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REPORT TO CONSTRUCTION TECHNOLOGY LABORATORIES
(PORTLAND CEMENT ASSOCIATION) ON SERVICES RELATED
TO CONTRACT CR7913-4330
IMPROVED CONTROL OF THE FINISH GRINDING PROCESS
IN CEMENT MANUFACTURE

Period: July 1, 1985 - September 30, 1985

J.M. Menacho

L. G. Austin

M.S. Cuhadaroglu

The Pennsylvania State University
Mineral Processing Section
University Park, PA 16802

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SUMMARY

Activities developed on Task 6 of the Cement Clinker Project from July 1, 1985 to September 30, 1985 are described in this progress report.

Results on eight continuous ball mill tests are included. Experimentation was performed in a 0.99 m diameter air-swept mill at the Kennedy Van Saun facilities in Danville.

In the first four runs, the effect of production rate on size distribution of product was tested for the powder filling level around 0.83. In the other tests, the powder filling was changed between 0.7 and 1.25. A preliminary analysis of the results indicates that the internal classification curve is moving in a narrow band even when the product size distribution is strongly affected by the different experimented condition.

Also the direct scale-up results from the 8 inch diameter batch mill to the 0.99 mill diameter in batch mode is reported. Predictions overestimate capacity for short times of grinding but they are in good agreement for long times. The presence of components having large and small rate of breakage and occurrence of abnormal breakage are discussed.

Future work includes detailed analysis of the data and simulation of continuous test results.

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1. INTRODUCTION

In the first P.S.U. report corresponding to the period March 1, 1985/June 30, 1985 (1), standard S and B parameters for the clinker sample were determined in a 0.20 m (8 inch) diameter batch ball mill. Tests were run using five different starting size materials, using four different U powder filling values. The normal breakage region was characterized by a large slope $\alpha = 1.52$ for sizes less than 850 micrometers. B values appeared nearly normalized under normal breakage conditions but in the abnormal region they are non-normalized and characterized by a bimodal function having a plateau for intermediate particle sizes.

Some preliminary results on tests run in the 0.99m diameter pilot ball mill at the Kennedy Van Saun Corp. were also included in the first P.S.U. report.

The objective of this second progress report is to describe results corresponding to the continuous tests performed in the 0.99m diameter air-swept ball mill, including preliminary data analysis.

2. MATERIAL, EQUIPMENT AND PROCEDURES

Experimental equipment and procedures were the same as those described in the first report⁽¹⁾.

3. RESULTS

All tests were conducted by personnel of the Kennedy Van Saun Corp. at Danville under the direction of Mr. Kenneth Brame. Results corresponding to eight continuous tests are included in this report. Tests 9, 11 and 13 could not be run because there was not sufficient clinker stock at K.V.S.

3.1 Tests 3 to 6 at K.V.S.

In order to determine the effect of the production rate (as set by air flow rate) on the size distribution of the product, four open-circuit continuous ball mill tests were run in the 0.99m diameter air-swept mill. A 0.85 nominal U value was set in all cases.

Test plant logs containing the main steady-state conditions and results are summarized in Table 1. Size distributions for feed product and clinker hold-up are tabulated in Tables 2, 3, 4 and 5 and plotted in Figures 1, 2, 3 and 4. Test 4 was repeated because the first time there was a disturbance in the clinker feed rate while the mill was being sampled. Only new results are reported.

3.2 Tests 7 to 12 at K.V.S.

Tests 7 to 12 are the same kind of tests as before but these were directed to explore the grinding response for different production rates and different U-values.

Test plant logs are summarized in Table 6, size distributions for feed, product and hold-up are presented in Tables 7, 8, 9 and 10 and plotted in Figures 5, 6, 7 and 8. The actual U-values varied between 0.7 and 1.2 and the clinker feed rate in between 1100 and 1900 lb/h (dry basis).

4. ANALYSIS OF RESULTS

4.1 Internal Classification

Austin et al. (2) have developed a model for air-swept grinding considering the mill as a series of m stages. In a first analysis of the present results, we will follow this approach.

In the model it is assumed that the powder acted on by the grinding action is the flowing powder and that the suspended powder is not subjected to breakage action, that is, the product size fraction p_i is equal to the fraction of mass size i , w_i , in the hold-up W . It is also assumed that a fraction η of the hold-up is exposed to the air stream by tumbling per mill revolution. For a mill rotation speed ω , the amount of size i material in W exposed per unit time is therefore $p_i \eta \omega W$. Another assumption is that the exposed material of size i has a probability c_i of being retained in the hold-up and hence the rate of removal of size i in the air stream is given by $p_i \eta \omega W (1 - c_i)$. Assuming that η and the specific rates of breakage S_i are constants along the

mill, it can be readily shown that the fraction of size i in the air swept product p_i' is given by: $\tau\eta\omega(1-c_i)w_i$, hence:

$$p_i'/w_i = \tau\eta\omega(1-c_i) \quad (1)$$

For the smaller sizes k , $c_k \approx 0$, that is $p_k'/w_k \approx \tau\eta\omega$ and also

$p_k'/w_k \approx \tau\eta\omega$; where $p_k' = \sum_{i=n}^k p_i'$ and $w_k = \sum_{i=n}^k w_i$. Once $\tau\eta\omega$ has been determined, c_i values can be computed for all sizes. Results

corresponding to tests 3 to 6 are shown in Table 11 and plotted in Figures 9 to 16. It is interesting to realize that $\eta\omega\tau$ is equal to an apparent internal circulating load of $1+C'$. The circulating load increases as the air flow/rate and mass feed flow/rate increase, being affected most by air flow rate.

According to Austin et al. (2), c_i versus x_i values can be modeled using the simple function:

$$c_i = 1/[1 + (d_{50}/x_i)^{\Lambda_c}] \quad (2)$$

where d_{50} is the particle size at which half of this size drops back into the powder hold-up and half continues in the air stream out of the mill. x_i is the particle size of class i and Λ_c is a characteristic parameter. Experimental d_{50} and Λ_c values are presented in Table 12. We have also included the corresponding air flow rates and linear air velocity u , the clinker U -filling and the total apparent flow rate to the internal classifier. Results from runs 3 to 6 indicates a proportionality between d_{50} and the air flow rate or the linear velocity u . Comparison of experiments 3 and 8 shows that d_{50} and Λ_c are not

affected by changes in the apparent feed to the internal classifier in the range from 1416 to 6553 lb/h. Similarly, comparison of experiments 7 and 8 support the conclusion that d_{50} and Λ_c value do not change significantly with changes of U-filling in between 0.70 to 1.25. Comparison of Λ_c values from runs 6 and 12 shows that the difference in Λ_c for U between 1.6 and 2.1 can be disregarded.

Accordingly, the most important variable on d_{50} is the linear air velocity u . If as a first approximation, we assume a linear dependance between d_{50} and u , a $+ 12.7 \mu\text{m}/(\text{m/s})$ slope is obtained, but the 95% confidence interval is in between -14.7 and $+40.1 \mu\text{m}/(\text{m/s})$, that is, the slope is not statistically different from zero under the experimented conditions.

According to the above analysis, we conclude that even when the product size distribution is strongly affected by the experimented conditions, the internal classification numbers lie in a narrow band characterized by $d_{50} = 117 \pm 10 \mu\text{m}$ and $\Lambda_c = 1.8 \pm 0.3$.

As the mill rotation speed ω is known and τ can be computed from the measured hold-up and feed flow rate, η values can be computed, given that the apparent circulating load $(1+C') = \eta\omega\tau$ is also known. The experimental effect of air flow rate on η can be represented by the empirical relation:

$$\eta = 1.23 \times 10^{-3} \exp(V/V_0) \quad (3)$$

where $V_0 = 25 \text{ min}^{-1}$ Equivalently:

$$\eta = 1.23 \times 10^{-3} \exp(u/u_0) \quad (4)$$

where $u_0 = 0.63 \text{ m/s}$

Equations (3) or (4) allow a good representation of experimental results as can be observed in Figure 17.

4.2 Scaling-Up of Batch Grinding Results

All size distributions obtained in the 0.99 m diameter mill exhibit a large plateau from around 250 μ m and up. This is characteristic of abnormal breakage and introduce a problem in the direct simulation of results using normal B_{1j} values. This can be seen in Figure 18 where direct scaling-up of the 0.20 m mill results is shown assuming normal breakage conditions. Parameters used in the simulation are those determined in the laboratory:

$a = 1.51$, $\alpha = 1.52$, $\mu = 0.74$, $\Lambda = 1.88$, $\gamma = 1.47$, $\phi = 0.66$, $\beta = 4.5$ and $\delta = 0$. Simulated curves cross experimental data such that curves are over the points for large sizes and below the points for small sizes. The effect is more evident for short times. In addition to the abnormal B values, prediction of over capacity of short times of grinding can also be explained, by postulating the presence of hard and soft components in the clinker sample. This point should be cleared prior to the simulation of results presented in Section 3.

5. FUTURE WORK

Future work includes the analysis of abnormal breakage fracture and simulation of continuous results obtained at K.V.S.

In addition, laboratory test related to the ball size effect on grinding parameters obtained under normal and abnormal breakage conditions will be completed using a second clinker sample from K.V.S. It was found that this sample appears to behave differently presumably due to the months of storage exposed to the atmosphere. It will be necessary to repeat some of the previous experiments.

6. References

- (1) Report to Construction Technology Laboratories Contract CR7913-4330 (March 1, 1985 to June 30, 1985), Penn State University.
- (2) Austin, L.G. et al., A Simulation Model for an Air-Swept Ball Mill Grinding Coal, Powder Technology, 38 (1984) 255-266.
- (3) Austin, L.G., Klimpel, R.R. and Luckie, P.T., Process Engineering of Size Reduction: Ball Milling, Ed. AIME, New Jersey, 1984.

Table 1. Steady state results for the continuous grinding of cement clinker. Air swept Mill 0.99 m in diameter. Open circuit; $J=0.27$. Different mass flow for the same nominal U value. Tests 3 - 6.

Operation Variable		TEST NO.			
		3	4	5	6
Feed rate dry (wet), kg/h		331(363)	497(523)	639(642)	724(767)
	dry (wet), lb/h	730(800)	1096(1154)	1408(1416)	1595(1690)
Production rate dry (wet), kg/h		329(330)	485(490)	585(588)	732(738)
	dry (wet), lb/h	724(728)	1069(1080)	1289(1297)	1615(1626)
Mill motor power draw, kW		16.7	17.0	16.6	15.9
Feeder set-point		14.0	19.0	21.0	24.5
% -200 U.S. mesh in the product		79.3	66.4	61.3	55.2
TEMPERATURE OF	Mill outlet set-point	213	200	203	183
	Mill outlet actual	208	200	200	183
	Air heater outlet	427	385	385	322
	Cyclone inlet	208	200	205	188
	Dust collector inlet	198	192	197	190
STATIC PRESSURE water inches	Air heater outlet	0.05	0.05	0.10	0.15
	Mill inlet	0.15	0.30	0.40	0.60
	Mill outlet	2.6	5.6	7.7	10.0
	Classifier inlet	4.2	7.5	9.8	14.7
	I.D. fan inlet	5.2	8.6	10.9	16.3
	I.D. fan outlet	15.8	12.3	9.7	4.3
	Dust collector inlet	0.30	0.65	0.80	0.92
	Dust collector outlet	0	0	0	0
MILL LEVEL	Sound level reading	42.2	42.5	42.5	42.5
	Estimated solid hold-up, kg(lb)(*)	138(304)	136(300)	136(300)	136(300)
	Estimated U-filling(*)	0.84	0.83	0.83	0.83
AIR HEATER	P.A. damper % open	30	30	30	30
	Fuel gal/h	0.98	1.30	1.30	1.30
	Tempering air damper % open	100	100	100	100
AIR FLOW RATE	I.D. fan damper % open	10.0	16.5	21.0	33.0
	I.D. fan inlet, ACFM	983	1252	1560	1930
MOISTURE %	Feed	8.7	5.0	5.5	5.6
	Hold-up	0.5	0.8	0.7	0.8
	Product	0.5	1.0	0.6	0.7

(*) Values estimated from results runs 7, 8, 10 and 12.

Table 2: Size distribution results test 3 at K.V.S.

Sieve size		Cumulative weight % less than size		
U.S. mesh	micrometers	feed	hold-up	product
0.530"	13200	100.00		
3/8"	9500	99.06	100.00	
0.265"	6700	93.69	96.11	
4	4750	88.82	90.25	
6	3350	84.04	88.37	
8	2360	80.13	87.39	
12	1700	76.78	87.14	
16	1180	73.34	86.97	100.00
20	850	70.86	86.85	99.99
30	600	66.56	86.70	99.97
40	425	60.54	86.47	99.94
50	300	45.30	85.71	99.11
70	212	27.51	83.40	99.56
100	150	13.60	75.26	96.96
140	106	6.85	64.24	91.05
200	75	3.99	49.70	78.75
270	53	2.96	36.72	64.13
400	38	2.74	28.11	50.44
% Moisture		8.7	0.5	0.5

Figure 1: Size distribution results of Test 3 at K.V.S.:
Wet screen analysis; cement clinker flow rate = 800 lb/h;
 $U = 0.84$; $J = 0.27$

Table 3: Size distribution results test 4 (repeated)
at K.V.S.

Sieve Size		Cumulative weight % less than size		
U.S. mesh	micrometers	feed	hold-up	product
0.530"	13200			
3/8"	9500	100.00	100.00	
0.265"	6700	91.22	98.19	
4	4750	85.47	95.08	
6	3350	78.57	93.79	
8	2360	74.16	93.26	100.00
12	1700	70.69	93.04	99.96
16	1180	67.82	92.88	99.96
20	850	65.53	92.74	99.96
30	600	61.64	92.49	99.95
40	425	55.95	92.12	99.93
50	300	41.89	90.82	99.71
70	212	24.56	86.62	98.13
100	150	10.67	75.79	92.72
140	106	4.94	59.48	81.63
200	75	2.48	40.72	66.43
270	53	1.77	28.01	48.40
400	38	1.53	20.67	32.53
% Moisture		5.0	0.8	1.0

Figure 2: Size distribution results of Test 4 (repeat) at K.V.S.:
 Wet screen analysis; cement clinker flow rate = 1154 lb/h;
 $U = 0.83$; $J = 0.27$

Table 4: Size distribution results test 5 at K.V.S.

Sieve Size		Cumulative weight % less than size		
U.S. mesh	micrometers	feed	hold-up	product
0.530"	13200	100.00		
3/8"	9500	94.52	100.00	
0.265"	6700	89.69	94.76	
4	4750	83.52	91.44	
6	3350	77.68	89.51	
8	2360	73.52	88.71	
12	1700	69.90	88.11	
16	1180	67.12	87.67	
20	850	65.15	87.44	100.00
30	600	61.56	87.00	99.97
40	425	56.25	86.47	99.92
50	300	42.62	84.61	99.40
70	212	26.59	79.35	96.85
100	150	11.88	63.53	90.24
140	106	5.79	49.00	77.15
200	75	3.12	31.65	61.32
270	53	2.43	21.52	44.48
400	38	2.21	16.26	30.04
% Moisture		5.5	0.7	0.6

Figure 3: Size distribution results of Test 5 at K.V.S.:
Wet screen analysis; cement clinker flow rate = 1416 lb/h;
 $U = 0.83$; $J = 0.27$

Table 5: Size distribution results test 6 at K.V.S.

Sieve Size		Cumulative weight % less than size		
U. S. mesh	micrometers	feed	hold-up	product
0.530"	13200			
3/8"	9500	100.00	100.00	
0.265"	6700	94.27	96.05	
4	4750	87.36	88.84	
6	3350	81.02	85.31	
8	2360	77.29	84.22	
12	1700	74.01	83.32	
16	1180	70.98	82.74	100.00
20	850	68.92	82.26	99.98
30	600	64.96	81.57	99.93
40	425	59.39	80.66	99.71
50	300	44.31	77.87	98.26
70	212	27.47	70.57	93.68
100	150	13.14	54.86	85.02
140	106	6.47	38.83	70.53
200	75	3.97	23.39	55.19
270	53	3.32	14.58	40.61
400	38	3.17	11.06	31.08
% Moisture		5.6	0.8	0.7

Figure 4: Size distribution results of Test 6 at K.V.S.:
 wet screen analysis; cement clinker flow rate = 1690 lb/h;
 - $U = 0.83$; $J = 0.27$

Table 6: Steady state results for the continuous grinding of cement clinker. Air swept mill 0.99 m in diameter. Open circuit; $J = 0.27$. Different mass flow for the same nominal U value. Tests 7-12.

Operation Variable		7	8	10	12
	Feed rate dry (wet), hb/h	498(572)	862(954)	559(625)	678(764)
	dry (wet), lb/h	1099(1260)	1901(2103)	1226(1377)	1494(1684)
	Production rate dry (wet), kg/h	488(494)	846(855)	555(555)	723(732)
	dry (wet), lb/h	1075(1089)	1865(1886)	1225(1232)	1594(1613)
	Mill motor power draw, kW	16.1	17.2	16.0	16.3
	Feeder set-point	20.5	24.0	17.3	21.5
	%-200 U.S. mesh in the product	67.9	45.1	75.8	52.0
TEMPERATURE °F	Mill outlet set-point	180	175	168	170
	Mill outlet actual	180	165	173	172
	Air heater outlet	453	530	515	413
	Cyclone inlet	180	165	170	173
	Dust collector inlet	180	165	175	173
STATIC PRESSURE water inches	Air heater outlet	0.05	0.05	0	0.15
	Mill inlet	0.03	0.20	0.05	0.6
	Mill outlet	5.6	6.0	2.3	10.0
	Classifier inlet	7.3	7.8	3.3	14.6
	I.D. fan inlet	8.4	8.2	4.4	16.6
	I.D. fan outlet	12.9	13.2	17.4	4.8
	Dust collector inlet	0.6	0.6	0.25	1.0
	Dust collector outlet	0	0	0	0
MILL LEVEL	Sound level reading	43	38	42.5	42
	Estimated solid hold-up, kg(lb)	254.5	452	300	330
	Estimated U-filling	0.70	1.25	0.83	0.91
AIR HEATER	P.A. damper % open	40	60	50	60
	Fuel gal/h	1.7	2.1	1.2	2.3
	Tempering air damper % open	100	100	100	100
AIR FLOW RATE	I.D. fan damper % open	16.5	15.0	4.0	33
	I.D. fan inlet, ACFM	1324	1322	844	1909
MOISTURE %	Feed	12.8	9.6	11.0	11.3
	Hold-up	1.2	1.7	1.6	1.4
	Product	1.3	1.1	0.6	1.2

Table 7: Size distribution results test 7 at K.V.S.

Sieve Size		Cumulative weight % less than size		
U.S. mesh	micrometers	feed	hold-up	product
0.530"	13200	100.00		
3/8"	9500	99.11		
0.265"	6700	89.72	100.00	
4	4750	79.41	94.80	
6	3350	69.93	92.61	
8	2360	63.51	91.89	
12	1700	59.77	91.60	
16	1180	56.77	91.33	
20	850	54.77	91.10	100.00
30	600	51.44	90.74	99.99
40	425	47.28	90.26	99.97
50	300	35.76	88.68	99.86
70	212	24.74	84.43	99.05
100	150	12.96	73.48	94.40
140	106	7.25	55.75	83.94
200	75	4.64	38.94	70.24
270	53	3.64	27.43	54.02
400	38	3.37	20.94	41.28
% Moisture		12.8	1.2	1.3

Figure 5: Size distribution results of Test 7 of K.V.S.:
 wet screen analysis; cement clinker flow rate = 1260 lb/h;
 $U = 0.70$, $J = 0.27$

Table 8. Size distribution results test 8 at K.V.S.

Sieve Size		Cumulative weight % less than size		
U.S. mesh	micrometers	feed	hold-up	product
0.530"	13200	100.00		
3/8"	9500	95.57	100.00	
0.265"	6700	89.69	95.76	
4	4750	84.15	92.78	
6	3350	78.92	91.54	
8	2360	74.49	90.55	
12	1700	70.81	90.09	
16	1180	67.71	89.68	100.00
20	850	65.33	89.14	99.99
30	600	61.11	88.45	99.97
40	425	55.69	87.42	99.88
50	300	41.10	83.69	98.92
70	212	26.64	74.87	94.50
100	150	12.97	57.26	81.91
140	106	7.11	34.96	63.96
200	75	4.51	18.79	45.11
270	53	3.40	10.51	32.14
400	38	3.15	6.88	21.84
% Moisture		9.6	1.7	1.1

Figure 6: Size distribution results of Test 8 at K.V.S.:
 wet screen analysis; cement clinker flow rate = 2103 lb/h;
 $U = 1.25$, $J = 0.27$

Table 9. Size distribution results test 10 at K.V.S.

Sieve Size		Cumulative weight % less than size		
U.S. mesh	micrometers	feed	hold-up	product
0.530"	13200	100.00	100.00	
3/8"	9500	98.56	98.17	
0.265"	6700	88.42	96.33	
4	4750	80.64	93.93	
6	3350	75.25	91.93	
8	2360	71.68	91.01	
12	1700	68.75	90.55	
16	1180	66.25	90.11	100.00
20	850	64.10	89.65	99.99
30	600	59.82	89.14	99.99
40	425	54.14	87.15	99.97
50	300	39.51	81.90	99.90
70	212	24.86	79.39	99.14
100	150	11.51	64.73	95.46
140	106	6.21	50.32	79.12
200	75	3.94	35.14	64.06
270	53	3.19	23.39	47.87
400	38	2.99	17.68	36.33
% Moisture		11.0	1.6	0.6

Figure 7: Size distribution results of Test 10 at K.V.S.:
 wet screen analysis; cement clinker flow rate = 1377 lb/h;
 $U = 0.83$, $J = 0.27$

Table 10. Size distribution results test 12 at K.V.S.

Sieve Size		Cumulative weight % less than size		
U.S. mesh	micrometers	feed	hold-up	product
0.530"	13200	100.00		
3/8"	9500	99.04	100.00	
0.265"	6700	94.02	99.43	
4	4750	87.96	96.69	
6	3350	81.25	94.75	
8	2360	77.00	93.73	
12	1700	73.84	93.16	100.00
16	1180	70.72	92.75	99.99
20	850	68.35	92.40	99.97
30	600	63.97	91.80	99.90
40	425	58.21	91.02	99.71
50	300	43.09	88.01	98.37
70	212	26.19	80.40	93.72
100	150	10.96	62.35	83.90
140	106	5.30	44.50	68.59
200	75	3.07	24.83	50.38
270	53	2.51	16.13	39.38
400	38	2.27	12.47	30.13
% Moisture		11.3	1.4	1.2

Figure 8: Size distribution results of Test 12 at K.V.S.:
 wet screen analysis; cement clinker flow rate = 1684 lb/h;
 $U = 0.91$, $J = 0.27$

Table 11: Calculation of the internal classification parameters. 0.99 m air-swept ball mill.

x_i μm	TEST 3				TEST 4				TEST 5				TEST 6			
	p_i %	ω_i %	p_i/ω_i	P_i/W_i	C_i	p_i	ω_i	p_i/ω_i	P_i/W_i	C_i	p_i	ω_i	p_i/ω_i	P_i/W_i	C_i	
9500	0	3.89	0	1.000	1.000	0	1.81	0	1.000	1.000	0	3.95	0	1.000	1.000	
6700	0	5.86	0	1.040	1.000	0	3.11	0	1.018	1.000	0	7.21	0	1.041	1.000	
4750	0	1.88	0	1.108	1.000	0	1.29	0	1.052	1.000	0	3.53	0	1.126	1.000	
3350	0	0.98	0	1.132	1.000	0	0.53	0	1.066	1.000	0	1.09	0	1.172	1.000	
2360	0	0.25	0	1.144	1.000	0.04	0.22	0.182	1.072	0.889	0	0.90	0	1.187	1.000	
1700	0	0.17	0	1.148	1.000	0.00	0.16	0.000	1.074	1.000	0	0.58	0	1.200	1.000	
1180	0.01	0.12	0.083	1.150	0.953	0.00	0.14	0.000	1.076	1.000	0	0.02	0.48	0.042	1.209	
850	0.02	0.15	0.133	1.151	0.925	0.01	0.25	0.040	1.078	0.976	0.03	0.05	0.69	0.072	1.215	
600	0.03	0.23	0.130	1.153	0.927	0.02	0.37	0.094	1.081	0.967	0.05	0.22	0.91	0.242	1.225	
425	0.03	0.76	0.039	1.156	0.978	0.22	1.30	0.169	1.085	0.897	0.52	1.45	2.79	0.520	1.236	
300	0.35	2.31	0.152	1.156	0.914	1.58	4.20	0.376	1.098	0.771	2.55	4.58	7.30	0.627	1.262	
212	2.60	8.14	0.319	1.194	0.820	5.41	10.83	0.500	1.113	0.696	6.61	8.66	15.71	0.551	1.327	
150	5.91	11.02	0.536	1.288	0.697	11.09	16.31	0.680	1.223	0.586	13.09	14.49	16.03	0.904	1.550	
106	12.30	14.54	0.846	1.417	0.522	15.20	18.76	0.810	1.372	0.507	15.83	15.34	15.44	0.994	1.816	
75	14.62	12.98	1.126	1.585	0.364	18.03	18.71	0.964	1.631	0.414	16.84	14.58	8.81	1.655	2.360	
53	13.69	8.61	1.590	1.746	0.102	15.87	7.34	2.162	1.728	-0.315	14.44	9.53	3.52	2.707	2.785	
38	50.44	28.11	1.794	1.794	-0.014	32.53	20.67	1.574	1.574	0.043	30.04	31.08	11.06	2.810	2.810	
$\eta_{\omega\tau}$				1.770					1.644					1.950	2.798	

Table II (Continuation)

CALCULATION OF THE INTERNAL CLASSIFICATION

PARAMETERS - 0.99m air-swept ball mill.

X_i μm	TEST-7			TEST-8			TEST-10			TEST-12		
	P_i %	w_i %	P_i/w_i P_i/W_i C_i	P_i %	w_i %	P_i/w_i P_i/W_i C_i	P_i %	w_i %	P_i/w_i P_i/W_i C_i	P_i %	w_i %	P_i/w_i P_i/W_i C_i
13400	0	0	0	0	0	0	0	1.83	0	0	0	0
9500	0	0	0	0	4.24	0	0	1.84	0	0	0.57	0
6700	0	5.26	1.000	0	2.98	0	0	2.40	0	0	2.74	0
4750	0	2.13	1.000	0	1.24	0	0	2.00	0	0	1.24	0
3350	0	0.72	1.000	0	0.99	0	0	0.92	0	0	1.02	0
2360	0	0.29	1.000	0	0.46	0	0	0.46	0	0	0.57	0
1700	0	0.27	1.000	0	0.41	0	0	0.44	0	0.01	0.41	0.024
1180	0	0.22	1.000	0.01	0.54	0.019	0	0.46	0	0.02	0.35	0.057
850	0.01	0.37	1.038	0.02	0.69	0.023	0.01	0.51	0.020	0.07	0.60	0.117
600	0.02	0.48	1.102	0.09	1.03	0.087	0.02	1.39	0.010	0.19	0.78	0.244
425	0.11	1.58	1.108	0.36	3.73	0.257	0.07	5.25	0.013	1.34	3.91	0.445
300	0.81	4.25	1.126	4.42	8.82	0.501	0.76	2.51	0.303	4.65	7.61	0.611
212	4.65	10.95	1.173	12.59	17.61	0.715	3.68	14.66	0.251	9.82	12.05	0.544
150	10.46	17.73	1.285	17.95	22.30	0.805	16.34	14.41	1.134	15.31	17.85	0.858
106	13.70	16.81	1.285	18.85	16.17	1.166	15.06	15.18	0.992	18.21	19.67	0.936
75	16.22	11.51	1.403	12.97	8.28	1.566	16.19	11.75	1.378	11.00	8.70	1.264
53	12.74	6.49	1.963	10.30	3.63	2.837	11.54	5.71	2.031	9.25	3.66	2.527
38	41.28	20.94	1.971	21.84	6.88	3.174	36.33	17.68	2.055	30.13	12.47	2.416
η_{wt}			1.970			3.116						2.429

Figure 9: Internal classification numbers c_i : Open circuit continuous test in the 0.99 m air-swept mill; clinker flow rate 800 lb/h; air flow rate = 983 ACFM (Test 3).

Figure 10: Internal classification numbers ci: Open circuit continuous test in the 0.99 m air-swept mill; clinker flow rate = 1154 lb/h; air flow rate = 1252 ACFM (Test 4).

Figure 11: Internal classification numbers c_i : Open circuit continuous test in the 0.99 m air-swept mill; clinker flow rate = 1416 lb/h; air flow rate = 1560 ACFM (Test 5).

Figure 12: Internal classification numbers c_i : Open circuit continuous test in the 0.99 m air-swept mill; clinker flow rate = 1690 lb/h; air flow rate = 1930 ACFM (Test 6).

Figure 13: Internal classification numbers c_i : Open circuit continuous test in the 0.99 m air-swept mill; clinker flow rates 1260 lb/h; air flow rate = 1324 ACFM; $U = 0.70$; $J = 0.27$ (Test 7).

Figure 14: Internal classification numbers c_i : Open circuit continuous test in the 0.99 m air-swept mill; clinker flow rate = 2103 lb/h; air flow rate = 1324 ACFM; $U = 1.25$; $J = 0.27$ (Test 8).

Figure 15: Internal classification numbers c_i : Open circuit continuous test in the 0.99 m air-swept mill; clinker flow rate = 1684 lb/h; air flow rate = 1909 ACFM; $U = 0.91$, $J = 0.27$ (Test 12).

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