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THE PREFERENTIAL COMMINUTION OF BINARY MIXTURES

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Abstract

Representative samples of limestone, ilmenite, and quartz, were dry batch ground separately and in binary mixtures of limestone-ilmenite and limestone-quartz in different compositions in the ball mill. The study aimed to investigate the effect of the feed mixture composition on the mill product characteristics as reflected on each of the two components. The results indicated that quartz affects as a tough, hard component more than the ilmenite as a heavy component on the grindability of limestone in their mixtures. Such behavior may be attributed to the ability of quartz to transfer the kinetic energy of the grinding media to limestone component more than ilmenite, which increases the preferential comminution of limestone by quartz more than that by ilmenite.

KEYWORDS: grindability, comminution of binary mixtures, Grinding of heterogeneous materials, physical and mechanical properties of rocks

1. Introduction

The comminution process as an important unit operation is widely applied in industries such as mineral processing, ceramics, cement, and chemical industries. Ball mills have been the most common equipment used for the comminution of ores in mineral industries because of their flexibility and versatility in reducing minerals to smaller sizes [1-3].

Most raw materials come from multiphase heterogeneous rocks that contain the target mineral. To free the target minerals, the rock should be comminuted to fine enough sizes [4]. The grinding behavior of solids is complex due to the effect of some or all of their mechanical properties, and the picture becomes even more complicated for such heterogeneous materials [5]. In the comminution of heterogeneous materials, an understanding of how the different constituents interact with each other may prove useful for optimizing the operation [6]. The particulates that exhibit heterogeneous breakage characteristics have been considered as a mixture of two individual components. Each component has its own breakage parameters, which are constant within each matrix [7]. Since the grinding environment in an industrial mill is never homogeneous, the next logical step would be to study the comminution kinetics of heterogeneous systems being ground in the tumbling mills. Heterogeneity in feed constituents can be presented by the presence of two minerals with different physical properties in the mill feed, or differences in the size distribution of the feed constituents. Hence, the study of mixture grinding can be classified into two categories [2], one in which the grinding of a mixture of a single size fraction of two minerals with different physical properties [8-10], and the other category in which a coarse size fraction is ground with fine particles of the same mineral [2,8]. Studies on the grinding kinetics of mixtures of two minerals with different physical properties have been performed wet by Zhao et al [8] and dry by Kapur and Fuerstenau [9]. Kapur and Fuerstenau studied the energetics and kinetics of mixture grinding by using the energy split factor. They found that this concept was highly useful for analyzing different aspects of mixture grinding. Two physically dissimilar materials were ground separately and in admixture in a ball mill by Rose and Matsumura [10]. They deduced an expression that relates the grinding times necessary for specified feed materials when the materials were ground separately or in a mixture. Fuerstenau

and Venkataraman [11] showed that calcite was ground faster when ground in the presence of hard quartz than if it was ground alone. Similarly, in a simultaneous grinding, Kanda et al [12] found that the grindability of limestone was higher when it was ground in a mixture than when it was ground separately. A model which makes possible complete distribution composition prediction has been developed by Barbery and Leroux [13]. This model predicts the composition distribution for particles obtained by breakage multiphase materials. Ipek et al [14] confirmed that if a mixture of three materials of similar density is being ground in a ball mill, the size distribution of the mixture product may be predicted if the grindability characteristics of the individual materials, their mass fractions in the mixture, and the total grinding energy input are known.

Fuerstenau et al [2] ground a coarse fraction (-1.651+1.168) μm of quartz, dolomite, and limestone in the presence of fine fractions (-147 μm) of the same materials. It was found that the three material systems, ground in a ball mill, behave similarly i.e., the breakage distribution functions were independent on the mill environment and the breakage rates were increased with decreasing the ratios of coarse to fine. Tavares and Kalleback [15] found that the accumulation of hard components in the mill was increased with decreasing the ratio of Bond work index values of the individual soft and hard components and with increasing the circulating load ratios. Wang [16] stated that understanding the role of texture and crack propagation can provide fundamental knowledge for predicting and improving the energy efficiency of comminution. The results of his study demonstrated that mineral distribution and minerals with lower tensile strength play a very important role in the breakage process. Xie et al [17] studied the breakage of heterogeneous coal and pyrite and coal and calcite. For mixtures of coal and pyrite, the fineness of pyrite progeny was higher than that from individual breakage. Instead, the coal in the mixture showed the opposite trend.

In this study, limestone-ilmenite and limestone-quartz binary mixtures were ground in a ball mill at different mixing feed ratios to illustrate the behavior of each component in the ground mixtures.

1 - Experimental Work

1.1. Materials

Representative samples of Assiut limestone, Abu-Ghalga ilmenite, and El-Barramyia tough Quartz, were used in this study. These rocks represent soft, heavy, and tough hard materials respectively. A narrow size range (-4+2 mm) from each rock was prepared carefully by screening process after the primary and secondary crushing steps. These samples were ground separately and as admixtures of (80%+20%), (60%+40%), (40%+60%), and (20%+80%) of limestone- ilmenite as well as limestone-quartz binary mixtures in a ball mill.

1.2. Some Physical and Mechanical Properties of Rocks

The compressive strength of each rock was obtained using the universal compression test machine shown in Fig. (1). The toughness of each studied rock, which is defined as the external work done to overcome the bonding force between crystals to fracture it, was determined by the area under the load-deformation curve [18-21]. Fig. (2) illustrates the load - deformation diagram for a limestone specimen as an example and the toughness of the three studied rocks was listed in Table (1).

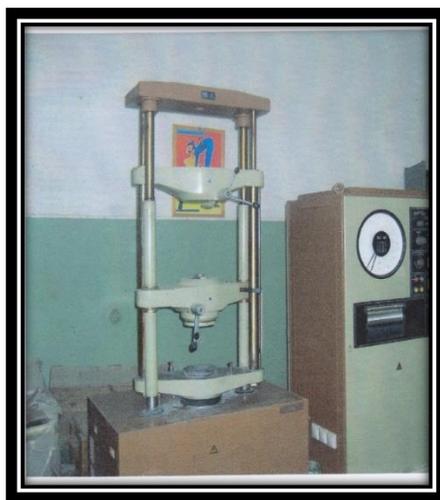


Fig. (1) Universal compression test machine

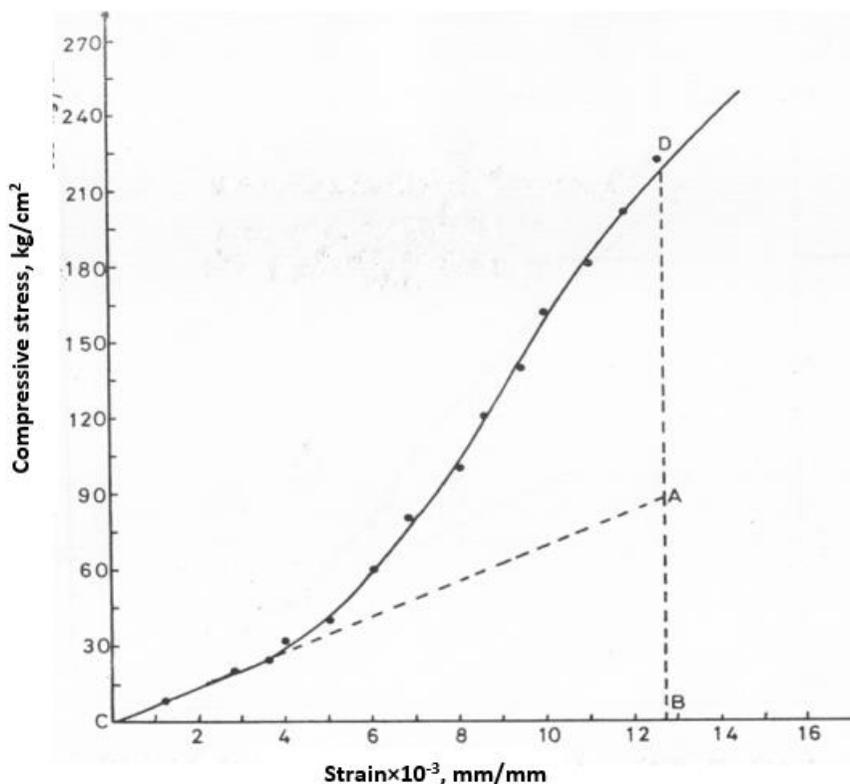


Fig (2). Stress strain diagram for a limestone specimen.

Regarding the hardness test, three specimens of the different studied rocks of dimensions $10 \times 10 \times 2$ cm each were polished and prepared for testing. The surface of each specimen was divided by grids to 16 spots. The hardness was measured at these spots by the Rockwell testing machine shown in Fig. (3). A preliminary load (p_0) that is equal to 10 kg, and an additional load (p) that is equal to 52.5 kg., for soft rock (limestone) and 140 kg for hard rocks (ilmenite, and quartz) were applied as shown in Fig. (4). The penetrator of the machine consisted of a diamond cone with edges of $120^\circ (\pm 2)$. The Rockwell-C-Hardness was expressed by Eq. (1) [22].

$$\text{HRC} = 100 - e/0.002 \quad (1)$$

Where: e is the remaining depth of indentation after the additional load has been removed.

Results were contoured to show the variation of the hardness number on the whole area of the specimen. Then, the mean HRC was calculated for each specimen.



Fig. (3) Rockwell testing machine

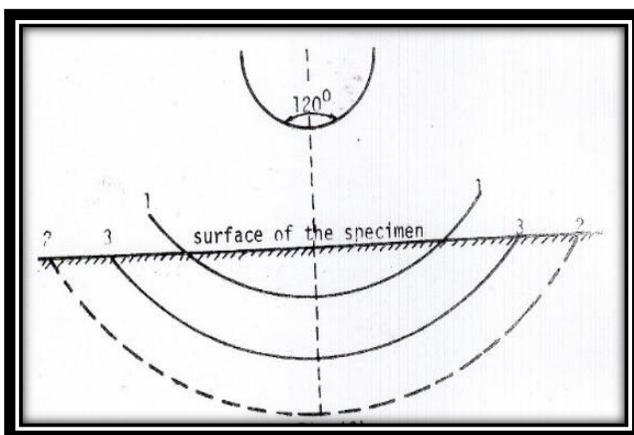


Fig. (4) Diamond cone, angle 120°

- 1-1 Penetration of cone under preliminary load (p_0)
- 2-2 Penetration of cone under total load ($p + p_0$)
- 3-3 Penetration of cone after removal of the additional load p , under preliminary load

Referring to the abrasion test, four cubic test specimens of 6 cm sides were cut from bulk samples of the different studied rocks. The specimens were carefully surface - finished to obtain parallel and

smooth faces, then worn down under a predicted pressure (1 kg/cm²) on a rotating cast iron grinding track of prescribed hardness. An abrasive substance (fine sand of $-0.63+0.50$ mm) was continuously fed under the test specimens. The test specimens were fixed in the holder of the machine shown in Fig. (5) and slowly rotated during the test in order to ensure their uniform wear. As soon as the abrasive disc has made a certain number of revolutions (1000 revolutions at a rate of 28-30 rpm), the machine was automatically stopped. The abrasion value was appointed as a ratio of loss in weight to the original weight of the specimen under the conditions mentioned above.



Fig. (5) Abrasion test machine

The measured physical and mechanical properties of the studied rocks were listed in Table (1).

Table (1) Some physical and mechanical properties of the studied rocks.

Rock name	Compressive strength, (kg/cm ²)	Toughness (cm ²)	Rockwell Hardness (HRC)	Abrasion value as a ratio	True density (g/cm ³)	Apparent density (g/cm ³)
Limestone	216.6	60.8	3.2	0.206	2.27	1.11
Ilmenite	630.70	100.3	3.8	0.014	4.50	1.76
Quartz	1026.72	138.6	7.0	0.011	2.32	1.29

2. Grinding Apparatus and Procedures

A laboratory scale ball mill of 14 cm in length and 16 cm internal diameter was used in dry batch grinding of these samples of rocks and their mixtures. The operating parameters were kept constant as follows:
 Feed particle size : -4+2 mm (closed size range) ;
 Volume of the mill occupied with the balls charge : 55% of the total mill volume.

The Balls charge consisted of:

3.2 kg steel balls of 2.5 cm diameter.
 3.2 kg steel balls of 2 cm diameter.
 1.6 kg steel balls of 1.5 cm diameter.
 Mill speed : 80 rpm = 75% of its critical speed.
 Grinding time : 10 minutes for all grinding tests.

The volume of voids between balls charge was measured by the displacement with water to be 700 cm³. 90% of this volume (630 cm³) was filled with material, as the grinding operation was dry, which corresponded to 700 g of limestone, 1111 g of ilmenite, and 813 g of quartz. Consequently, the bulk density of the used closed-size range (-4+2 mm) of each studied rock was calculated and listed in Table (1). The true density of each studied rock was appointed by using the density bottle. Weights of mixtures components were calculated and listed in Table (2)

Table (2) Weights of feed mixtures components at the different mixing ratio of feed.

Feed mixture components		limestone-Ilmenite mixture		limestone-Quartz mixture	
		limestone (g)	Ilmenite (g)	limestone (g)	Quartz (g)
Limestone (%)	Ilmenite or quartz %				
100	0	700	0	700	0
80	20	560	222.2	560	162.6
60	40	420	444.4	420	325.2
40	60	280	666.6	280	487.8
20	80	140	888.8	140	650.4
0	100	0	111.0	0	813.0

Each ground sample was mixed thoroughly and three representative samples of it were analyzed by sieving with a screen set from 3.15 mm to 0.063 mm using a vibrating sieve shaker.

Three representative samples, each weighing 5 g of -200 μm from each ground sample of the mixture were dissolved for leaching out the limestone with diluted hydrochloric acid with water (50% HCL + 50% water) and the remaining ilmenite or quartz was weighed after filtration and drying. It was assured that the fine fraction (-200 μm) of ilmenite or quartz did not react chemically with the dilute acid, which indicated that they did not contain any traces of limestone.

3. Results and Discussions:

Table (3) summarizes the results whereas Table (A.1) in Appendix I list the screen analyses of the separately ground samples of limestone, ilmenite, and quartz, respectively. The reduction ratio was calculated by dividing the median size of the feed (3000 μm) by the median size of the ground sample, where the median size of the ground sample was calculated as Eq. (2) [23].

$$\text{Median size of ground sample} = \frac{\sum D \times W_i}{\sum W_i} \quad (2)$$

Where: D = the mean size fraction, μm ,
 W_i = weight percent retained, %,
 $\sum W_i = 100$

From Table (3) limestone has the highest reduction ratio and quartz has the smallest one, while ilmenite has the in-between value. This behavior may be due to the low values of toughness as well as the hardness of limestone, while quartz has high toughness and hardness as seen in Table (1). Table (A.2) (Appendix I) represents the mean particle size analyses of the ground limestone-ilmenite mixture at different percentages of ilmenite. From this table, it is clear that the reduction ratio decreases as the percentage of ilmenite increases in the feed. Table (A.3) (Appendix I) illustrates similar results regarding the limestone-quartz mixture. Table (3) concludes the final results of the ground mixtures. The achieved limestone% in the fine portion (-200 μm) of each ground mixture was calculated as Eq. (3) [24].

$$\text{Limestone\%} = \frac{\text{\% of fine part in the product} \times \text{\% of limestone in it}}{\text{\% of limestone in the feed}} \quad (3)$$

Fig (6) represents the effect of the blending ratio of the feed on the reduction ratio of the ground mixtures. This figure show that the reduction ratio decreases as the percentage of ilmenite or quartz increases in the mixture because of increasing of the heavy or tough component (either ilmenite or quartz). It is also seen that the reduction ratio of limestone-ilmenite mixture is higher than that of limestone-quartz mixture due to the difference in their hardness and toughness. Fig (7) illustrates the effect of feed blending ratio on the achieved limestone in limestone-ilmenite and limestone-quartz mixtures. From this figure, at any mixing ratio, the size of limestone achieved by grinding with quartz is higher than that achieved by grinding with ilmenite. This behavior may be due to the fact of quartz as a hard tougher component that transfers the kinetic energy of the grinding media to the limestone more than ilmenite as a heavy component. This finding agrees with that predicted by Fuerstenau et al [2], Kanda et al [12], and Gupta [25].

Table (3) Reduction ratios and achieved limestone in the fine portion (-200 μm) of the ground limestone-ilmenite and limestone-quartz mixtures

Limestone-ilmenite mixture					Limestone-Quartz mixture			
% of ilmenite or quartz in the feed	Reduction ratio	% of fine in the prod.	% of limestone in the fine.	Achieved limestone in the fine%	Reduction ratio	% of fine in the prod.	% of limestone in the fine.	Achieved limestone in the fine %
0	6.87	-	-	-	6.87	-	-	-
20	4.41	48.43	70.26	42.53*	3.20	40.51	96.62	48.93**
40	3.23	36.34	65.32	39.56	2.33	29.78	85.02	42.20
60	2.69	28	48.36	33.85	2.13	24.91	59.52	37.07
80	1.93	14.1	42.14	29.71	1.81	12.27	54.81	33.63
100	2.58	-	-	-	1.44	-	-	-

$$* \frac{48.43 \times 70.26}{80} = 42.53$$

$$** \frac{40.51 \times 96.62}{80} = 48.93$$

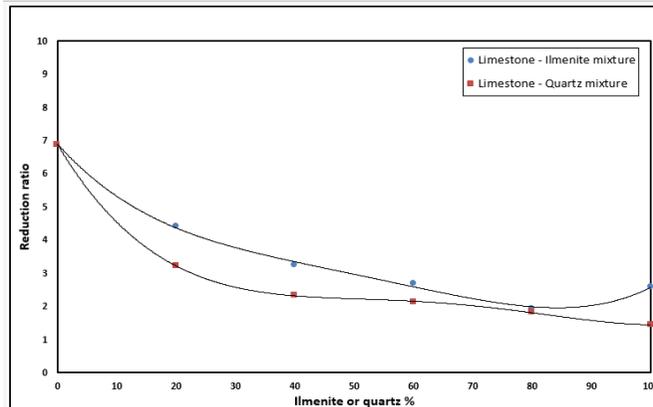


Fig (6): Effect of ilmenite or quartz% in the feed on the reduction ratio of limestone –ilmenite and limestone – quartz mixtures

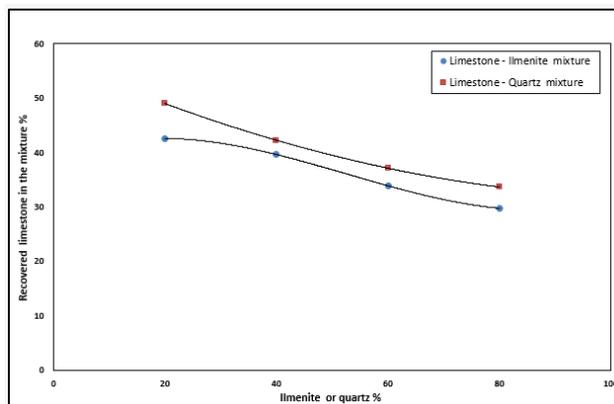


Fig (7): Effect of ilmenite or quartz% in the feed on the percentage of achieved limestone% in the fine product (-200 μm) of the limestone-ilmenite and limestone-quartz mixtures.

4. Conclusion and Recommendations

From the results of this investigation and their discussions, it can be concluded that:

- Toughness has a very important effect on the preferential comminution of binary mixtures.
- The percentage of the achieved limestone in the fine of the ground limestone-quartz binary mixture is higher than that of limestone-ilmenite one as quartz is tougher and harder than ilmenite.

- Mineral particles with high toughness act as energy transfer agents to increase the grinding of soft mineral particles in their mixed feed.
- It is recommended to execute the idea of this work by using the breakage rate function to make the results clearer.

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الطحن التفاضلي للمخاليط الثنائية

تم طحن عينات ممثلة للحجر الجيري كمادة هشة. والألمنيت كمادة عالية الكثافة (ثقيلة) والكوارتز كمادة عالية الصلابة والصلادة كل على حدة، وعلى صورة مخاليط ثنائية من الحجر الجيري والألمنيت والحجر الجيري والكوارتز بنسب خلط مختلفة لخام التغذية في الطاحونة الدوارة ذات الكرات كوسط طاحن. تهدف الدراسة إلى إظهار تأثير مكونات خليط التغذية على مواصفات كل مكون للخليط في ناتج الطحن. وقد أظهرت الدراسة أن الكوارتز كمادة عالية الصلابة والصلادة يؤثر بصورة أكبر على طحن الحجر الجيري في خليطهما أكبر من تأثير الألمنيت كمادة عالية الكثافة في خليطهما. وقد تم تفسير ذلك بأن المادة الصلبة عالية الصلادة (الكوارتز) أكبر قدرة على نقل طاقة حركة الوسط الطاحن (الكرات) إلى الحجر الجيري من المادة الثقيلة (الألمنيت) مما يؤدي إلى زيادة الطحن التفاضلي للحجر الجيري بالكوارتز عنه بالألمنيت.

Appendix I

Table (A.1) Mean particle size analyses of the ground separately limestone, ilmenite, and quartz rocks.

Particle size (μm)	Mean particle size, μm . D	Limestone		Ilmenite		Quartz	
		wt.% ret.	wt.% ret. $\times D$	wt.% ret.	wt.% ret. $\times D$	wt.% ret.	wt.% ret. $\times D$
-4000+3150	3575	0.61	2180.75	11	39325	30	107250
-3150+2500	2825	2.12	5989	10.5	29662.5	22	62150
-2500+2000	2250	1.22	2745	8	18000	10	22500
-2000+1600	1800	0.91	1638	7	12600	5	9000
-1600+1000	1300	3.03	3939	5	6500	2	2600
-1000+630	815	6.06	4938.9	2	1630	1	815
-630+400	515	12.13	6246.95	2	1030	1	515
-400+315	357.5	7.88	2817.1	3	1072.5	1	357.5
-315+200	257.5	46.04	11855.3	6.34	1632.55	4	1030
-200+160	180	1.18	212.4	8	1440	4.32	777.6
-160+125	142.5	2.12	302.1	8	1140	4.9	698.25
-125+100	112.5	0.94	105.75	7	787.5	5.62	632.25
-100+71	85.5	2.12	181.26	6	513	6.02	514.71
-71+63	67	2	134	8.5	569.5	1.57	105.19
-63+0.0	31.5	11.64	366.66	7.66	241.29	1.57	49.46
Σ		100	43652.17	100	116143.84	100	208994.9
Median particle size (μm)			436.52		1161.44		2089.95
Reduction Ratio			$\frac{3000}{436.52}$ = 6.87		$\frac{3000}{1161.44}$ = 2.58		$\frac{3000}{2089.95}$ = 1.44

Table (A.2) Mean particle size analyses of the ground Limestone – ilmenite mixture at different percentages of ilmenite.

Particle size (μm)	Mean particle size. D	20% ilmenite		40% ilmenite		60% ilmenite		80% ilmenite	
		wt.% ret.	wt.% ret. $\times D$	wt.% ret.	wt.% ret. $\times D$	wt.% ret.	wt.% ret. $\times D$	wt.% ret.	wt.% ret. $\times D$
-	3575	1.2	4290	1.11	3968.25	1.17	4182.75	0.94	3360.5
3000+3150	2825	5.10	14407.5	8.01	22628.25	9.32	26329	15.40	43505
-	2250	6.30	14175	10.90	24525	14.40	32400	24.98	56205
3150+2500	1800	3.75	6750	3.78	6804	8.05	14490	10.74	19332
-	1300	8.69	11297	14.02	18226	13.34	17342	16.20	21060
2500+2000	815	9.59	7815.85	10.68	8704.2	11.12	9062.8	8.87	7229.05
-	515	6.74	3471.1	6.68	3440.2	6.78	3491.7	4.09	2106.35
2000+1600	357.5	2.40	858	2.01	718.6	2.32	829.4	1.40	500.5
-	257.5	7.80	2008.5	6.47	1666.03	5.50	1416.25	3.28	844.6
1600+1000									
-1000+630									
-630+400									
-400+315									
-315+200									
Σ		51.57	65072.95	63.66	90680.53	72.00	109543.9	85.90	154143
-200+160	180	3.35	603	2.23	401.4	2.21	397.8	1.14	205.2
-160+125	142.5	2.90	413.25	2.23	317.8	1.92	373.6	0.95	135.38
-125+100	112.5	2.64	297	1.91	214.9	1.62	182.25	0.89	100.13
-100+71	85.5	5.41	462.6	3.67	313.8	2.80	239.40	1.59	135.9
-71+63	67	3.09	207.03	2.23	149.4	1.47	98.47	0.83	55.6
-63+0.0	31.5	31.04	977.76	24.07	758.2	17.98	566.33	8.70	274.1
Σ		48.43	2960.64	36.34	2155.5	28.00	1857.85	14.1	906.31
Median particle size (μm)			680.34		928.36		1114.02		1550.49
Reduction ratio			$\frac{3000}{680.34}$ = 4.41		$\frac{3000}{928.36}$ = 3.23		$\frac{3000}{1114.02}$ = 2.69		$\frac{3000}{1550.49}$ = 1.93

Table (A.3) Mean particle size analyses of the ground Limestone – quartz mixture at different percentages of quartz.

article size (μm)	Mean particle size D	20% quartz		40% quartz		60% quartz		80% quartz	
		wt.% ret.	wt.% ret $\times D$	wt.% ret.	wt.% ret $\times D$	wt.% ret.	wt.% ret $\times D$	wt.% ret.	wt.% ret $\times D$
-	3575	2.86	10224.5	4.79	17124.25	7.73	27634.8	5.95	21271.3
4000+3150	2825	11.90	33617.5	17.02	48081.5	18.44	52093	24.16	68252
-	2250	6.19	13927.5	11.17	25132.5	10.73	24142.5	15.62	35145
3150+2500	1800	3.33	5994	6.65	11970	5.58	10044	7.06	12708
-	1300	10.47	13611	10.10	13130	9.87	12831	11.15	14495
2500+2000	815	9.99	8141.85	7.98	6503.7	8.15	6642.3	8.18	6666.7
-	515	6.19	3187.85	5.06	2605.9	5.58	2873.7	6.32	3254.8
2000+1600	357.5	2.38	850.85	1.86	664.95	2.58	922.35	2.61	933.1
-	257.5	6.18	1591.35	5.59	1439.43	6.43	1655.73	6.68	1720.1
1600+1000									
-1000+630									
-630+400									
-400+315									
-315+200									
Σ		59.49	91146.4	70.22	126652.23	75.09	138838.98	87.73	164446
-200+160	180	2.63	473.4	2.69	484.2	2.60	468	1.49	268.2
-160+125	142.5	2.50	356.25	1.95	277.9	2.15	306.4	1.26	179.6
-125+100	112.5	2.10	236.25	1.71	192.4	1.47	165.4	0.93	104.6
-100+71	85.5	4.34	371.07	3.42	292.4	2.89	247.1	1.71	146.21
-71+63	67	3.68	246.56	1.47	98.50	1.64	109.9	0.71	47.6
-63+0.0	31.5	25.26	795.69	18.54	584.01	14.16	446	6.17	194.4
Σ		40.51	2479.22	29.78	1929.41	24.91	1742.8	12.27	940.6
Median particle size (μm)			936.26		1285.82		1405.82		1653.87
Reduction ratio			$\frac{3000}{936.26}$ = 3.2		$\frac{3000}{1285.82}$ =		$\frac{3000}{1405.82}$ =		$\frac{3000}{1653.87}$ = 1.81
					2.33		2.13		

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