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DESIGN, FABRICATION AND PERFORMANCE ANALYSIS OF A PLANETARY ROLL MILL FOR FINE GRINDING

Ajaka E. O. and Akinbinu V. A.
Department of Mining Engineering, Federal University of Technology, Akure, Nigeria
E-Mail: deleajaka@yahoo.com

ABSTRACT

Reducing milling cost in mineral processing is a problem that has defiled all serious attempts while milling still takes up to 60% of comminution cost. The planetary roll mill is a new innovation for faster and finer grinding. It is designed and fabricated with grinding rolls rotating in a number of arms inside a grinding sphere. A test run of the complete machine with crushed granite and sandstone shows that the machine grinds to fine consistency within a short period of time. A comparison of the products of the machine with that of a standard Denver Laboratory Ball Mill shows that the machine is about 30% more efficient than the ball mill in terms of duration of grinding to a particular size consistency. One advantage of the planetary roll mill is that is can be used as a ball mill if the need arises. It is therefore recommended that this mill be developed for both research and industrial uses.

Keywords: planetary, roll mill, grinding efficiency, milling cost.

INTRODUCTION

Minerals, the primary source of major materials used for human inventions occur in the earth crust in forms that are not directly useable as raw materials unless they are first concentrated or processed (Runge, 1996; Vogley, 1985). Even native elements such as gold and silver are usually found in association with other non-valuable minerals (Ammen, 1997; Anthony, 1993; Barnes, 1988). Additionally, most mineral ores (with the exception beach sand and a few friable ores) occur in rock forms having varying degree of hardness. Since the mineral components of an ore are aggregated at the grain size level, it becomes important that the grains are first liberated from each other through the process of comminution before any meaningful separation of mineral types can take place. Comminution, which is achieved through crushing and grinding is said to be the most costly unit operation in the mineral processing plant; and because reduction ratio in grinding is far higher than in crushing, grinding in turn takes the largest portion of the total comminution cost (Mosher and Bigg, 2002; Morrison and Richardson, 2002; Barratt and Sherman, 2002). Sometimes, as in aggregate production, size reduction is done to produce a marketable final product (Levine, 2000).

Crushing and grinding can be carried through primary, secondary, tertiary and sometimes quaternary stages (Anon, 2001, Broadbent, 1988, Lewis, 1983). These comminution stages relate to the type of equipment (i.e., crushers and mills) used; but while different crushers are used at different crushing stages, especially for primary and secondary crushing, the same type of mill may be used at different stages of grinding with reducing efficiency as the required product size becomes finer (Kelsell and Reid, 1997, Kawatra and Eisele, 1988). Thus the major problem with some concentration processes like floatation, microbiological processes and similar others is the production of the optimum particle size that gives the best result. Mills of various type, design, and capacity have been used for applications in the mineral processing industry. Common among these are ball mills, rod mills, Autogenous (AG) and semi-Autogenous (SAG) mills, high power grinding rolls, ring-roller mill, vibratory mill, and stirred mill for ultra-fine grinding and others (Wills 1997, Kelly and Spottistwood 1982; Callow and Moon 2002; Williams and Meloy, 1997).

The end of the First World War and the outbreak of the second saw the development of operations research techniques which initially employed network analysis with simple linear programming techniques. This technique developed so rapidly into the application of complex mathematical models for simulating complex industrial processes of modern time including mineral processing technology (Herbst *et al*., 2002; Jeffrey, 2001; Williams and Meloy, 1997; Herbst *et al*., 2002; Herbst and Nordell, 2002). The introduction of models for problem simulation in mineral processing evidently started with the use of Bonds equation (Equation 1) in empirical models for determination of work index and thus the energy required for comminution. This equation has been used to design many ball and rod mill circuits for many years and it is still been used as the basis for most ball mill design but it has some limitations in terms of details required in process analysis and optimization work (Herbst and Nordell, 2002; Williams and Meloy, 1997).

$$W = 10w_i\left[\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}}\right] = \frac{P}{T} \text{............................} Eq.\,1$$

Where W = specific energy (Kwh/t)

w_i = work index (Kwh/t)

P_{80} = 80% passing size of the products (μ)

F_{80} = 80% passing size of feed (μ)

P = power drawn (Kw)

T = mass processed (tonnes per hour)

The result of application of modeling and simulation to mineral processing plant design through research over some years is now such that various models have been developed leading to the availability of efficient simulators, most of which are high fidelity programmes that can be used to simulate plant responses. Some of these simulators (for example JKSmith Simulator) are designed to simulate plant responses in part and there are many of such partial plant simulators especially in the areas of comminution and particle sizing (Herbst, *et al*., 2002). Some like the USIMPAC Series however are designed to simulate plant responses from crushing to refining. In recent years considerable progress has been made in developing method for theoretical analysis of size reduction (Taggart, 1999; Perry and Chilton, 1998). Unfortunately, the widespread use of these methods is restricted by the scarcity of scale-up information and although some data are already available to some equipment manufacturing companies, it appears that it will take sometime before it is available in the literature.

The major problem however, is that the aforementioned improvements in comminution are limited the efficiency of available mills because grinding to a given size consistency with the existing mills is still difficult and costly especially for local application. It is therefore necessary to develop a simple and cheap means of milling minerals locally. The planetary roll mill (Figures 1, 2 and 3) was designed to achieve faster grinding to sub-micro sizes as required in some concentration processes.

The mill which works on the principle of counter-rotation of a roll carrier against the inner surface of the cast grinding sphere of the equipment has been improved upon since the first model shown in Plate 2 was tested in the year 2004. The counter rotation principle simply implies that while the roll carrier rotates clock-wisely, the grinding sphere goes anti-clockwise (Figure-3). The rolls appear like planets revolving around the center position, thus the description: “planetary roll mill (Figure).

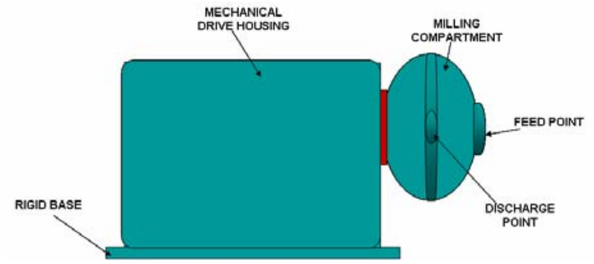

Figure-1. A sketch of the general external features of the mill.

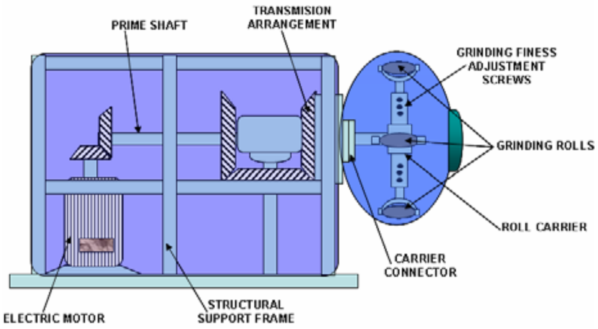

Figure-2. Some internal features of the planetary roll mill.

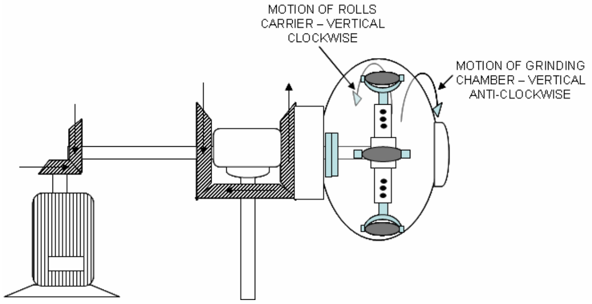

Figure-3. Directions of motion of some parts of the mill.

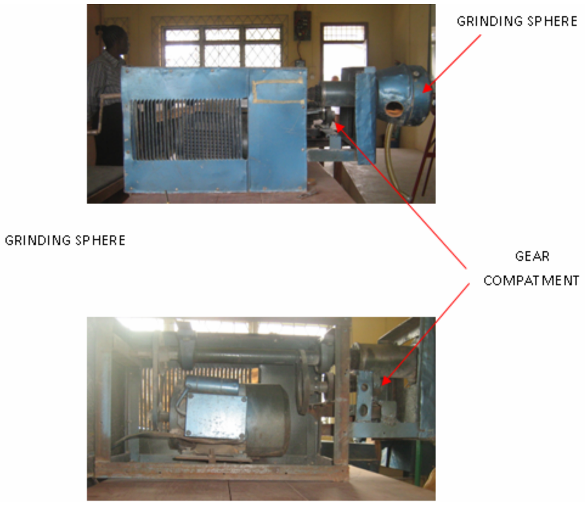

Figure-4. First model of the planetary roll mill.

This paper presents the performance evaluation of the machine by comparing the results of a test run with those obtained from standard tests with a Denver laboratory ball mill under various conditions.

MATERIALS AND METHODS

The materials used in the fabrication of the machine are the common steel members shown in Table-1. These were prepared according to the designed features using the common fabrication processes. To ensure high integrity of welded joints especially the roll carrier parts, Lincoln 6010, φ2.5mm low hydrogen electrode was used for penetration of prepared joints and a 7018, φ4mm low hydrogen electrode for filling and capping with a 500Amps Kaleida DC welding machine. Gears, bearings, electric motor, steel rod and other parts were purchased as specified in the design. An industrial lathe machine, grinding machines, portable drilling machine and other tools were used. Specifications of the major parts as contained in the design drawing are shown in Table-1.

Table-1. Specifications of some of the components of the mill.

S.No.	Component	Specification	Quantity	Location
1	Bearings	$\phi 75mm\ x\ \phi 50mm$	7	P, Q, R, S, T, U, W of Figure
2	Bevel Gears	$\phi 25mm \begin{bmatrix} Teeth = 16 \\ Pitch\phi = 35mm \end{bmatrix}$ $\phi 75mm \begin{bmatrix} Teeth = 32 \\ Pitch\phi = 85mm \end{bmatrix}$ $\phi 100mm \begin{bmatrix} Teeth = 48 \\ Pitch\phi = 110mm \end{bmatrix}$	1 3 1	A B,C,D E of Figure-5
3	Electric Motor	$1500rpm,\ 760W$	1	
4	Main Shaft (Prime shaft)	$\phi 50mm\ x\ 600mm\ Steel\ Rod$	1	Figures-2 and 5
5	Grinding Sphere	Forged from 6mm steel plate, max.ф450mm	1	
6	Grinding Rolls	Oval shaped, machined from 110mm steel rod	6	
7	Frame	$2mm$ angle iron $1mm$ steel plate	1 1	
8	Roll Carrier	75mmф /4mm steel pipe	6	

The 100mm steel rod was cut to size and turned on the lathe to form the grinding rolls which were heat treated to enhance their performance.

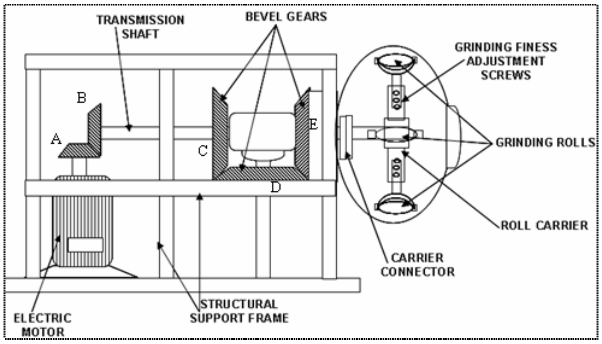

Figure-5. General motion transmission systems of planetary roll mill.

General description of features of the mill

Grinding principle

The planetary roll mill grinds by attrition between the rolls, the feed and the grinding shell. The transmission arrangements enables the grinding shell and roll carrier to be driven in opposite directions (Figures 3 and 5). The rolls can be made to rotate about their connection axes or be tightened to prevent rotation. The more this freedom of rotation, the less the grinding force since the rolls rotate in the direction of motion of the feed. Thus the grinding force is higher when only the roll carrier rotates and the rolls prevented from rotating about their axes.

The drive system

The drive mechanism is by gear arrangement. There are five gears involved in the grinding motion of the planetary roll mill. These are marked G1 to G5 in Figure-6. G1 is connected to the motor and so is the prime or driver gear. Its speed ratio to G2 is approximately 1: 2. G2 and G3 are carried on the main shaft and so have the same vertical-clockwise direction of motion as the main shaft which also determines the direction of motion of the grinding roll carrier. G3 however induces a horizontal anti-clockwise motion on G4 which drives G5 in a vertical anti-clockwise direction. As shown in Figure-6, G3 and G4 have same diameter and so same speed. Because G5 is connected rigidly to the grinding chamber, it drives the grinding sphere in the same vertical anti-clockwise direction. Thus, the grinding sphere and the rolls carrier move in opposite directions (Figures 3 and 9). But the size of G4 is about two third that of G5 which implies that their speed ratio is approximately two to three (2:3). This means that the grinding sphere makes two complete revolutions for every three revolutions of G4; and since G3 and G4 have equal speed, then the grinding sphere makes two complete revolutions for every three revolutions of the grinding rolls.

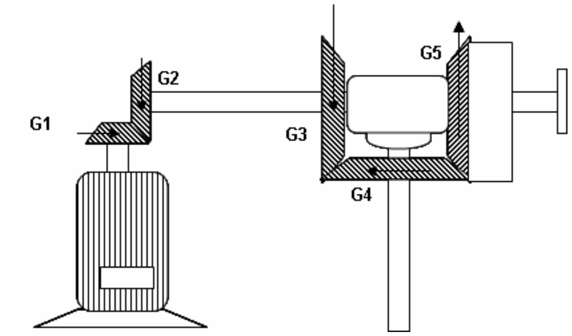

Figure-6. Transmission system of the mill.

The grinding rolls

The grinding rods are six prepared into an oval shape from 100mm steel rod. Each of the rods is 150mm long and diameter 80mm. The rods are connected directly to a hexagonal roll carrier with bolt and not system. As the shaft drives roll carrier in a clockwise rotation.

The roll carrier connector

The planetary roll mill is designed for fast fine dry grinding. When grinding is not intended for such however, the mill can be used as a ball mill by simply removing the entire roll carrier through the carrier connector and use balls as grinding media instead of the rolls as shown in Figures 7 and 8.

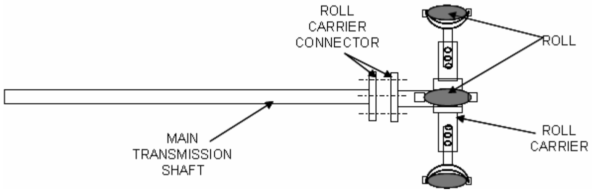

Figure-7. Roll carrier and main shaft connector.

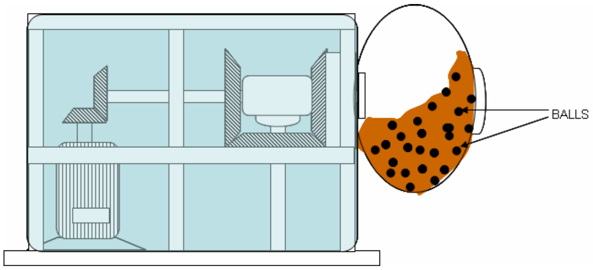

Figure-8. Using Balls instead of rolls as grinding media.

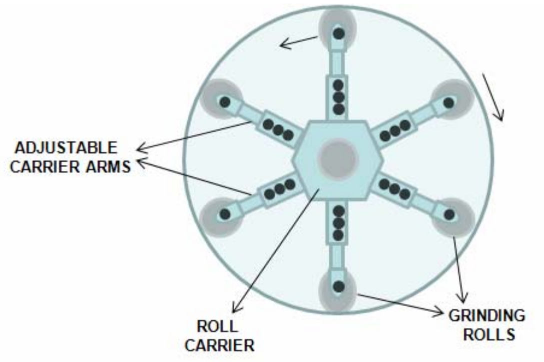

Figure-9. Arrangement of the grinding rolls on the roll carrier - front view.

Test procedures

The main objective of the tests was to determine the effectiveness of the machine in grinding mineral materials to the required consistency for adequate liberation of components. Thus the tests were carried out as a form of grindability tests on samples of granite rock and sandstone. The procedure compared the results of grindability tests on the new planetary roll mill with that of a standard Denver laboratory ball mill. The granite and sandstone lumps were broken with sledge hammer to sizes of about 50mm that conveniently pass the gape of the laboratory jaw crusher (Austin and Bharia, 1997). The materials were then crushed and sieved to obtain uniform product of size +4.75mm as feed for the grindability tests in the two mills. The planetary roll mill was run for five (5) minutes and the products collected and sieved. Each of the runs was repeated two more times making a total of three runs per test and the average value recorded. The run was repeated with the same feed size for durations of 10, 15 and 20 minutes, respectively for both samples. The entire experimental procedure was repeated with the Denver ball mill.

RESULTS AND DISCUSSIONS

The results of all experimental test runs performed with the completed machine are shown in Tables 2 to 13 and these results are represented graphically in Figures 10 to 13.

The results shown in the tables and figures here give an interesting preview of the efficiency of this innovation in milling operations. In the 5 minutes milling runs with the planetary roll mill (PRM) for granite, the modal nominal product size is +2000 microns and this represented over 17% of the entire sieve fraction (Table-2). This modal size kept moving down and in the runs for 20 minutes with granite, the modal sieve size has moved down to +212 representing approximately 19% of the total weight of material in the mill.

The same trend was observed in milling runs with sandstone. However, unlike the test runs with granite where the larger portion of the products appeared to be concentrated very close to the modal sieve class on both sides but skewed to right

(Figure-10), the products of runs with sandstone appeared to spread a little around the modal class (Figure-11). The grinding runs with granite did not follow these observed trends, but its modal class moved gradually away and downward from the feed size (Figure-12)

In all, it appeared as if the modal class for grinding with the Planetary Roll Mill was going to stagnate at 212 microns and remained there as grinding continued. This is because it was observed that the sieve fractions below the 212 size (i.e., 150, 75, +53 and -53) were not increasing in proportion to increaseing grinding time. While those fractions above 212 were increasing in volume toward the 212 size fraction. This trend was gradually becoming noticeable with increasing grinding time as the seeming symetry around the modal class became obvious at grinding test for 10 minutes and well distinct from 15 minutes and 20 minutes grinding durations, (Figures 10 and 11). It is obvious that as grinding continues and all material above 212 microns (or whatever the stagnation size is) are ground to this stagnation size. the skewness of the plot will change to the left because the size fractions bellow the stagnation size will still inevitably be produced with increasing grinding time, while all material above the stagnation class will be ground to this size. The reason for this class or size stagnation may be due to the set adjustment of the grinding rolls because the grinding tests with the Denver ball mill (DBM) did not produce this size stagnation.

In order to compare the grinding performance of the PRM for different materials (sandstone and granite) and with the performance of the DBM, sieve analysis of the grinding runs for different grinding durations are compared. But the polynomial trends of the microsoft excel plots of the sieve analysi resuls (Figures 14 to 17) which produced the best goodness of fit (R^2) of over 99% (0.99) are used to explain the performance trend rather than the direct plots of the sieve analysis results (An example of a direct plot is shown in Figure-13).

What is obviously visible from the seive analysis plots shown in figures 14 to 17 is the size with equal volumes of oversize and undersize materials (that is $d_{50/50}$ - 50% oversize and 50% undersize). In the grinding runs for 5 minutes, the $d_{50/50}$ size produced by the PRM was 900microns for granite and 1175 microns for sandstone while the DBM produced 1275 microns for granite. In the runs for 10 minutes, the $d_{50/50}$ size moved doen to 775 microns for granite with PRM, 850microns for sandstone with PRM and 1100microns for granite with DBM. However, in the grinding runs for 15 minutes and 20 minutes, the size moved down and almost coincided for both granite and sandstone at about 625microns and 550microns for 15 minutes and 20 minutes respectively for PRM, while the DBM produced 950microns and 875microns for granite at 15 minutes and 20 minutes, respectively.

Although we are not able to explain precisely here why granite which is harder than sandstone was initially reduced faster to finer sizes than sandstone, but it is obvious that the gradual shift in the $d_{50/50}$ size to finer size with increasing grinding time shows that size reduction progresses systematically with time.

Comparison of the performance of PRM with that of the DBM, clearly shows that the PRM grinds faster to finer sizes than the ball mill, but unlike the ball mill which will continue to grind to infinetely finer size with increasing time, it appears that the PRM may grind to a particular size (stagnation size) determined by the roll set and remains at this size even with increasing grinding time. This is shown by the difference in the $d_{50/50}$ size for granite for the same grinding duration with the PRM and DBM. For example at 5 minutes grinding duration for granite(Figure-4), the $d_{50/50}$ for PRM was 900microns and 1275 microns for DBM.

One other advantage of the PRM over the DBM is the possibility of controlling grinding and thus may be able to grind to about 90% oversize of a chosen size which control is not possible with the ball mill. The agregation of size fractions with higher values around the modal seive size (Figures 10 to 12) shows that the grinding mechanism in the PRM is systematic and gradually grinds to a set-size.

CONCLUSIONS

The results of performance of the machine described above shows that it is a promsing innnovation toward reducing both milling time and cost. The successful design and fabrication of two models of the machine also indicateed that if further work is done on improving the design and materials selection for the various components of the machine, it is possible to produce a machine that will change the course of milling and communition research in the mineral industry . However, since the PRM grinds more by attrition than impact, it is necessary to measure the wear rate of the rolls and the grinding chamber so as to determine the overall cos effectiveness of the machine

TABLES

Table-2. Sieve analysis of runs on the planetary roll mill for 5 minutes with granite.

Nominal aperture (μ)	**Weight** (g)	**Cum weight undersize** (g)	**% Cum weight undersize**	**% Cum weight oversize**	**% Weight**
2000	78.34	370.36	82.54	17.46	17.46
1700	72.73	297.63	66.33	33.67	16.21
1180	58.08	239.55	53.39	46.61	12.94
850	57.22	182.33	40.64	59.36	12.75
600	53.17	129.16	28.79	71.25	11.85
425	43.83	85.33	19.02	80.98	9.77
212	38.73	46.6	10.39	89.61	8.63
150	16.7	29.9	6.66	93.34	3.72
75	10.71	19.19	4.28	95.72	2.39
53	11.82	7.37	1.64	98.36	2.63
0	7.37	0	0	100	1.64

Table-3. Sieve analysis of runs on the planetary roll mill for 10 minutes with granite.

Nominal aperture (μ)	**Weight** (g)	**Cum weight undersize** (g)	**% Cum weight undersize**	**% Cum weight oversize**	**% Weight**
2000	49.32	411.38	89.30	10.71	10.71
1700	53.53	357.85	77.68	22.33	11.62
1180	62.84	295.01	64.04	35.97	13.64
850	73.73	221.28	48.03	51.97	16.00
600	70.77	150.51	32.67	67.33	15.36
425	50.24	100.27	21.77	78.24	10.91
212	45.13	55.14	11.97	88.03	9.80
150	18.22	36.92	8.01	91.99	3.96
75	14.08	22.84	4.96	95.04	3.06
53	13.81	9.03	1.96	98.04	3.00
0	9.03	0	0	100	1.96

Table-4. Sieve analysis of runs on the planetary roll mill for 15 minutes with granite.

Nominal aperture (μ)	**Weight** (g)	**Cum weight undersize** (g)	**% Cum weight undersize**	**% Cum weight oversize**	**% Weight**
2000	30.56	433.04	93.41	6.59	6.59
1700	30.88	402.16	86.75	13.25	6.66
1180	47.11	355.05	76.59	23.42	10.16
850	55.04	300.01	64.71	35.29	11.87
600	68.77	231.24	49.88	50.12	14.83
425	77.12	154.12	33.24	66.76	16.64
212	73.08	81.04	17.48	82.52	15.76
150	30.14	50.9	10.98	89.02	6.50
75	21.06	29.84	6.44	93.56	4.54
53	17.07	12.77	2.76	97.25	3.68
0	12.77	0	0	100	2.76

Table-5. Sieve analysis of runs on the planetary roll mill for 20minutes with granite.

Nominal aperture (μ)	**Weight** (g)	**Cum weight undersize** (g)	**% Cum weight undersize**	**% Cum weight oversize**	**% Weight**
2000	22.17	449.89	95.30	4.70	4.70
1700	28.05	421.84	89.36	10.64	5.94
1180	42.01	379.83	80.46	19.54	8.90
850	50.56	329.27	69.75	30.25	10.71
600	68.03	261.24	55.34	44.66	14.41
425	76.08	185.16	39.22	60.78	16.12
212	89.27	95.89	20.31	79.69	18.91
150	45.95	49.94	10.58	89.42	9.73
75	19.06	30.88	6.54	93.46	4.04
53	16.77	14.11	2.99	97.01	3.55
0	14.11	0	0	100	2.99

Table-6. Sieve analysis of runs on the planetary roll mill for 5minutes with sandstone.

Nominal aperture (μ)	**Weight** (g)	**Cum weight undersize** (g)	**% Cum weight undersize**	**% Cum weight oversize**	**% Weight**
2000	68.73	415.99	85.82	14.18	14.18
1700	67.12	348.87	71.97	28.03	13.85
1180	62.13	286.74	59.16	40.84	12.82
850	58.72	228.02	47.04	52.96	12.11
600	53.33	174.69	36.04	63.96	11.00
425	51.07	123.62	25.50	74.50	10.54
212	45.72	77.9	16.07	83.93	9.43
150	28.43	49.47	10.21	89.79	5.87
75	20.23	29.24	6.03	93.97	4.17
53	14.13	15.11	3.12	96.88	2.92
0	15.11	0	0	100	3.12

Table-7. Sieve analysis of runs on the planetary roll mill for 10 minutes with sandstone.

Nominal aperture (μ)	**Weight** (g)	**Cum weight undersize** (g)	**% Cum weight undersize**	**% Cum weight oversize**	**% Weight**
2000	43.17	441.73	91.10	8.90	8.90
1700	51.91	389.82	80.39	19.61	10.71
1180	56.02	333.8	68.84	31.16	11.55
850	68.44	265.36	54.73	45.28	14.11
600	70.35	195.01	40.22	59.78	14.51
425	63.27	131.74	27.17	72.83	13.05
212	48.63	83.11	17.14	82.86	10.03
150	29.93	53.18	10.97	89.03	6.17
75	22.04	31.14	6.42	93.58	4.55
53	15.16	15.98	3.30	96.71	3.13
0	15.98	0	0	100	3.30

Table-8. Sieve analysis of runs on the planetary roll mill for 15 minutes with sandstone.

Nominal aperture (μ)	**Weight** (g)	**Cum weight undersize** (g)	**% Cum weight undersize**	**% Cum weight oversize**	**% Weight**
2000	32.08	454.92	93.41	6.59	6.59
1700	40.18	414.74	85.16	14.84	8.25
1180	42.19	372.55	76.50	23.50	8.66
850	57.88	314.67	64.61	35.39	11.89
600	79.24	235.43	48.34	51.66	16.27
425	77.83	157.6	32.36	67.64	15.98
212	59.25	98.35	20.20	79.81	12.17
150	34.11	64.24	13.19	86.81	7.00
75	25.02	39.22	8.05	91.95	5.14
53	20.98	18.24	3.75	96.26	4.31
0	18.24	0	0	100	3.75

Table-9. Sieve analysis of runs on the planetary roll mill for 20 minutes with sandstone.

Nominal aperture (μ)	**Weight** (g)	**Cum weight undersize** (g)	**% Cum weight undersize**	**% Cum weight oversize**	**% Weight**
2000	22.23	465.08	95.44	4.56	4.56
1700	26.04	439.04	90.10	9.91	5.34
1180	42.33	396.71	81.41	18.59	8.69
850	51.08	345.63	70.93	29.07	10.48
600	75.82	269.81	55.37	44.63	15.56
425	81.03	188.78	38.74	61.26	16.63
212	68.33	120.45	24.72	75.28	14.02
150	41.18	79.27	16.27	83.73	8.45
75	29.04	50.23	10.31	89.69	5.96
53	26.11	24.12	4.95	95.05	5.36
0	24.12	0	0	100	4.95

Table-10. Sieve analysis of runs on ball mill for 5 minutes with granite.

Nominal aperture (µ)	**Weight** (g)	**Cum weight undersize** (g)	**% Cum weight undersize**	**% Cum weight oversize**	**% Weight**
2000	103.51	385.85	78.85	21.15	21.15
1700	81.24	304.61	62.25	37.75	16.60
1180	73.33	231.28	47.26	52.74	14.99
850	62.48	168.8	34.49	65.51	12.77
600	51.21	117.59	24.03	75.97	10.47
425	40.02	77.57	15.85	84.15	8.18
212	30.11	47.46	9.70	90.30	6.15
150	24.92	22.54	4.61	95.39	5.09
75	11.02	11.52	2.35	97.66	2.25
53	9.08	2.44	0.50	99.50	1.86
0	2.44	0	0	100	0.50

Table-11. Sieve analysis of runs on ball mill for 10minutes with granite.

Nominal aperture (µ)	**Weight** (g)	**Cum weight undersize** (g)	**% Cum weight undersize**	**% Cum weight oversize**	**% Weight**
2000	89.22	398.82	81.72	18.28	18.28
1700	70.12	328.7	67.35	32.65	14.37
1180	66.86	261.84	53.65	46.35	13.70
850	61.27	200.57	41.10	58.90	12.55
600	58.01	142.56	29.21	70.79	11.89
425	50.22	92.34	18.92	81.08	10.29
212	35.19	57.15	11.71	88.29	7.21
150	26.85	30.3	6.21	93.79	5.50
75	13.37	16.93	3.47	96.53	2.74
53	11.02	5.91	1.21	98.79	2.26
0	5.91	0	0	100	1.21

Table-12. Sieve analysis of runs on ball mill for 15 minutes with granite.

Nominal aperture (μ)	**Weight** (g)	**Cum weight undersize** (g)	**% Cum weight undersize**	**% Cum weight oversize**	**% Weight**
2000	76.61	412.99	84.35	15.65	15.65
1700	62.32	350.67	71.62	28.38	12.73
1180	63.17	287.5	58.72	41.28	12.90
850	63.15	224.35	45.82	54.18	12.90
600	60.02	164.33	33.56	66.44	12.26
425	58.22	106.11	21.67	78.32	11.89
212	41.16	64.95	13.27	86.73	8.41
150	29.07	35.88	7.33	92.67	5.94
75	15.48	20.4	4.17	95.83	3.16
53	14.23	6.17	1.26	98.74	2.91
0	6.17	0	0	100	1.26

Table-13. Sieve analysis of runs on ball mill for 20 minutes with granite.

Nominal aperture (μ)	**Weight** (g)	**Cum weight undersize** (g)	**% Cum weight undersize**	**% Cum weight oversize**	**% Weight**
2000	62.15	421.01	87.14	12.86	12.86
1700	58.12	362.89	75.11	24.89	12.03
1180	58.05	304.84	63.09	36.91	12.02
850	60.04	244.8	50.67	49.33	12.43
600	61.21	183.59	37.99	62.00	12.67
425	63.72	119.87	24.81	75.19	13.19
212	48.38	71.49	14.80	85.20	10.01
150	32.01	39.48	8.17	91.83	6.63
75	17.07	22.41	4.64	95.36	3.53
53	15.22	7.19	1.49	98.51	3.15
0	7.19	0	0	100	1.49

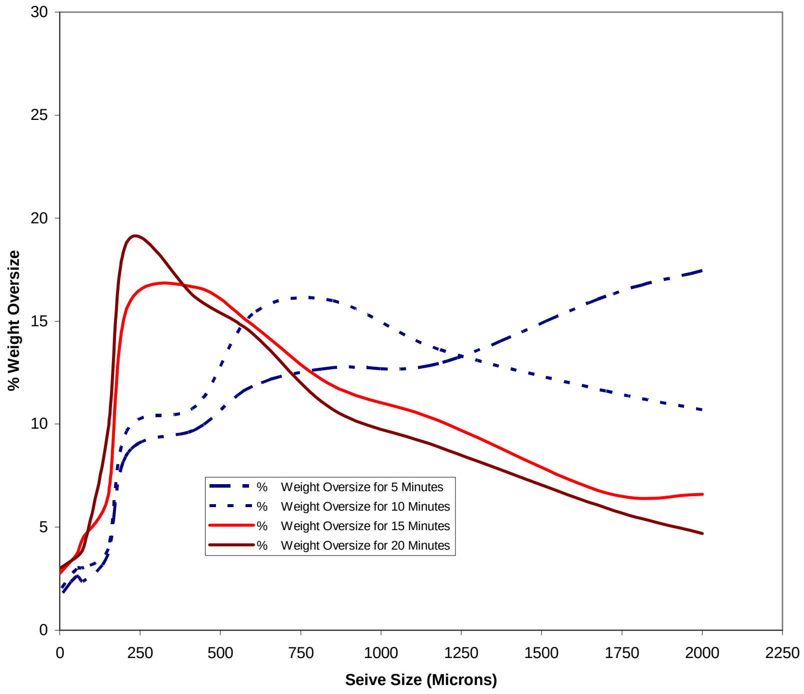

Figure-10. Skewness comparison for grinding runs with PRM for granite.

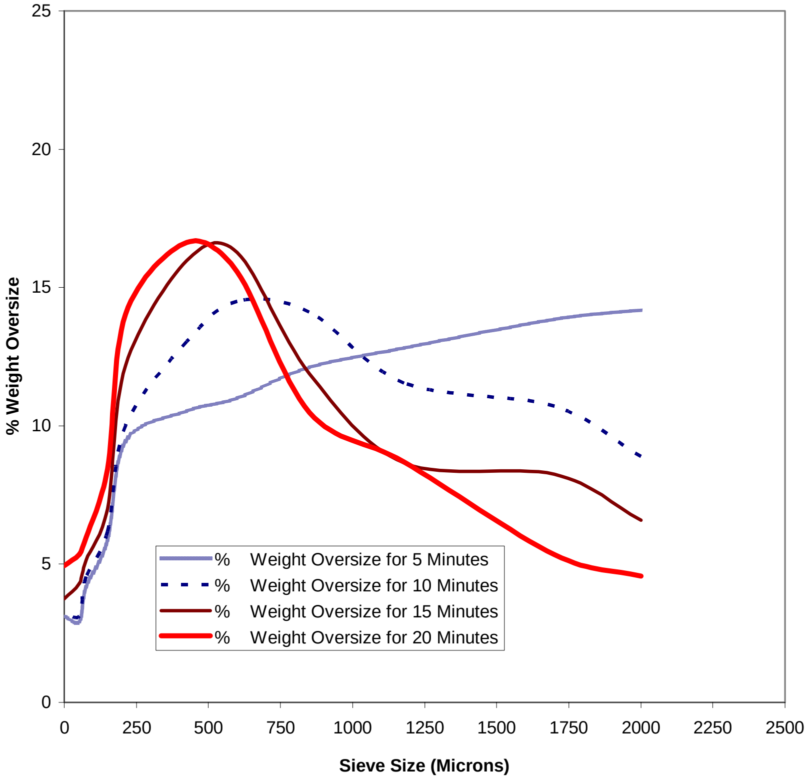

Figure-11. Skewness comparison for grinding runs with PRM for sandstone.

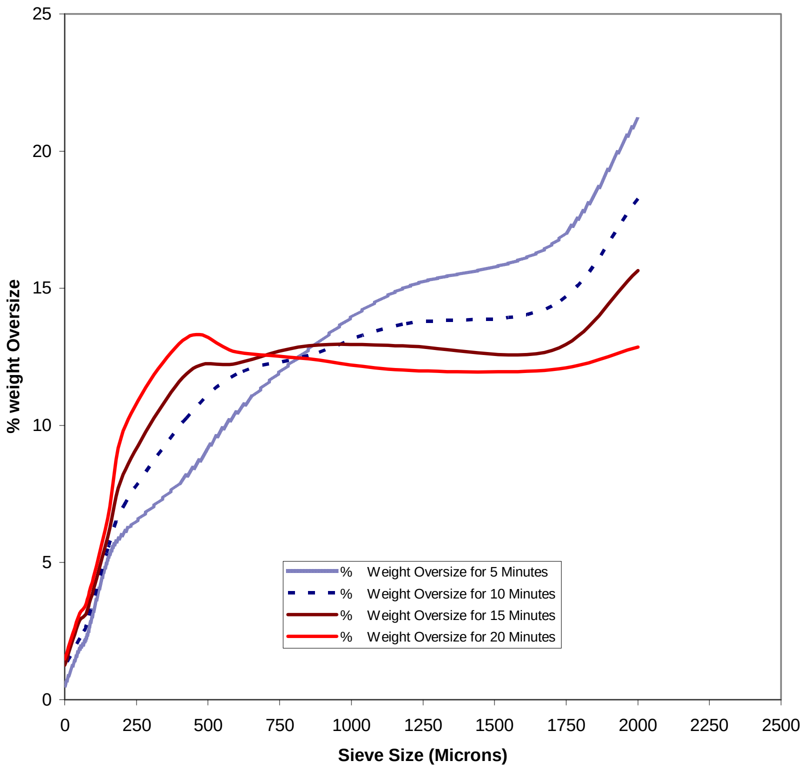

Figure-12. Skewness comparison for grinding runs with DBM for granite.

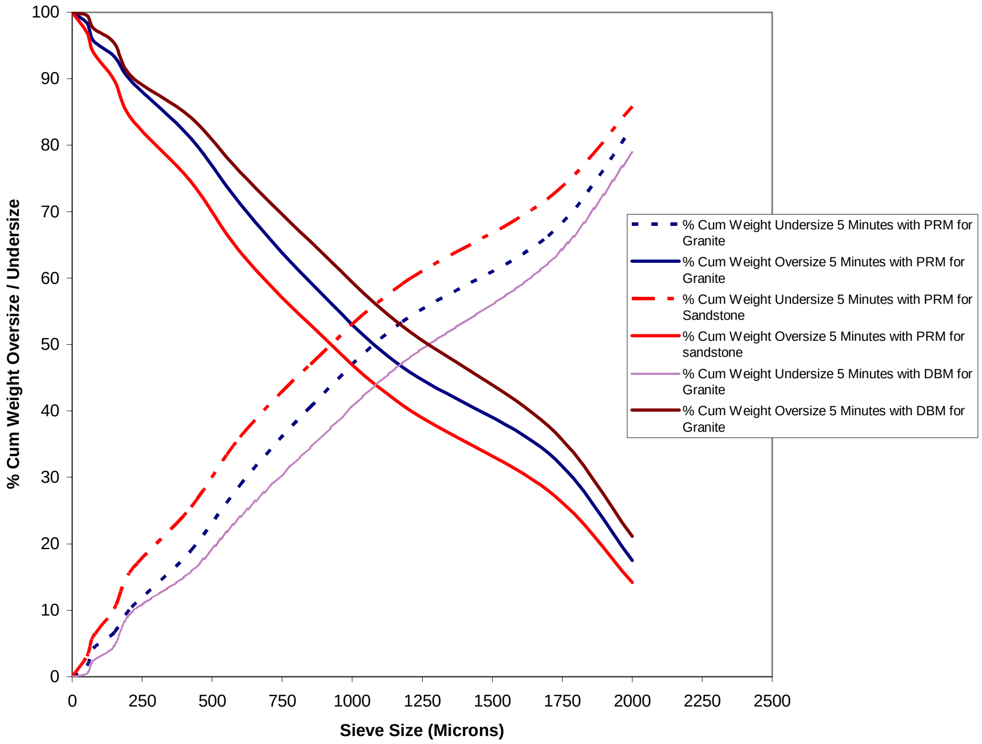

Figure-13. Direct plot of grinding tests with selected materials for 5 minutes (Direct Plot).

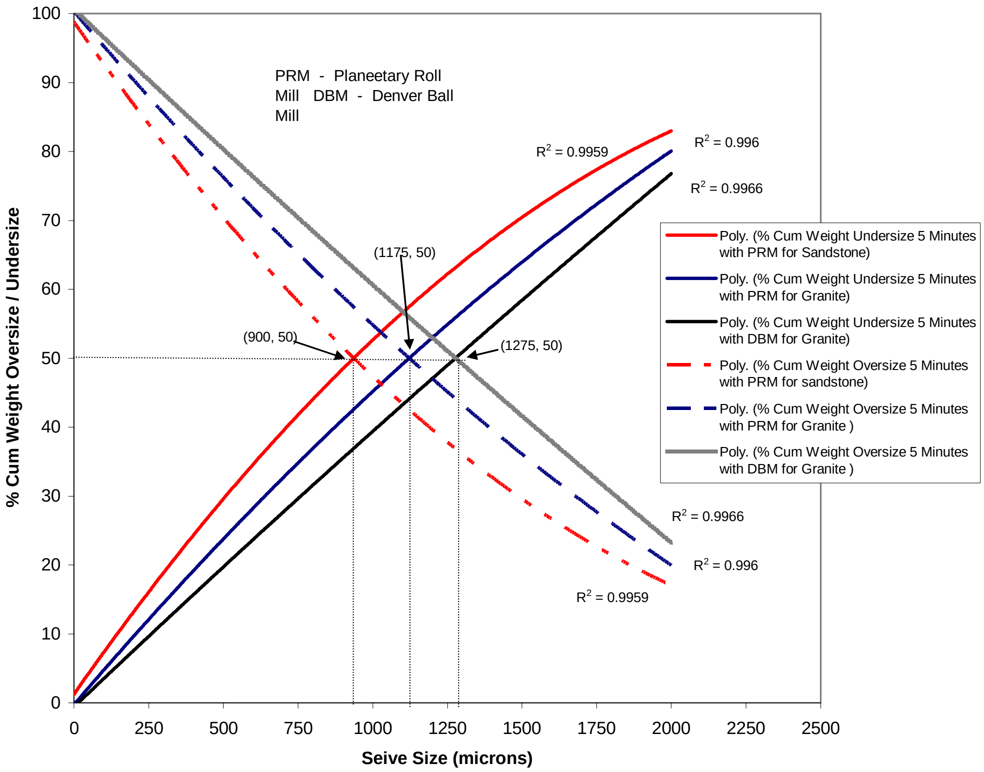

Figure-14. Comparision of grinding trend with selected materials for 5 minutes (Poly Trend).

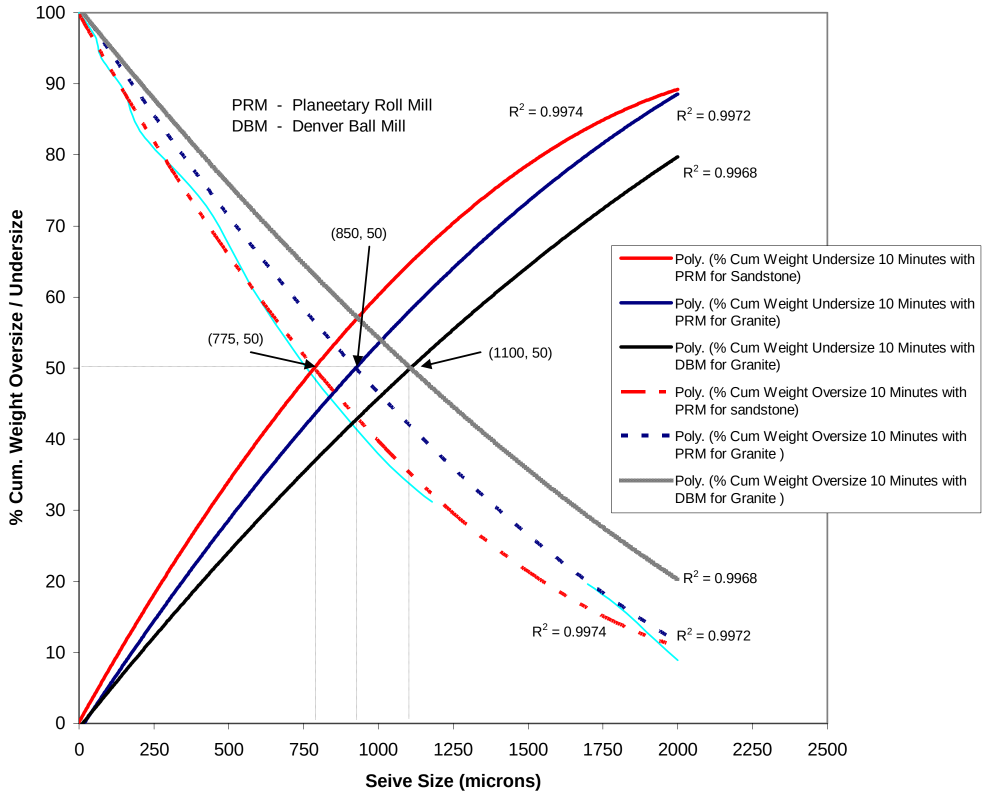

Figure-15. Comparision of grinding trend with selected materials for 10 minutes (Poly Trend).

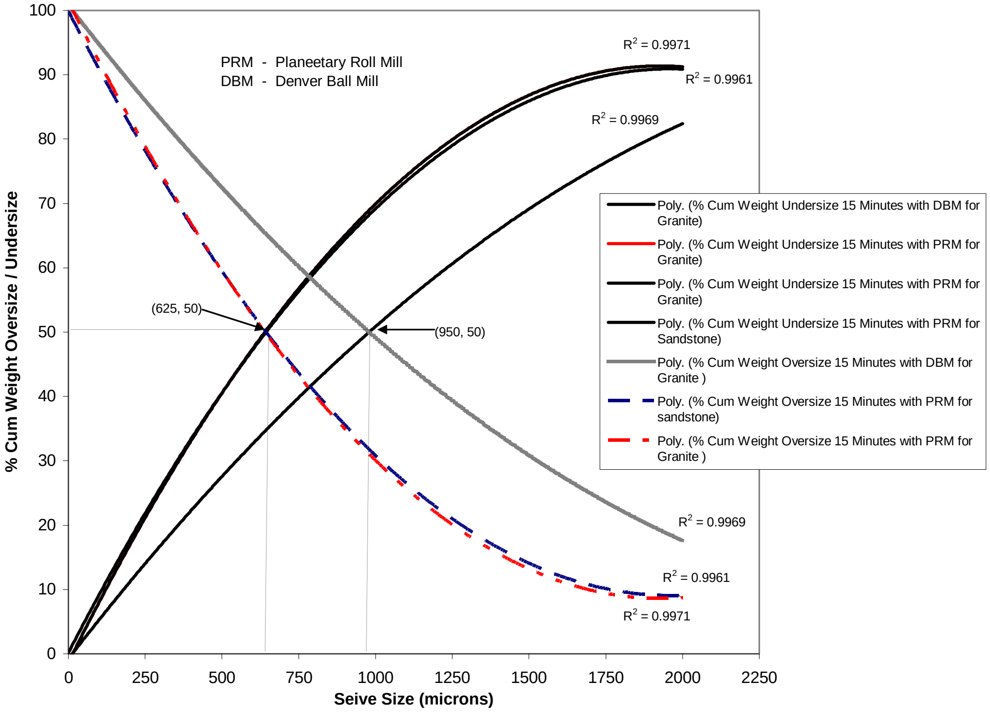

Figure-16. Comparision of grinding trend with selected materials for 15 minutes (Poly Trend).

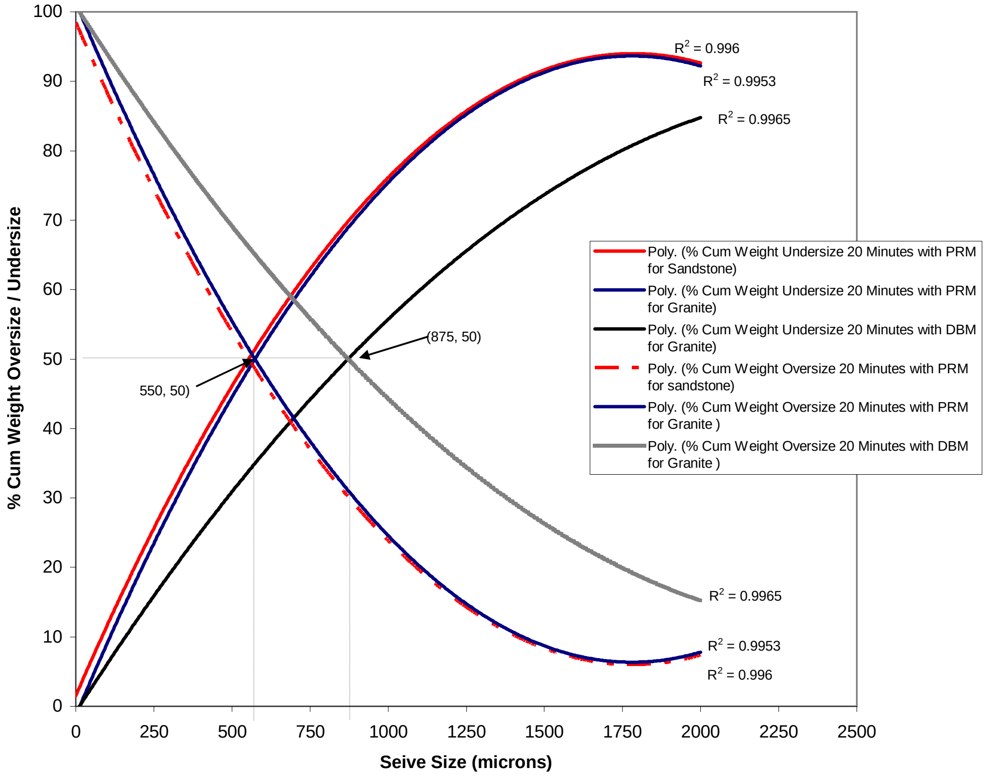

Figure-17. Comparision of grinding trend with selected materials for 20 minutes (Poly Trend).

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