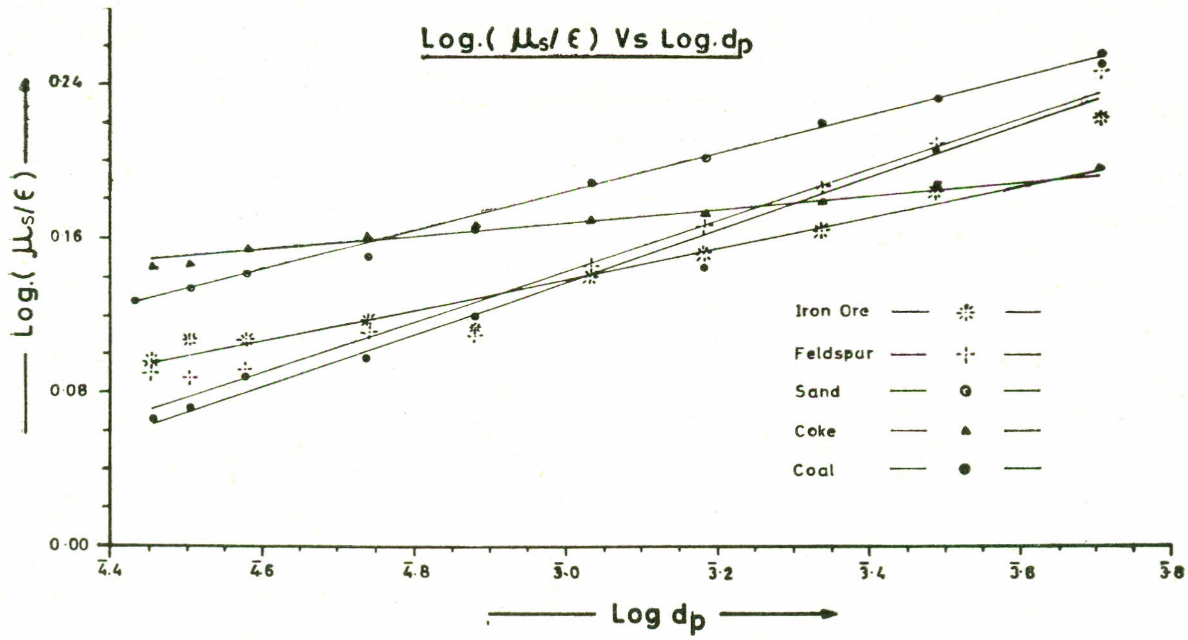
Log.(μs/ ϵ) Vs Log.dp
Log.(μs/ ϵ)
0·24
0·16
0·08
0·00
4̄.4
4̄.6
4̄.8
3̄.0
3̄.2
3̄.4
3̄.6
3̄.8
Log dp
Iron Ore
Feldspar
Sand
Coke
Coal

Fig. 5.

TABLE 4.— $\mu_{s,d}/\varepsilon$ AS FUNCTION OF dp. $(1-\varepsilon)^3$.

No.	Particle size ft. (dp)	Coke			Coal			Sand			Felspar			Iron-Ore		
		$\mu s/\varepsilon$	$\mu d/\varepsilon$	$dp(1-\varepsilon)^3 \times 10^{-5}$	$\mu s/\varepsilon$	$\mu d/\varepsilon$	$dp(1-\varepsilon)^3 \times 10^{-5}$	$\mu s/\varepsilon$	$\mu d/\varepsilon$	$dp(1-\varepsilon)^3 \times 10^{-5}$	$\mu s/\varepsilon$	$\mu d/\varepsilon$	$dp(1-\varepsilon)^3 \times 10^{-5}$	$\mu s/\varepsilon$	$\mu d/\varepsilon$	$dp(1-\varepsilon)^3 \times 10^{-5}$
1.	5.050×10^{-3}	1.565	1.75	29.8	1.78	2.09	75	1.840	2.05	82	1.77	2.00	63	1.68	1.87	39.20
2.	3.038× ,,	1.590	1.76	22.2	1.62	1.91	39	1.730	1.96	51	1.63	1.860	32.8	1.55	1.784	22.30
3.	2.150× ,,	1.505	1.70	16.2	—	—	—	1.680	1.865	36.80	1.53	1.740	20.60	1.46	1.64	15.451
4.	1.508× ,,	1.492	1.67	12.25	1.405	1.63	13.6	1.605	1.78	23.80	1.47	1.654	13.40	1.43	1.61	11.10
5.	1.071× ,,	1.485	1.67	—	—	—	—	1.56	1.745	17.10	1.40	1.590	9.00	1.42	1.57	9.10
6.	0.754× ,,	1.477	1.65	7.7	1.319	1.55	6.5	1.47	1.64	10.80	1.29	1.505	5.85	1.305	1.47	5.74
7.	0.542× ,,	1.450	1.60	5.9	1.254	1.45	4.17	1.42	1.61	6.40	1.29	1.465	3.96	1.31	1.414	4.36
8.	0.375× ,,	1.415	1.57	2.92	1.225	1.36	2.60	1.403	1.53	3.50	1.240	1.42	2.4	1.31	1.43	2.97
9.	0.317× ,,	1.415	1.575	3.24	1. 18	1.31	1.84	1.371	1.49	2.54	1.225	1.42	1.95	1.29	1.41	2.34
10.	0.270× ,,	1.420	1.575	2.76	1.165	1.30	1.50	1.345	1.47	2.00	1.240	1.40	1.63	1.26	1.39	1.88

TABLE 5.

Particle size in ft.	Coal						Coke						Sand				
	θs			θd			θs			θd			θs			θd	
	Obserd.	Cald.	%Devi.	Obserd.	Cald.	%Devi.	Obserd.	Cald.	%Devi.	Obserd	Cald.	%Devi.	Obserd.	Cald.	%Devi.	Obserd.	Cald.
5.05×10^{-3}	39.8	40.2	+1.005	44.5	43.55	2.14	43.7	44.8	2.5	46.90	48.1	2.56	39.00	39.15	0.39	42.3	42.5
3.038× ,,	38.7	39.7	+2.58	43.6	43.00	1.38	42.7	42.5	0.47	45.7	45.8	0.22	37.75	37.75	0	41.3	41.1
2.15× ,,	—	—	—	—	—	—	40.94	41.3	0.88	44.4	44.7	0.68	37.05	36.75	0.81	40.05	40.1
1.508× ,,	37.7	39.5	+4.5	42.0	42.6	1.9	40.40	39.9	1.01	43.4	43.25	0.35	36.4	36.1	0.83	39.3	39.5
1.071× ,,	—	—	—	—	—	—	39.15	38.25	2.30	42.2	41.5	1.66	35.6	34.9	2.00	38.5	38.25
0.754× ,,	36.30	37.5	+3.27	40.9	40.85	0.12	38.15	36.75	3.76	41.25	40.1	2.80	34.9	34.6	0.86	37.95	38.00
0.542× ,,	35.8	37.0	+3.35	39.90	40.3	1.00	37.2	35.4	4.85	40.10	38.7	3.5	37.9	34.95	7.8	39.55	38.25
0.375× ,,	35.8	36.25	+1.26	39.05	39.5	1.13	37.1	34.4	7.3	40.0	37.75	5.6	37.5	35.00	6.65	40.05	38.4
0.317× ,,	35.82	36.3	+1.29	38.95	39.6	1.65	37.0	34.00	8.1	40.1	37.75	5.9	37.8	35.0	7.4	40.0	38.4
0.270× ,,	35.80	35.9	+0.28	39.00	39.25	0.64	37.1	34.00	8.4	40.1	37.00	7.8	37.95	34.95	8.1	40.4	38.25

Average percent deviation for static angle of repose = 2.67; Average percent deviation for dynamic angle of repose = 2.00

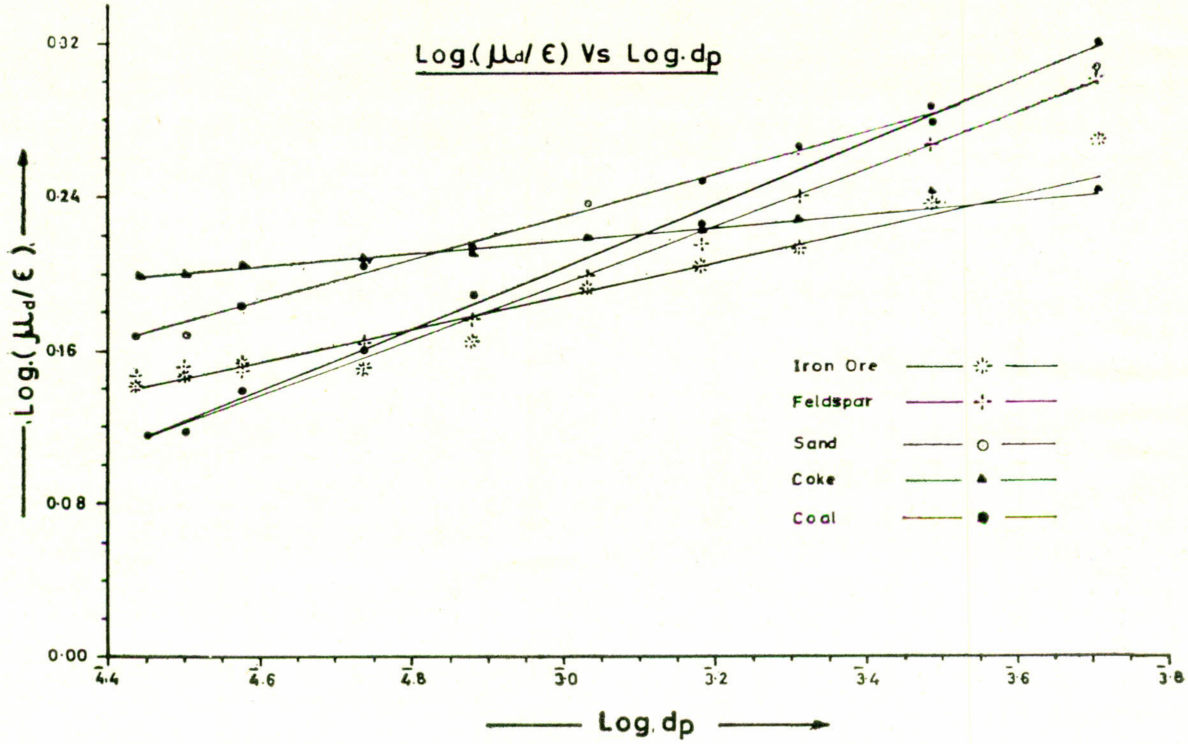
Log.(μd/ε) Vs Log.dp
Log.(μd/ε)
0·32
0·24
0·16
0·08
0·00
Iron Ore
Feldspar
Sand
Coke
Coal
4̄.4
4̄.6
4̄.8
3̄.0
3̄.2
3̄.4
3̄.6
3̄.8
Log.dp

Fig. 6.

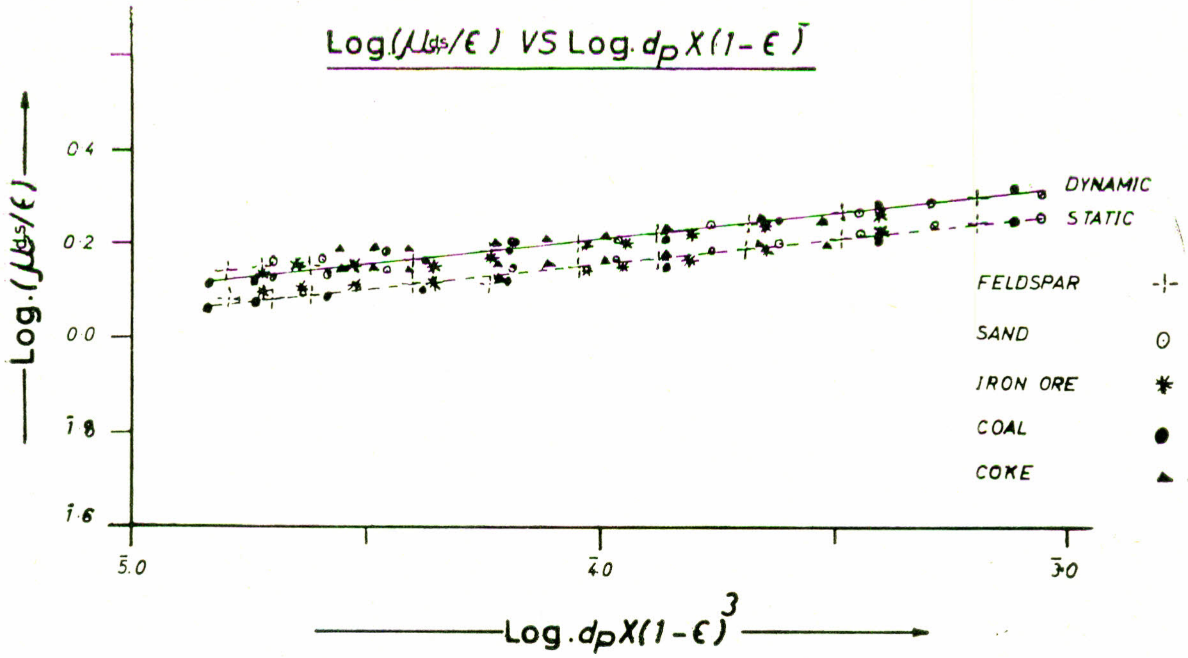
Log.(μds/ε) VS Log.dp X(1-ε)³
Log.(μds/ε)
0.4
0.2
0.0
1̄.8
1̄.6
DYNAMIC
STATIC
FELDSPAR
SAND
IRON ORE
COAL
COKE
5̄.0
4̄.0
3̄.0
Log.dpX(1-ε)³

Fig. 7.

(vesicular materials), converge to meet near the maximum particle-diameter. The arrangement of the lines is such that the derivation of a general correlation does not seem possible.

Table 5 (a).

%Devi.	Felspar						Iron-Ore					
	θ s			θ d			θ s			θ d		
	Obserd.	Cald.	%Devi.	Obserd.	Cald.	%Devi.	Obserd.	Cald.	%Devi.	Obserd.	Cald.	%Devi.
0.47	41.5	41.5	0	45.1	44.85	1.66	43.9	43.85	0.11	47.0	47.15	0.32
0.48	40.4	40.75	0.87	44.2	44.1	0.22	42.0	42.45	1.07	45.2	45.8	1.33
0.12	39.7	40.3	1.51	43.3	43.6	0.69	40.4	41.5	2.7	43.8	45.0	2.74
0.51	39.1	39.5	1.05	42.5	42.9	0.94	39.6	40.3	1.78	43.0	43.65	1.51
0.65	38.1	38.75	1.71	41.75	42.1	0.84	37.75	38.65	2.4	41.32	42.0	1.65
0.13	36.5	38.00	4.1	40.8	41.3	1.22	36.95	38.0	2.84	39.70	41.4	4.3
3.3	36.85	37.15	0.78	40.46	40.5	0.1	36.6	36.8	0.55	38.75	40.1	3.48
4.1	36.6	36.5	0.27	40.45	39.8	1.61	36.6	35.75	2.32	39.2	40.39	3.4
4.00	36.55	36.00	1.5	40.65	39.4	3.1	36.8	35.5	3.53	39.2	38.8	1.04
5.4	37.0	35.65	3.65	40.60	39.00	3.94	36.5	35.2	3.56	39.3	38.5	2.04

Finally on regrouping and re-arranging, when $\tan(\theta)_s/\varepsilon$ and $\tan(\theta)_d/\varepsilon$ was plotted against $dp \times (1-\varepsilon)^3$ (see Table 4), a set of smooth curves was obtained. A log-log plot (Fig. 7) gives two parallel straight lines one for the static and the other for dynamic angle, which are represented by the following equations:

$$\mu_s = \tan\theta_s = 3.97\ \varepsilon\ [dp\ (1-\varepsilon)^3]^{0.11} \qquad (6)$$

$$\mu_d = \tan\theta_d = 4.47\ \varepsilon\ [dp\ (1-\varepsilon)^3]^{0.11} \qquad (7)$$

Dividing equation (7) by (6), we get

$$\tan\theta_d = 1.126 \tan\theta_s \qquad (8)$$

This would mean that $\tan\theta_d$ is 1.26 times the $\tan\theta_s$.

Notations :—

θ_s = Static angle of repose degrees.
θ_d = Dynamic angle of repose ,,
$\mu = \tan\theta$ = Coefficient of friction = Sin θ/Cos θ
ke = Volume coefficient of an equidimensional particle.
ε = Voidage fraction = $(1-P_B/P_t)$.
P_t = True-density lbs./C. ft.
P_B = Bulk-density ,, ,,
d_{av} = Average particle-diameter ft.
dp = Mean sieve diameter ft.
f = Shape-factor.
Q = Coefficient depending on geometric-form.
R = Surface roughness.
a, b, c, d and k are constants.
m = Elongation-ratio
n = Flatness-ratio.

Conclusion

The correlation suggested above is based on the bulk-density and eventually the voidage. Its application as compared with the other equations is much simpler and convenient and the overall error does not exceed ±3 percent (see Tables 5 and 5(a). In order to determine the value of the angle of repose, only the knowledge of the variables such as the particle-size, the true and the bulk-density is necessary. It is obvious that no elaborate and time consuming processes and methods are involved in determining these variables.

References

1. W.J.M. Rankine, *Applied Mechanics* (Griffin, London, 1865), fourth edition.
2. D. Train, J. Pharm. Pharmacol (Suppl.), **10,** 127T (1958).
3. R.L. Brown and J.C. Richards, Trans. Inst. Chem. Engrs., **37,** 178 (1957).
4. F.C. Franklin and L.N. Johanson, Chem. Eng. Sci. **4,** 119 (1955).
5. R.T. Fowler and F.A. Wyatt, Australian J. Chem. Eng., **1,** 5 (1960).
6. R.T. Fowler and W.B. Chodziesner, Chem. Eng. Sci., **10,** 157 (1959).
7. F.M. Lea and R.W. Nurse, Trans. Inst. Chem. Engrs., (Suppl.) **25,** 47 (1947).
8. P.C. Carman, Trans. Inst. Chem. Engrs., **15,** 150 (1937).
9. E. Nakajima, T. Morioka, Y. Ikegami and I. Tanaka, *Studies on Fluidity of Powders. VI. Effect of Particle-size and Surface Rugosity on Fluidity of Powders, Stimagawa Plant* (Sankyo Co., Ltd., Japan).
10. H. Heywood, Powder Met., **7,** 127 (1961).
11. J.M. Dallavalle, Micromeritics (1948).
12. A.S.T.M. Standards, Part III, 242 (1939).