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Auditing approach at the finish mill to reduce energy consumption in cement production in Indonesia

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OBJECTIVES Cement plants are substantial consumers of both thermal and electrical energy, with these energy expenditures accounting for over 40% of the overall production cost. A pivotal factor in this energy-intensive process is the clinker finish mill, a cornerstone of the cement industry. This study, therefore, centered its focus on a detailed examination of the performance of a tube-type finish mill equipped with two chambers and steel balls as the grinding medium. METHODS The methodology employed in this investigation included a comprehensive longitudinal test involving a series of meticulous steps to gauge and optimize the mill's performance. These steps encompassed steel ball sampling, the measurement of material levels within the mill, filling degree assessment, and sampling at one-meter intervals along the mill, with each sample weighing approximately 1 to 2 kilograms. This meticulous approach involved sampling during a period when the mill was operating steadily for at least 8 hours before a controlled shutdown, known as a "crash stop." The subsequent evaluation of the tube mill's performance extended to both its operation during the steady run and the crash stop. RESULTS The findings stemming from this thorough audit are nothing short of remarkable. It is clear that the systematic evaluation conducted in this study led to a substantial enhancement in the production capacity of the finish mill, boasting an impressive 13.24% increase. Furthermore, the study also recorded a significant reduction in specific power consumption, effectively decreasing it by 3%. CONCLUSIONS These outcomes not only underscore the vital importance of regular audits in cement grinding operations but also demonstrate the tangible benefits in terms of both increased production capacity and improved energy efficiency. Such improvements are not only pivotal for cost reduction but also contribute to the sustainability and competitiveness of cement production in an increasingly energy-conscious and cost-competitive industrial landscape.

KEYWORDS ball mill; blaine; green technology; longitudinal test; steel ball

1. INTRODUCTION

Energy is observed to be one of the major producers of greenhouse gas (GHG) emissions, which is a key contributor to global warming and climate change (Li et al. 2022; Nasim and Nasim 2023). The industry was responsible for 28.3% of worldwide energy and 38.5% of CO_2 emissions (Huang et al. 2016; Rahman and Maulana 2023). This is due to the fact that a typical well-equipped plant requires approximately 4 GJ of energy to produce 1 ton of cement, and approximately 3.6 billion tons are normally produced per year throughout the world (Cantini et al. 2021; Atmaca 2023; Tian 2023). Moreover, there is a continuous increase in the need for cement in Indonesia every year due to the developmental growth of the country (Rahman and Rahayu 2021). This situation has triggered players in the cement industry to increase production to achieve the actual capacity, while new factories are also being constructed. The trend shows the need to implement efforts towards increasing energy efficiency even though cement products need to meet ASTM C 109 and Indonesian national requirements SNI 15-7064-2014 for quality (Madlool et al. 2011; Ghalandari and Iranmanesh 2020; Huang et al. 2016).

The finish mill is one of the central units in cement production production (Duda 1985; Pareek and Sankhla 2021). The unit is normally fed with clinker material from the kiln and several corrective materials such as limestone, trass, blast furnace slag, and gypsum as retarders (Santos et al. 2022). The fineness of the output material from the finish mill is a crucial parameter due to its ability to determine the compressive strength of concrete during application (Virendra et al. 2015; Kim and Shin 2023). Unfortunately, approximately 39% of energy is normally used in this finishing process, and this means it is necessary to ensure plants operate

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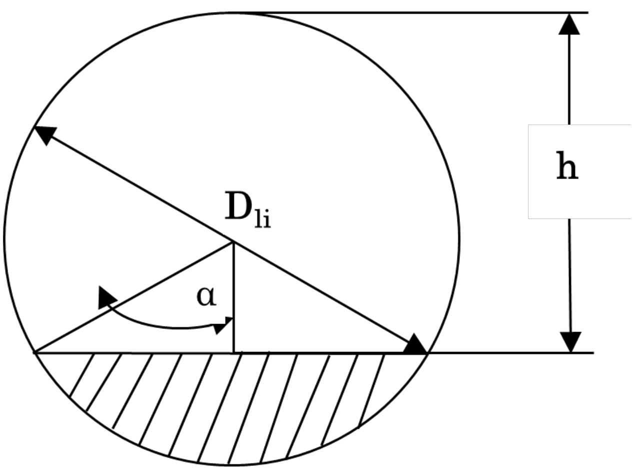


FIGURE 1. The filling degree configuration.

at high efficiency for a certain period during the operation. It is undeniable that mill performance usually decreases over time due to changes in feed materials and machine life (Nomura 2022).

The decline in finish mill performance can generally be indicated by several factors, such as the grinding process requiring a longer time, the number of tailings being more extraordinary, and the production of a lesser number of total products (Pareek and Sankhla 2021). Most previous studies have focused on the technical aspect of this performance, but this study emphasizes the possibility of energy conservation measures in audit management (Madlool et al. 2011). The intention is to predict mill performance by calculating the decrease in performance when there is a change in feed conditions (K Sharma and Khurana 2020). The process involves using the longitudinal test as the audit method with the fine material and steel ball samples applied based on two conditions, including when the mill is working and when it suddenly stops or crashes after being operated for at least 8 hours in a stable condition (Alsop 2007).

Therefore, this study aims to observe the performance of a tube-type finish mill made of steel cylinders with several parts, such as steel balls, liners, and diaphragms. The process involves producing Portland Composite Cement (PCC) and Premix Limestone Cement (PLC), which are two types of cement with different corrective materials. PCC-type cement uses trass, while PLC-type cement uses limestone (Rahman and Mulyani 2023). Moreover, the central part, which is a steel ball applied to smoothen the materials, can erode over time due to friction with hard corrective materials such as slag and limestone (Yin et al. 2019). Steel balls can also experience erosion due to rubbing by rubbing against each other, the liner, and the diaphragm (Pareek and Sankhla 2021; Bartholomew et al. 2018; Rodriguez and Tobon 2020). The audit results can be used as material to monitor and evaluate the production process in order to prevent higher operational costs (Virendra et al. 2015), especially to improve the performance of non-optimal grinding systems. This method is very useful as a reference for similar companies to change or modify the efficiency of milling as well as analyze system weaknesses.

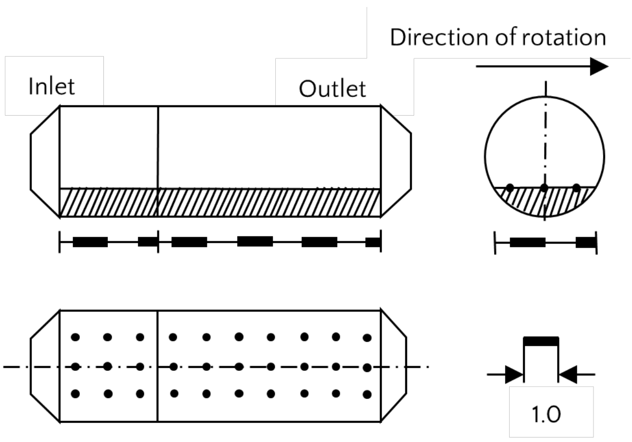


FIGURE 2. Layout for meter sampling.

2. MATERIALS AND METHODS

Some of the tools used in this study include shovels, cement spoons, buckets, laser distance meters, labeled plastic bags, sieves, and cameras. Moreover, the performance of the tube mill was investigated using a method similar to the one presented by (Nomura. 2020), which focused on saving energy during the evaluation.

2.1 Sampling of fine materials

The first sample was obtained after the mill operated for at least 8 hours non-stop under stable conditions. Another sample was also taken when the mill stopped suddenly (crash stop). The process involved the patroller opening the head-wall after turning off the draft dust collector or bag filter. The samples were retrieved every one meter along the mill using a shovel at a depth of 10–20 cm below the surface of the steel ball after the temperature was low enough. The first-meter point was measured from a distance of 0.5 m from the mill inlet for chamber 1 and a distance of 0.5 m from the intermediate diaphragm for chamber 2. Each meter sample was taken at 3 points, which were the midpoint, 1 m to the right, and 1 m to the left.

2.2 Sampling of steel ball procedure

Steel balls were also sampled using the same procedure applied to the fine materials. A half bucket of steel balls was taken with the same volume per meter, and those sampled were combined with the materials.

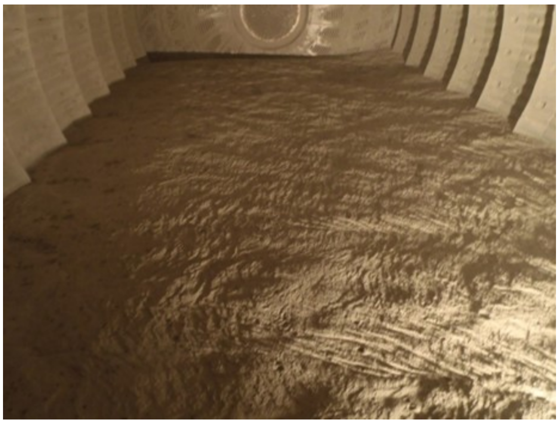
The average steel ball diameter, the number of balls, and the total weight of the ball samples were required to be calculated to evaluate the condition of the ball charge and check the classifying effect on the liner (Nomura 2020). The ball was weighed using an analytical balance at 2 decimal places, while the average steel ball diameter at the sampling point was calculated using the formula (1). Where $\rho = 7.85\, T/m^3$; W = weight of samplel n_b = number of steel balls.

$$D_m = 2\left[\frac{W}{n_b}\frac{1}{\rho}\frac{1}{3/4\pi}\right]^{1/3} \quad (1)$$

2.3 Filling degree measurement procedure

The filling degree was determined using the free height (Dli) from the surface of the ball charge and measured at the inlet, middle, and outlet positions in each chamber. Each po-

(a)



(b)

FIGURE 3. (a) a.Material level in Chamber 1, and (b) Material level in Chamber 2.

sition was measured similarly to observe the level variations as shown in Figure 1. The situation when the material layer was higher than the ball charge required that the steel ball be uncovered before measuring the free height (Dli). The filling degree and volume percentage were calculated using the formulas (2) and (3).

$$f = \frac{\alpha}{180^0}\frac{\sin\alpha\cos\alpha}{\pi},$$

$$with\cos\alpha = 2\frac{h}{D_{li}} - 1 \tag{2}$$

$$vol.(\%) = \frac{\frac{2\pi}{360}\,\alpha\,r^2 - r\sin\alpha\,(h-r)}{\pi\,r^2} \tag{3}$$

3. RESULTS AND DISCUSSION

Several parameters were measured to analyze mill performance, and these include the residue for each particle size along the mill at each meter, residue and blaine, material level, filling degree, mill inspection, and steel ball condition. Furthermore, longitudinal tests were conducted on a tube mill-type finish mill unit, and the data contained in the handbook were used for comparison (Duda 1985). Each meter sample was taken at 3 points, which were the midpoint, 1 m to the right, and 1 m to the left, as shown in Figure 2, later placed into a plastic bag, and labeled according to the sampling point.

3.1 Residue and blaine

The longitudinal test results presented in Table 1 show an increase in the percentage of residue in the 7th and 9th meters for all mesh sizes in chamber 2. This was due to the lesser number of steel balls with a diameter of 80 mm and 90 mm in chamber 1, which limited the optimal crushing process in the chamber. There was also a gap between the plates in the diaphragm intermediate, which allowed the coarse material in chamber 1 to pass into chamber 2. The occurrence of the phenomenon at meter 15 led to an increase in the percentage of residue due to the failure to pass through the diaphragm outlet slot with a size of 8 ± 1 mm.

Table 1 shows that blaine from meter to meter increased, except for the 15th meter, which decreased slightly. This problem was probably caused by the escape of coarse material from chamber 1 to chamber 2 through the gap in the diaphragm intermediate. The coarse material was stuck at the 15th meter and was unable to be refined. Consequently, Blaine at the 15th meter achieved less than the maximum, which was only 2350 gr/cm^2 from the supposed 2800 gr/cm^2.

3.2 Filling degree

The filling degree results for the two chambers of the tube mill were required to meet the specifications according to SNI 15-7064-2014. Based on that standard, chamber 1 was expected to have a filling degree capacity of 28%, while cham-

(a)

(b)

FIGURE 4. Steel ball samples for each chamber of tube mill (a) Chamber 1, and (b) Chamber 2.

TABLE 1. The percentage of residue at each sampling point from 1st to 15th meter.

	Sampling Point	Blaine (cm^2/gr)	Residue (%)					
			20 μm	35 μm	45 μm	65 μm	90 μm	200 μm
Chamber 1	M-1	800	96.99	94.99	92.51	86.67	80.24	66.76
	M-2	1010	96.70	94.43	92.14	87.10	81.55	67.64
	M-3	1210	94.76	91.86	89.10	82.98	76.02	55.77
	M-4	1350	88.61	82.40	76.83	64.95	51.92	19.79
	M-5	1380	87.61	81.39	75.90	64.01	50.73	18.88
Chamber 2	M-6	1560	83.89	76.43	70.82	59.43	46.92	16.29
	M-7	1780	84.58	77.14	71.48	60.41	48.73	18.82
	M-8	1830	81.13	72.74	66.82	55.46	43.72	16.02
	M-9	1880	81.56	73.89	68.47	57.99	47.05	19.48
	M-10	2030	77.25	68.04	61.67	49.65	37.53	11.73
	M-11	2080	72.49	61.19	53.62	39.96	27.01	4.43
	M-12	2090	71.86	60.12	52.29	38.37	25.44	3.81
	M-13	2190	70.66	58.85	51.34	38.48	26.77	6.06
	M-14	2380	65.66	52.05	43.66	29.84	18.12	1.92
	M-15	2350	69.39	56.84	48.94	35.50	23.62	4.54

ber 2 had a capacity of 30%. Table 2 shows the average free height of each chamber, which was used to calculate the filling degree. Some of the data, such as radius (r), surface height to center (b), elevation angle (a), chamber length (l), and triangle area, are shown in Table 3. However, the results showed the values of filling degree for each chamber were only 26% and 29%, respectively, as shown in Table 3. This may affect finish mill performance in terms of residence time because the material was in the mill for a longer period of time than usual.

3.3 Fine material level

In chamber 1, the material level was the same as the steel ball surface level; hence, the steel ball surface was not covered with material. This indicated good conditions for the material level. For chamber 2, the material level was also good enough, even though it covered the surface of the steel ball

TABLE 2. Average free high of chambers 1 and 2 (n = 3±SD).

Observation	Free high (a)
Chamber 1 (m)	2.926±0.003
Chamber 2 (m)	2.873±0.002

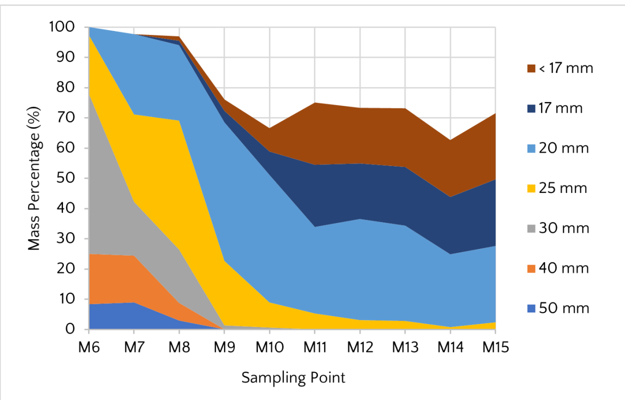


FIGURE 5. Steel ball classification from 6th to 15th meter of tube mill.

with a thickness of ±30 mm, as shown in the Figure 3.

3.4 The mill performance

he inspection of the mill showed that there were limestone blocks with a size of more than 100 mm in chamber 1. This was associated with the too-large diameter of the feed materials entering the mill, which made it impossible for steel balls with a size of 90 mm to break up the chunks. It was also linked to the insufficient filling degree in chamber 1, with only 26%. Therefore, it was recommended that steel balls with a diameter of 90 mm be added to raise the filling degree in order to ensure an optimal crushing process (Geng et al. 2016). The lack of filling degree in chamber 1 also led to the existence of materials in front of the intermediate diaphragm measuring up to 5–10 mm. The intermediate diaphragm was in poor condition due to the 15-mm gap between the plates, which was caused by continuous expansion and vibration or poor installation. The gap allowed the material to enter the diaphragm intermediate, which eventually passed into chamber 2. This could be avoided by welding the round bar to ensure there was no nip and limiting the entrance of foreign metal and cement materials (Pareek and Sankhla 2021). The inspection results further showed that chamber 1 liner was thinning due to continuous use, and this has reduced the lifetime significantly. It was recommended that the entire lifting liner be replaced in the following preventive maintenance schedule to return to the optimal milling process. Moreover, loose liners in chambers 1 and 2 should be tightened routinely.

The slot on the diaphragm outlet was observed to be 30% closed or starting to get blocked. This was associated with the inclusion of nips as well as foreign material in the form of metal and steel ball shards. Therefore, it was recommended that cleaning be regularly conducted on a preventive maintenance schedule (Paul 2019). The implementation of good slot conditions was also suggested to increase capacity and quality (Sengul et al. 2023). Observations showed that, in front of the diaphragm outlet, there was a material with a size of 5 mm at the 15th meter. This problem was associated with

TABLE 3. Calculation of filling degree in chambers 1 and 2.

Parameter	Chamber 1	Chamber 2
Radius (r)	2.11 m	2.15 m
Free high (a)	2.926 m	2.873 m
Surface height to center (b)	0.81 m	0.72 m
C	1.95 m	2.02 m
A	67.42°	70.43°
chamber length (l)	4.51 m	8.98 m
Arc area = (2 /360°) * π * r^2	5.23 m^2	5.68 m^2
Triangle area	1.58 m^2	1.46 m^2
Width of the section (steel ball) = L. arc - L.Δ	3.65 m^2	4.22 m^2
Steel ball volume = L. section * chamber length	16.46 m^3	37.89 m^3
Mill Volume = $\pi r^2 l$	63.05 m^3	130.34 m^3
Filling degree = steel ball vol./mill vol.	26.10 %	29.07 %

the poor grinding efficiency in chamber 1, which led to the passage of the coarse materials into chamber 2, where they could not be refined and remained stuck.

3.5 The steel ball measurement

A half bucket of steel balls was taken with the same volume per meter, and those sampled were combined with the fine materials, as can be seen in Figure 4. The results of weighing the steel ball mass for each meter along the mill were measured. Moreover, the percentage of steel ball mass for each diameter in chamber 1 is presented in Table 4, which is both actual and design in comparison.

In chamber 1, steel ball sampling with a diameter of 90 mm was not represented because the sample taken was too small. This proved the steel ball-wearing rate was very high, as indicated by the usage of values in the range of 80 mm, which only reached 6.19%, and the diameter was 70 mm. Moreover, the subsequent diameter experienced wear and tear, and this showed that steel ball sampling with a diameter of 70 mm, 60 mm, and 50 mm reached the most dominant percentage.

Energy generated from the cataract movement under these conditions was observed not to be optimal, thereby requiring a longer time to reach the targeted blaine (Leś and Opaliński 2023). Similarly, the change in steel ball composition required understanding the new capacity (Chimwani et al. 2015). Under these conditions, an average product of 96.71 tons/hour was produced for 7 days before the test instead of 110 tons/hour, and this was considered detrimental to the company.

The average mass of steel balls was calculated to be 1.69 kg/pc, and this showed that there were insufficient steel balls with a diameter of 90 mm and 80 mm in chamber 1, thereby limiting the grinding from reaching the standard of 1.83 kg/pc (Duda 1985). The percentage of steel ball mass for each diameter in chamber 2 is presented in Table 5, which shows the actual and design in comparison.

The percentage of the actual steel ball samples in chamber 2 was found to be reducing, and this proved that the diameter of each steel ball experienced wear and tear in the same way as those in chamber 1. Therefore, 11.23% were discovered to be below 17 mm, which was not part of the design, thereby leading to an increase in power consumption. The average diameter of steel balls per meter along chamber 2 was calculated for classification purposes, and the results are presented in the Figure 5. It shows that steel balls at the finish mill target were classified as being in good condition because those with diameters of 50 mm, 40 mm, and 30 mm did not exist at the outlet of chamber 2. Similarly, those with 20 mm, 17 mm, and under 17 mm were also not found at the inlet. The phenomenon showed that 20 mm and 17 mm steel balls were the most dominant, and this was considered very useful in the refining process to achieve the specified Blaine target.

4. IMPACT OF THE AUDIT

The longitudinal test analysis showed that it needed to add some 90- and 80-mm-diameter steel balls. This led to an increase in mill performance, as presented in the following Ta-

TABLE 4. Steel ball mass percentage in chamber 1: from 1st to 5th meter of tube mill.

Sampling Point	Steel ball Chamber 1 (weight %)					
	90 mm	80 mm	70 mm	60 mm	50 mm	Total
M1	-	16.67	33.33	16.67	33.33	100
M2	-	14.29	28.57	14.29	42.86	100
M3	-	-	28.57	71.43	-	100
M4	-	-	28.57	42.86	28.57	100
M5	-	-	42.86	28.57	28.57	100
Actual	-	6.19	32.38	34.76	26.67	100
Design	15.63	29.17	18.75	26.04	10.42	100

TABLE 5. Mass percentage steel ball in chamber 2: from 6th to 15th meter of tube mill.

Sampling Point	Steel ball Chamber 2 (weight %)							
	50 mm	40 mm	30 mm	25 mm	20 mm	17 mm	<17 mm	Total
M6	8.33	16.67	52.78	19.44	2.78	-	-	100
M7	8.89	15.56	17.78	28.89	26.67	2.22	-	100
M8	2.94	5.88	17.65	42.65	25.00	4.41	1.47	100
M9	-	-	1.26	21.38	45.91	27.67	3.77	100
M10	-	-	0.60	8.33	42.26	41.07	7.74	100
M11	-	-	-	5.26	28.71	45.45	20.57	100
M12	-	-	-	3.12	33.43	45.04	18.41	100
M13	-	-	-	2.81	31.46	46.29	19.44	100
M14	-	-	-	0.75	24.13	56.22	18.91	100
M15	-	-	-	2.36	25.30	50.35	21.99	100
Actual	2.02	3.81	9.01	13.50	28.56	31.87	11.23	100
Design	4.57	6.29	9.14	18.29	24.00	33.71	-	100

bles 6 and 7 as a comparison. The results show that the audit approach can increase production significantly from 95.73 to 108.41, or, in other words, an increase of 13.24%. Apart from that, there was a decrease in energy requirements from 42.45 to 41.2, or 3%.

5. CONCLUSIONS

In conclusion, the comprehensive audit approach has revealed critical findings pertaining to the overall functionality of the mill. One of the primary concerns that emerged was the pressing need for the replacement of certain mill components, with the lift liner being a key example. Furthermore, it was evident that loose bearings in chambers 1 and 2 necessitated periodic tightening to ensure the efficient operation of the mill machinery. In light of these findings, it is imperative to implement a well-structured maintenance program, executed on a scheduled basis, to facilitate an optimal grinding process, which is essential for consistent productivity.

What's particularly encouraging is the tangible impact that such maintenance and audit-driven improvements can have on production. The audit results indicate that by implementing these changes, there's the potential for a substantial increase in production capacity. Specifically, the mill's output could surge from its current level of 95.73 to an impressive 108.41, representing an impressive upswing of 13.24%. Additionally, it's worth noting that the audit approach not only enhances production but also contributes to a more sustainable and resource-efficient process. A notable outcome of the audit is the reduction in energy consumption, with a decrease from 42.45 down to 41.2 units, marking a noteworthy 3% decrease.

6. ACKNOWLEDGEMENT

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7. NOMENCLATURE

1. ρ : Density [kg m^{-3}]
2. D_m : Average diameter of steel ball [m]
3. w : Weight of sample [kg]
4. Dli : effective diameter [m]
5. n_b : Number of steel ball
6. α : Elevation angle
7. f : filling degree [%]
8. r : radius [m]
9. h : Free height [m]
10. l : chamber length [m]

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