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Investigation of ball mill optimization based on kinetic model and separator separation particle size

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Abstract: A key attribute of an industrial ball mill is its output capacity, quantified in tons per hour. The production capacity depends on the size of the mill, whether it is an overflow or grate discharge type, how fast it spins, how much material is loaded, the size of the final product compared to the starting material, the material's work index, the power of the mill shaft, and the specific gravity of the material. The details are carefully examined, and a practical relationship is suggested, showing how the mill's capacity depends on the mill shaft power and the energy used in grinding. The mining industry aims to enhance energy efficiency in fine-size releases. In this setting, the significance of research on dry ball mills is progressively escalating. Furthermore, with grinding diameters under 45 microns, mill efficiency significantly diminishes, leading to a considerable increase in energy consumption that renders grinding economically impractical. Therefore, it is essential to execute efficient optimizations. In the study, researchers looked at how fast particles break by measuring their sizes from samples collected every meter during mill shutdowns to improve the process. The research presented a novel methodology for optimization investigations. Furthermore, the particle sizes of the separator overflow were compared to pre- and post-optimization, with the optimization assessed in an alternative dimension. Consequently, it was determined that optimization efficiency could be assessed using the kinetic model technique during the experiments.

***Keywords*:** grinding, ball mill optimization, separator performance

1. Introduction

The optimal approach to comprehending the cement sector is to examine the substantial correlation between consumption data and the degree of economic growth, since cement is mostly used in contemporary infrastructure and building. Consequently, the cement sector has expanded alongside emerging economies. In 1950, worldwide cement output was around 200 million tons; however, the average production over the last decade has reached 4.1 billion tons (Energy Technology Network, 2010). The cement business is evidently energy-intensive, with specific energy consumption ranging from 90 to 120 kWh per ton of output. The cement sector consumes around 2% of worldwide electrical energy, with electricity comprising 30 to 40% of cement manufacturing costs. While electricity is used during all phases of the manufacturing process, 67% of the total electrical energy is spent on crushing and grinding processes. Once again, 38% of the total is used only by finished product (cement) grinding activities. Cement grinding procedures have been systematically analyzed and refined, with diverse designs used to augment process efficiency (Schneider, 2008).

The finish grinding process is the most energy-intensive activity in cement production. Nonetheless, hardly 2–20% of the energy provided is used for size reduction inside the grinding machine. A significant portion is dissipated as friction, sound, heat, vibration, and other inefficiencies during mechanical transfers (Duda, 1985). Consequently, optimizing grinding is an ongoing need to get more efficiency from the system. Various grinding technologies have been developed and used to enhance

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the process. Alongside the long-established closed-circuit, two-compartment ball mills, combination grinding systems with closed-circuit high-pressure grinding rollers and subsequent closed-circuit ball mills have been used for over two decades. The objective of this advancement and the use of various grinding methods is to attain greater efficiencies and reduce energy consumption.

Moreover, in addition to energy consumption, the quality of the cement produced is strongly correlated with the grinding method used. The grinding process must not only achieve the requisite specific surface area but also produce a particle size distribution conducive to attaining the specified performance characteristics of the cement. The 3 to 30µm size fraction is crucial for the strength development of cement. Particles below 3µm size are only effective at beginning intensities, whereas hydration is gradual and less impactful on strength over 60µm size (Duda, 1985; Altun, 2013). Consequently, the efficacy of classifiers in the grinding circuit is significant since they affect the distribution of product size.

The ball mill-air classifier combination, which has a history of 100 years, still has an important place in the cement grinding process. Today, closed-circuit ball mills are operated inefficiently for many reasons. Discussing the reasons and producing solutions for these inefficiently operated systems also reduces the amount of energy spent on this process in the world (Mejeoumov, 2007; Ghiasvand et al., 2014).

In a typical circuit consisting of a ball mill and classifier, there are many design and operating variables that affect the performance of the circuit, such as equipment dimensions, ball load and size, classifier variables, the hardness of the material, and particle size distribution. Obtaining the desired particle size product with minimum specific energy consumption in the circuit depends on the correct equipment selection and operating the circuit under optimum operating conditions. The ball mill selection is made using laboratory or pilot-scale test results (Tiggesbäumker and Müller, 1983; Hosten et al., 2012; Benzer, 2001-a).

With the development of mathematical modeling and simulation techniques, significant progress has been made, especially in the optimization of grinding circuits. Although the use of models in the design field is less, Herbst and Fuerstenau (1980), Austin et al. (1982), Kavetsky and Whiten (1984), Morrell and Man (1997) are some researchers who have proposed approaches in this regard. All of the methods include laboratory or pilot-scale test data, a ball mill model based on the equivalence of the amount of material in each size fraction, and different scale-up processes. Since the methods based on modeling and simulation consider the circuit as a whole, the interaction between other equipment and the ball mill can be determined, and therefore the effect of any changes to the design and operating variables on flow tonnages and grain size distributions can be calculated (Özer, et. al., 2006; Schnatz, 2000).

This study aimed to assess how efficiently the mill works at the plant level based on the 2015 investment in the pre-crusher system and the results of optimizing the mill using a kinetic model and changes in the product from the separator. Because the size of the grains fed to the mill was reduced, the needed intermediate partition diaphragm was taken out and changed to a single-chamber system. Following this change, the ball load was adjusted.

In the first part of the studies done at the facility, the mill's design settings stayed the same before optimization, the grinding performance was assessed using the kinetic model, and a detailed review of the current grinding system was done, paying special attention to how effectively the separator worked. After the mill was optimized, similar reviews were done again. The data collected in both cases were compared, and the benefits of model-based optimization were revealed.

2. Materials and methods

2.1. Materials

The sample used in this study obtained from the Traçim Cement Industry and Trade Inc. cement grinding facility in Vize (Kırklareli), as illustrated in Fig. 1. For chemical analysis, a Panalytical brand Zetium model XRF device was used in the factory. The chemical analysis for the sample fed to the mill within the scope of the study is given in Table 1. Chemical analysis is presented to provide information about what kind of material is ground in the mill. Necessary analyses were conducted on the particles using the Malvern brand (Mastersizer 3000) particle size analyzer, with the average results calculated and presented in Fig. 2, Fig. 4, Fig. 5 and Fig. 7.

The efficacy of ball mills directly influences the expenses related to mineral processing. Grinding medium profoundly impacts the efficiency of a ball mill by directly influencing the breakage rate, mill load dynamics, power consumption, and total energy expenditure. The parameters substantially affect the energy consumption of tumbling mills and the total operating expenses. As a result, finding the best ball characteristics (size, density, shape, microstructure, and hardness) and operating parameters (mill speed, pulp density, and media filling) makes the mill work better. The grinding medium affects power consumption in ball mills, breakage characteristics, and the particle size distribution (PSD) of the output. Therefore, they must have the greatest surface area and have considerable weight (Umucu et al., 2015; Benzer et al., 2001-b; Genç, 2008;2016).

Table 1. Average chemical results of the samples used in the cement plant

Compound	SO_3	CaO	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	Cl	Cr^{+6} (ppm)	LOI	Total
Content (%)	3.57	1.39	19.73	4.85	3.34	63.98	1.60	0.64	0.92	-	1.40	2.47	100.00

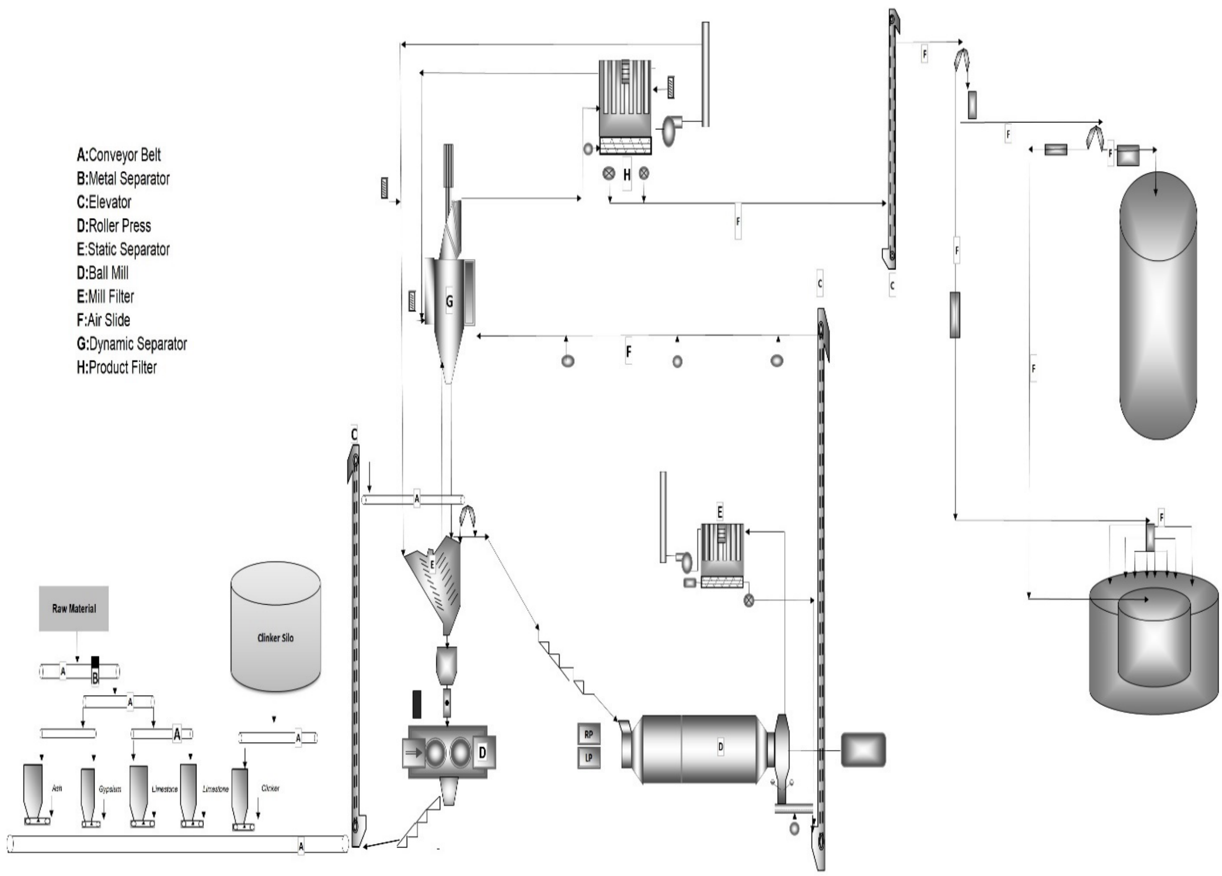

Fig. 1. Cement grinding plants of Traçim Cement Industry and Trade Inc.

The grinding phase is crucial in cement factories. Any change during the grinding process causes major differences in the entire factory and cement quality.

In this study, the optimization process in the cement grinding unit, the biggest cause of change, was examined. Instead of using a normal optimization study, a specific method for figuring out the fracture speed was used. It was based on the kinetic model of the mill and how the cement behaved while it was being ground as seen in Fig. 1. However, the fact that each unit in the system has a very serious effect on the others serves the purpose of the study.

2.2. Methods

Measuring the performance of grinding circuits and monitoring the performance of equipment in the circuit are important factors that increase operational performance. For reasons such as timely detection of sudden performance changes in the circuit and timely intervention, and to assist in preventive maintenance, circuit performance must be monitored at certain intervals.

There are various factors affecting ball mill grinding systems in the cement industry (Gouda, 1981; Benzer, 2000). It is understood that mill and classifier operation, design variables, and material properties are effective on circuit performance.

The most important operational parameter affecting efficiency for ball mills is the grinding media size, and the empirical approach still used for determining this size was developed by F.C. Bond (Bond, 1960). Using this approach, the maximum ball size to be used in the mill can be successfully determined. In the studies conducted, it was determined that fine balls should be used for fine grinding and coarse balls for coarse grinding (Austin et al., 1984). However, there is no proven approach for determining the ball size distribution in the mill. Many researchers (Austin et al., 1975; 1984; Zhang, 1988; 1992; Benzer, 2000; 2001-a/b; Slanewski, 1985; Viswanathan, 1988; Ozer, 2006) have studied how to use mathematical models to improve and simulate cement mills using the population balance model (PBM). However, today there is extensive research on the parameters of grinding models and the analysis of how dry grinding circuits operate, including functions for breakage and discharge rates based on scaled industrial data. In the study, measurements were made with the kinetic model developed by Austin as a result of any parameter changes made related to the mill. The measurements are the first study made on an industrial scale.

The most effective method to free the determination of ball size distribution from theoretical approach and to determine the most suitable ball distribution for changing conditions is to determine the breakage velocities for different ball size distributions. For this purpose, particle size analyses of samples taken from the circuit and inside the mill were performed and used in breakage rate and separator efficiency analyses. A roller press unit was built in the facility's cement mill in 2015. After this phase, the intermediate component of the chamber mill was severed and transformed into a conventional ball mill. The parameters and design data used in the mill design are shown in Tables 2, 3, and 4.

Recently, researchers were focused on assessing size reduction in ball mills by using concepts of specific breakage rates and primary daughter fragment distributions. Austin and colleagues evaluated the advantages of this method and showed that laboratory results may be extrapolated to industrial mills in many studies (Austin et al., 1981; 1984).

Following the integration of a roller press into the grinding unit, the maximum ball size in the distribution was determined as 30 mm. Table 4 indicates that the ball size distribution in grinding was designated as coarse.

Table 2. Mill Information before revision

Ball Mill (m)		Mill Feed		
Diameter	4.25	Fresh Feed	145	t/h
Length	14.53	Return	250	t/h
		Circulating Load	272	%

Table 3. Mill design parameters

EF1	EF2	EF3	EF4	EF5	EF6	EF7	EF8	$\prod$EF	W_i	P_{80}	F_{80}
1.3	1	0.914	1	1.23	-	1.04	1	1.52	16	20	98
Tonnage (kWh/t) 180			3609					kWh/t			
			4840					HP			

Dry grinding coefficient, EF1	Open circuit grinding coefficient, EF2	Mill diameter coefficient, EF3
Coarse size coefficient, EF4	Fine size coefficient, EF5	Ball mill reduction coefficient EF7
Bond Work Index, Wi	Particle size at which 80% of the product passes, P80	Particle size at which 80% of the feed passes, F80

Table 4. Ball load distributions before revision

Ball Size (mm)	Amount (t/m^3)	
30	35.57	t
25	53.02	t
20	69.10	t
17	76.72	t
Total	236.41	t
Volume	206.02	m^3

In analyzing the fragmentation materials, it is advantageous to assume that the fragmentation of each size fraction follows a first-order process. The rate of size 1 material loss from breakage is directly related to the amount of size 1 material in the mill's storage bins (Austin and Luckie, 1971).

$$-\frac{d[w_1(t)W]}{dt} \infty w_1(t) \tag{1}$$

Given that the mill holds up, W, is constant, this simplifies to:

$$dw_i = \frac{(t)}{dt} = -S_1 w_1(t) \tag{2}$$

S_1, being the proportionality constant, is designated as the specific rate of breaking, measured in units of time^{-1}. Austin and Bhatia (1972) assert that S_1 maintains its constant value over time.

$$w_1(t) = w_1(0)\, exp(-S_1 t) \tag{3}$$

that is,

$$log[w_1(t)] = log[w_1(0)] - \frac{S_1 t}{2.3} \tag{4}$$

The weight fraction of size 1 mill retained at time t is represented by w1(t) (Austin and Bagga, 1981). Austin et al. proposed a formula that describes the relationship between particle size and the specific rate of breakage. Si is,

$$S_i = a_T \left(\frac{X_i}{X_0}\right)^{\alpha} Q \tag{5}$$

where Xi represents the upper limit of the size interval indexed by i, X_0 is defined as 1 mm, and a_T and a are parameters of the model that depend on the characteristics of the material and the conditions of grinding.

3. Results and discussion

Prior to the mill revision, the samples were collected from the mill by executing abrupt halts. The samples were collected from the grinding circuit to assess grinding efficiency and separator performance, followed by their analyses as illustrated in Figs. 2, 3 and 4.

Given the significance of the number of the sample points in the mill, the samples were collected independently from each meter, with three distinct points sampled from each meter to monitor variations in particle size reduction. The particle size distribution of the samples was assessed using the Malvern-Mastersizer particle size measurement device, with the results presented in Fig. 2. Then, curves indicating the particle size analysis relationship depending on distance were obtained. Also, these curves can be regarded as the primary fracture curves for each particle size of the material. The slopes of these curves are defined as primary breakage velocities. A specific breakage curve is obtained from the primary fracture curves. In this context, these calculations were made for the mill before and after the revision (Figs. 2,3,5,6).

Materials transported by air from the mill are given to either the silo product or the separator feed in applications. When these materials are sent to the product silo, the distribution taken from the separator top stream is usually compared with the grain size. The most appropriate test to control this is to determine the separator efficiency. In this way, both grinding efficiency and product grain size distribution can be made.

Upon attaining the mill balancing condition, two samples were collected from each shift for the measurement of classification performance. The separator's performance illustrates the effects of modifications in the mill design. The separation particle size of the separator was ascertained to be 20.7µm size, while the target oversize fraction of the 32µm size in the product was 3.4%. Fig. 4 illustrates that the By-Pass ratio is 19.93%, whereas the Fishhook value is around 10%.

The mill's grinding performance was examined by taking samples from each meter. As a result of the obtained samples, the grinding medium design values (Tables 5, 7) and quantity (Table 6) were recalculated.

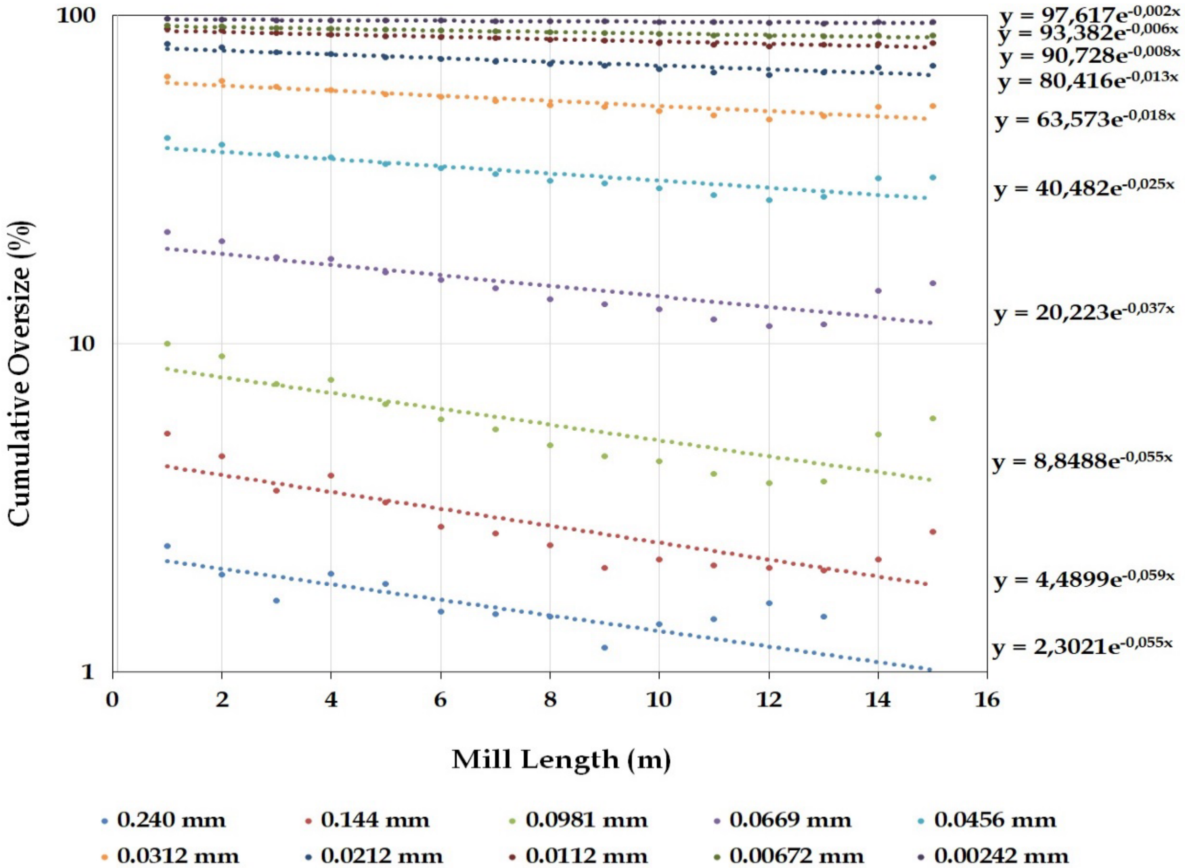

Fig. 2. Change in particle size distribution in the mill before the revision

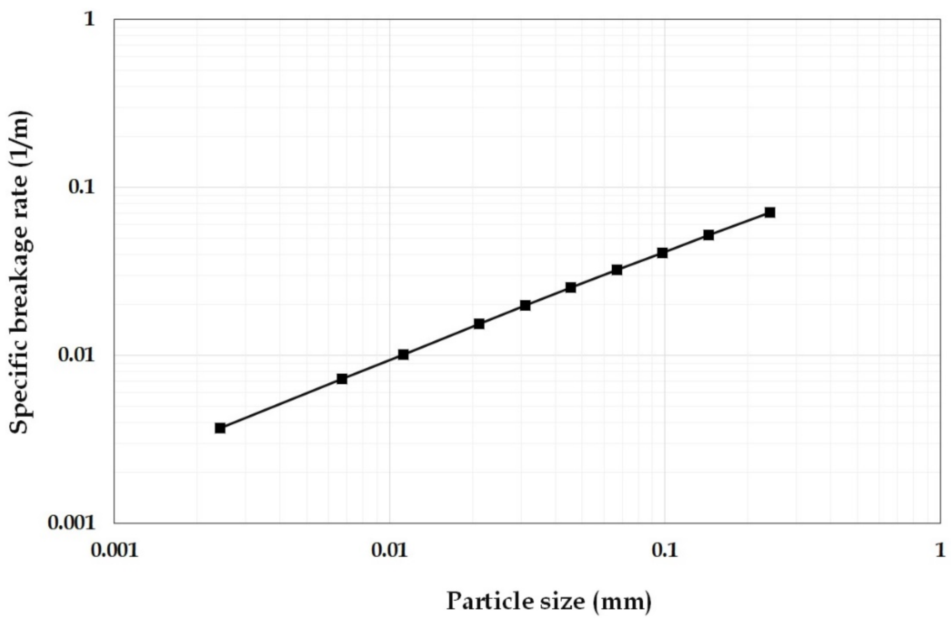

Fig. 3. Specific breakage rate in the mill before the revision

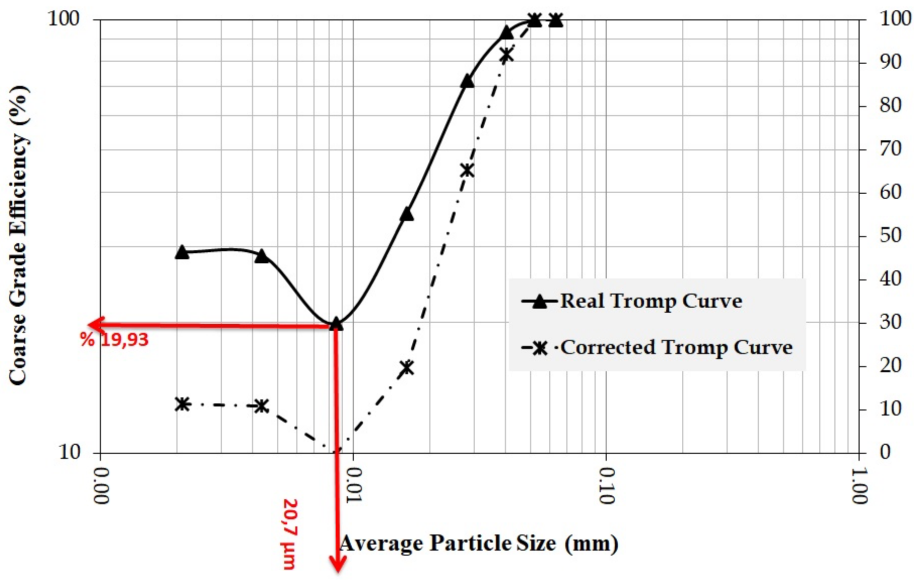

Fig. 4. Trump curves before revision

Table 5. Mill information after revision

Ball Mill (m)		Mill Feed		
Diameter	4.25	Fresh Feed	144	t/h
Length	14.53	Return	250	t/h
		Circulating Load	274	%

Table 6. New Ball Size Estimation

K	F	W_i	S_g	C_s	D
335	666	16	3.15	75.61	4.25
Ball Size			20.21 mm		

K; Dry grinding coefficient / F; Maximum particle size fed (µm size) / Wi; Bond Work Index (kWh/t); S_g; Specific gravity (g/cm^3) / C_s; Critical speed (rev/min) / D (m)

Table 7. New ball charge after revision

Ball Size (mm)	Amount (t)
30	0.00
25	62.52
20	72.41
17	85.76
Total	220.69

Primary breakage velocity graphs are presented in Fig. 5, created with data from grain size analysis performed on samples taken from each meter inside the mill. Then, the first order breakage graph was created, and model parameters are given in Table 8.

Fig. 7 illustrates an improvement in separator efficiency after the adjustment. The particle size (d50) of the revised separation remained unchanged. While Fig. 7 indicates that the By-Pass ratio is 14.56%, the Fishhook value is roughly 8%.

According to the data presented in Table 8, the model parameter values for the various optimizations deviate from those reported in the literature before and after revision.

The best indicator of the optimization result is given in Table 9. Table 9 shows how much the change in the produced grain size depending on the production capacity affects the consumed specific energy (kWh/t). Again, the effect of the optimization is understood by looking at the change in energy consumption.

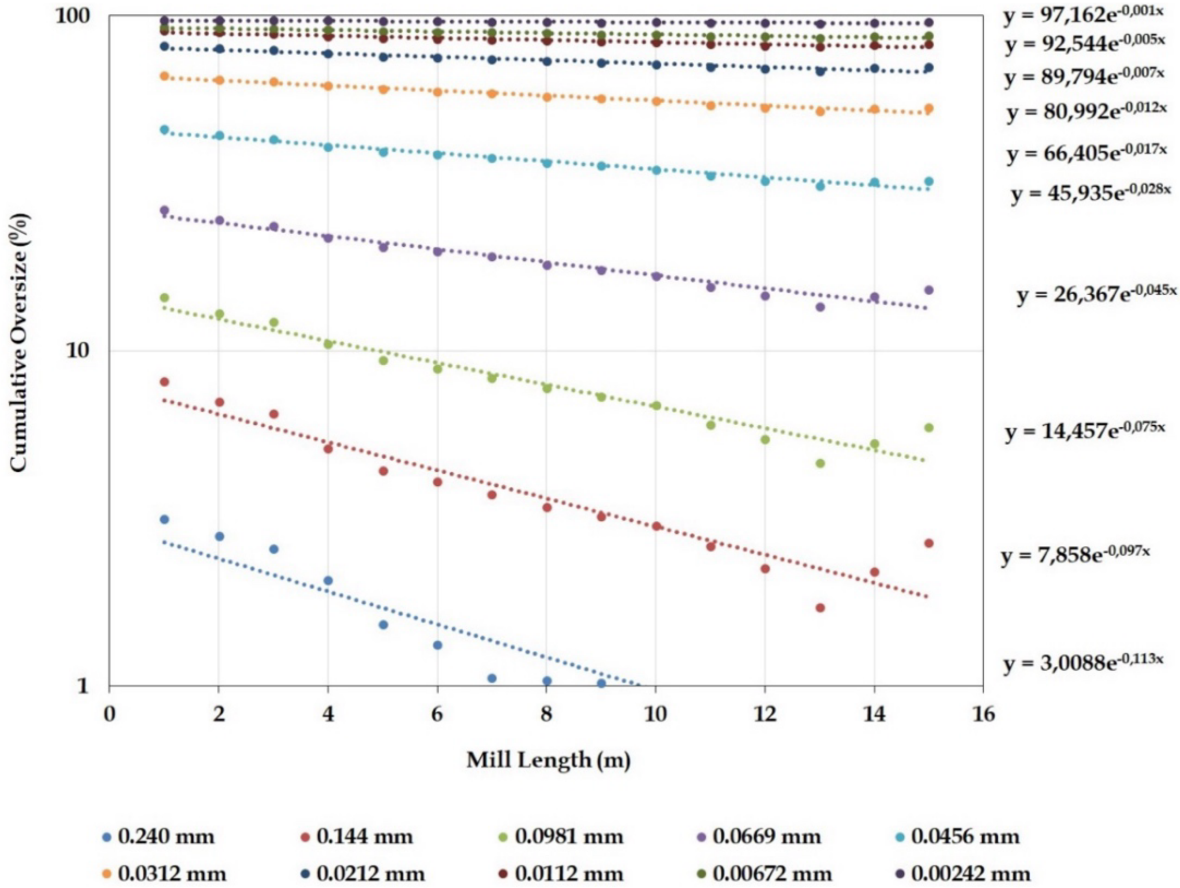

Fig. 5. Change in sieve size distribution in the mill after the revision

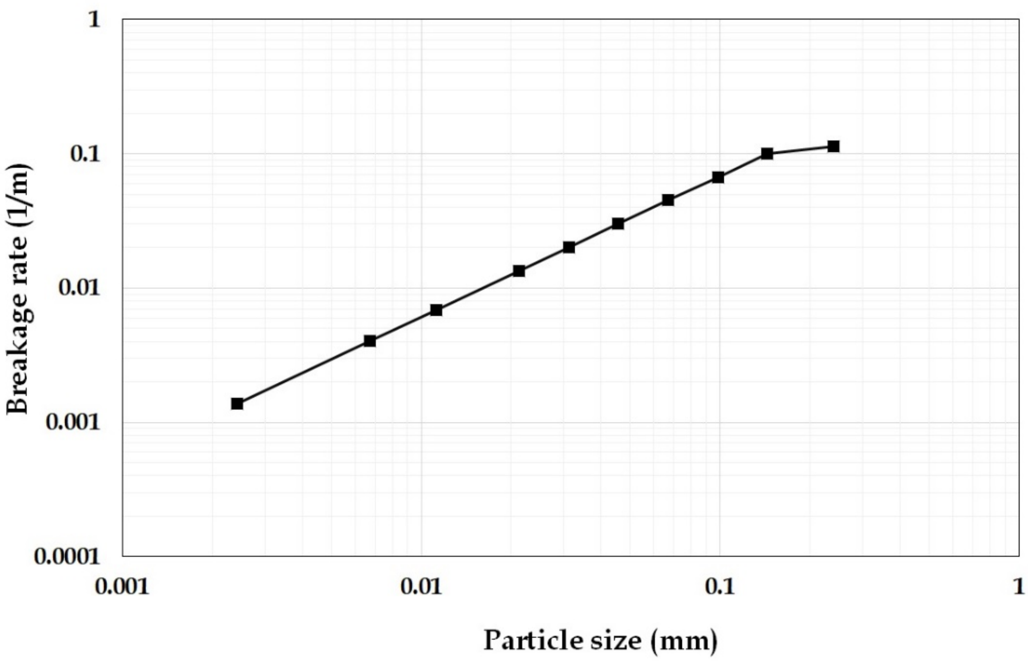

Fig. 6. Specific breakage rate in the mill after the revision

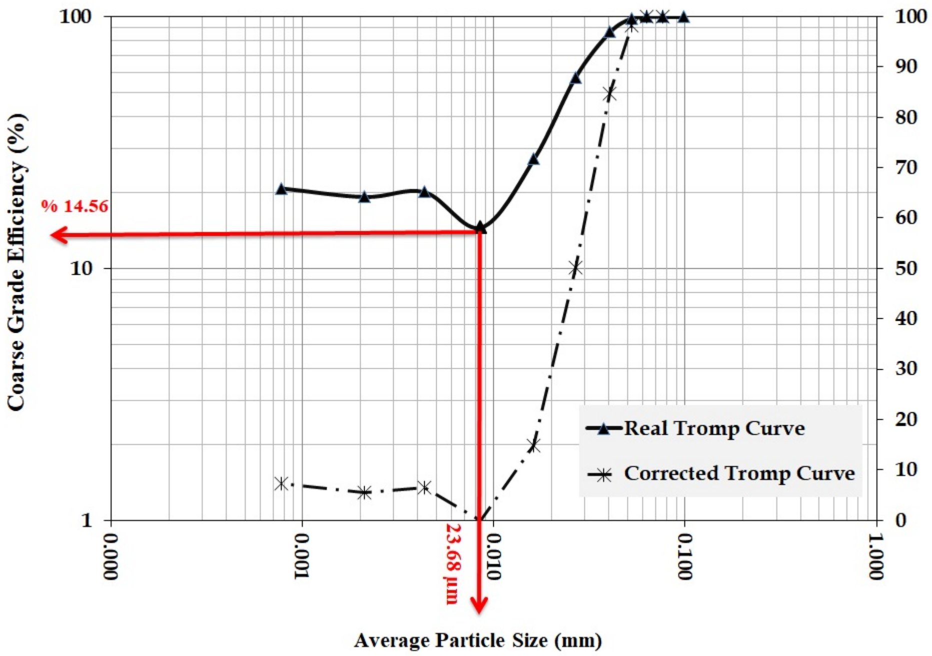

Fig. 7. Trump curves after revision

Table 8. Specific breakage rate parameters in the mill before and after the revision

Revision time	Kinetic model parameters			
	a_T	α	μ	Λ
Before	0.22	0.67	6.31	0.54
After	0.40	1.06	0.21	2.49

Table 9. Product data across the years

Years	Product (tons/year)	Working hours (h)	Tonnage (t/h)	Energy (kW/year)	Specific energy (kWh/t)	∑Over size (32µm size)	Blaine (g/cm²)	Limestone (%)
2022	1.785.314	12.230	146	75.606.266	40,09	3,40	4117	3,70
2023	1.970.642	13.610	145	71.566.742	38,37	3,10	4106	4,70

4. Conclusions

According to the results, the mill is capable of handling materials no larger than 0.67 mm under the current operating system. The 30 mm balls occupy excessive space in the mill, while the smaller fraction balls deform too quickly, leading to an increased trash ball ratio under these circumstances.

For optimal efficiency, the results indicate that a maximum ball size of 20.21 mm is required. The fineness curves show that the 30 mm ball takes up extra room in the mill. The main drive motor is overloaded due to excessive charge, according to the calculations. Thus, it is verified that the mill's ball filling rates correspond to the previous records.

A new ball charge of 220.69 tons with a maximum ball diameter of 25 mm was established for the mill because of the investigation. There has been no change in the mill capacity despite a decrease in performance from last year's 32µm size. As the separation size reached 23.68µm size, an analysis of the separator's efficiency showed that product loss from the mill decreased.

There is now less unnecessary strain on the main drive motor thanks to the mill. There was a 1.72 point drop in specific energy (kWh/t) usage, although the mill capacity remained the same (Table 9). One of the most important points in Table 9 is that the mill's working hours are higher than before the revision, while the energy consumed by the mill is lower. According to the data obtained, it has been determined that the optimization study was carried out with a correct approach.

The model parameters from the breaking speeds of the particles in the mill where the measurements were made show that the a_T value was 0.22 before the revision and 0.40 afterward. The breaking speed increased due to the reduction of the largest ball diameter in the mill and the decrease in the gaps between the balls, as well as the high ball-particle interaction. As a result, there was an increase in the amount of material ground per unit time. A similar situation was seen in other parameters.

When Table 8 is examined, it was established that the revision resulted in quicker grinding. It was observed that both the breakage rate and the breakage rates of the larger sieve sizes decreased as sieve sizes became finer. This scenario is caused by the removal of large balls and the increase in the number of fine balls after revision. The breakage rates of each grain size after revision were found to be close to each other.

In this study, the success of the optimization of a mill used in cement production was measured with an industrial-scale kinetic model. This study revealed that the kinetic model approach used in laboratory-scale mill designs can also be used to measure the grinding success of an industrial-scale ball mill.

The results obtained show that ball sizes with different distributions give different breakage velocities in the mill. It is shown in the studies that there is a relationship between ball size distribution and breakage velocity change. Simulation studies using the obtained data will contribute to determining the appropriate ball size distribution based on the distribution of feed grain sizes.

Optimizing cement grinding systems is also essential for reducing energy consumption, enhancing product quality, and ensuring sustainable production practices. By adopting modern technologies and refining existing processes, manufacturers can significantly improve efficiency, reduce operational costs, and contribute positively to environmental conservation.

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