Nigerian Journal of Technology (NIJOTECH)
Vol. 45, No. 1, March 2026, pp. 228- 238
www.nijotech.com

Print ISSN: 0331-8443
Electronic ISSN: 2467-8821
https://dx.doi.org/10.4314/njt.v45i1.17

CLINKER COOLER PERFOMANCE, CEMENT GRINDING PROCESS AND WATER CONSUMPTION: A CASE STUDY OF BALL MILLS

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ARTICLE HISTORY:
Received: June 16, 2024.
Revised: February 04, 2026.
Accepted: February 07, 2026.
Published: April 29, 2026.

KEYWORDS:
Ball Mill, Cement Mill Outlet Temperature, Clinker, Clinker Cooler, and Water Consumption.

ARTICLE INCLUDES:
Peer review

DATA AVAILABILITY:
On request from author(s)

EDITORS:
Chidozie Charles Nnaji

FUNDING:
None

Abstract

*Clinker cooler determines the life span and the efficiency of any cement grinding station. Clinker is cooled by injecting fresh cold air into the cooler via a series of fans across the layer of hot clinker. The recovered heat (air) during this process are reused for the pyro-processing, that is, the main burner uses secondary combustion air in the rotary kiln and pre-heater uses the tertiary air. Inadequate heat recovery from the clinker resulted in use of larger volume of water at the cement grinding stations, thereby increasing operating and maintenance costs and the loss of revenue. This paper assessed the effect of inefficient clinker cooler at cement grinding plant and its water consumption. The cement grinding stations, are places where the clinker and other additives are been milled to the final products known as powder cements. The grinding process includes: (ball mill), milling chambers, liners, grinding medias clinker and other cement additives. The ball mill rotary in a circular form, whereby causing a frictional forces insider the mill. The impact of the frictional forces between the grinding media balls, liners, and the raw materials inside the cement milling chambers increases the material temperature from 85 °C to temperature above 121 °C***.*** *The rise in material temperature inside the milling chambers necessitates the high volume of water consumption (7300 liters per hour). This high volume of water was used to maintain the cement outlet temperature below 122 °C. It was observed, that the excessive use of water in quenching the material temperature, recorded a huge negative impact on the storage facilities and other critical operating equipment. For the ball mills to work effectively and efficiently, the exiting clinker temperature from the clinker cooler most be less than 100 °C and the cement mill clinker weigh-feeder temperature most less than 68 °C.*

1.0 INTRODUCTION

Cement has contributed immensely to modern architecture development and advanced infrastructure development. The major types of cement produced in the world are Ordinary Portland Cement (OPC), Portland Composite Cement (PCC), Hydraulic Cement (HC) and White cement (WC). Ordinary Portland Cement is the largest when compared to the other types of cement produced and it is the most used type of cement around the globe, with an annual global production records of around 3.8 million cubic meter per year, Studies, as shown that HC is more environmental friendly and lesser carbon emission

HOW TO CITE:
Oyepata, J. S. "Clinker Cooler Perfomance, Cement Grinding Process and Water Consumption: A Case Study of Ball Mills", *Nigerian Journal of Technology*, 2026. 45(1), pp. 228- 238. https://dx.doi.org/10.4314/njt.v45i1.17

factor[1- 4]. The raw material used for the production of OPC are: clinker, gypsum, and other additives [5, 6], as shown in Table 1. The production process of clinker is obtained by grinding raw mix which includes limestone, clay, iron ore, shale etc. These raw materials (raw mix) are grinded at the raw meal grinding station. The grinded material are stored in a homogenizing silos and subsequently transferred to the pre-heater for calcination process at a temperature between 900 ºC to 930 ºC, this material from the final preheater stage flow into the rotary kiln at a temperature of above 930 ºC and clinker are formed at temperature between 1350 to1450 ºC inside the rotary kiln [8]

The clinker cooling process is one of the most vital processes in cement manufacturing. Clinker cooling is largely done inside the clinker cooler which can also be called a heat exchanger. The clinker cooler is expected to drop clinker temperature from 1150 - 1250 ºC at the cooler inlet to less than 100 ºC at the cooler exit before transporting it to a clinker storage thereafter to the cement grinding station [4]. The clinker cooler has suction fans that suck in cold air and discharge it into a layer of hot-flowing clinker resulting in a multi-flow process. The recovered heat/energy from this process is charged into the pyro-process (rotary kiln and pre-heater). This recovered energy is reused for the combustion of the main burner fuel for the rotary kiln and the burning process at the pre-heater/pre-calciner**,** [7 - 10].

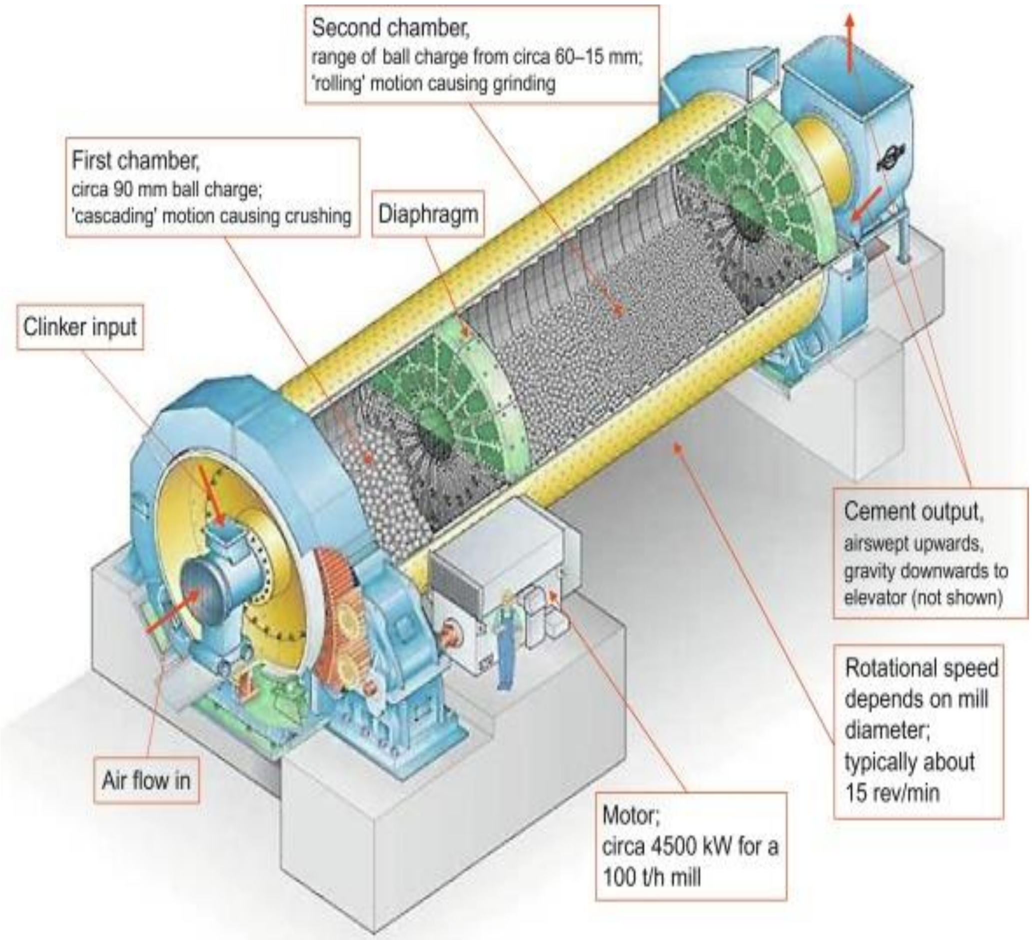

Figure 1: Overview of horizontal or ball mill [21]

To produce OPC cement, the clinker is grind to a consistent surface area or Blaine (2800-6000 cm^2/g) with 3-5% gypsum, which controls the setting time of the cement, and with additives between 5-25%, see Table 1. Ball mill operation is similar to that of raw meal grinding. The energy needed to grind clinker, gypsum, and other additives in the ball mill is between 32 to 48kWh/ton of cement depending on the efficiency of the mill and the type of OPC produced.

Cement grinding operations is the final stage of the cement production process in cement manufacturing. European standard EN 197-1 divides OPC into five (5) groups, as shown in Table 1, [11- 16]. The

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milling process starts in chamber one or first chamber for crushing the clinker and its additives and then chamber two or second chamber for final cement grinding as described in Table 1 and shown in Figure 1 [17- 21].

Table 1: Cement european union (EU) standard and composition [5, 11, 12].

	Types of Cement	Clinker %	Other Constituents
CEM I	Portland	95-100	
CEM II	Portland-slags	65-94	Blast furnace slag
	Portland-silica fumes	90-94	Silica fume
	Portland-pozzolana	65-94	Pozzolana
	Portland-fly ash	65-94	Fly ashes
	Portland-burnt shale	65-94	Burnt Shale's
	Portland-lime stones	65-94	Limestone
	Portland-composites	65-94	Additives mix
CEM III	Blast furnaces	5-64	Additives mix
CEM IV	Pozzolanic	45-89	Additives mix
CEM V	Composite	20-64	Additives mix

This research look at the production of OPC, the impacts of inefficient clinker cooler on cement mill grinding processes and it water consumption using a ball mill grinding process as a case study. The findings from this work can be apply to any other cement plants that are faced with similar challenge.

2.0 MATERIALS AND METHODOLOGY

This research work will focus on hot clinker from the clinker cooler, ball mill cement grinding operations, water consumption, and impact of poor clinker cooling on cement grinding process. Table 2 provides some details about the clinker cooler used for this research: average operating parameters, some design capacity and cooler efficiency. Some of the data used are direct input and output of a running plant, the data information are supplied by the equipment manufacturers. The ball mill has a design capacity of 200 tons per hour. Figure 2 and Figure 3 shows the installed ball mill and clinker weigh-feeder at a cement grinding station.

Table 2: Average operating parameters of an existing clinker cooler [19 - 24]

Description	Value
Fan energy	4.6 (MWh/kg clk)
Cooler speed	16 (stroke/min)
Clinker mass flow	72 (kg/s)
Clinker inlet Temp	1350 (^{o}C)
Clinker Outlet Temp	250 (^{o}C)
Cooler Length	30 (m)
Cooler width	5 (m)
Secondary air Temp	950 (^{o}C)
Specific Number	1.7 (Nm^3/kg of clk)
Energy Efficiency	59.2 (%)
Recoverable Energy Efficiency	49.2 (%)
Exhaust air Temp	265 (^{o}C)

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Figure 2: Installed Ball Mill Shell

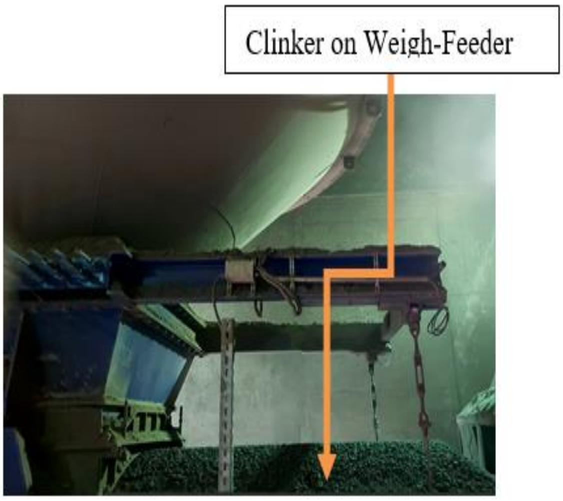

Figure 3: Installed Clinker Weigh-Feeder

The qualities of the lifters or liners in the ball mills chambers and the quantities of ball charged (grinding media) contributed to time taken to produce 200tph OPC and also the rate of collisions in the mill will increases the OPC outlet temperatures. The rate of collision and grinding processes of moving materials between the hot clinker (136 tons), limestone (45.9 tons) and gypsum (8.5 tons), grinding media (420 tons) increases the heat generation inside the mill.

The following assumption were considered for this research:

- The quantities of lifters have a significant impact based on a phenomenon known as counteracting (It is the movements of the grinding balls from the topmost position when the cement mill running and its fall downwards and on particle streams, the quantities of falling materials and particle streams increases with increase in the number of lifters
- The cement mill speed have a significant impact on the movement of grinding balls and their trajectories. The mill critical speed is expected to be between 70% to 80%, observed by simulation method DEM laboratory results [16, 17, 19].
- At a specified speed of the mill, the height of the lifting liner will affects the path of the
- falling grinding media balls. When the height of the lifting liners is worn off, most of the grinding balls will move relatively slow and the mill efficiency will be reduced. When the height of the lifting liners is very high, it is expected that the paths of the falling of materials are very high too.

2.1 Design Analysis of the Ball Mills

Figure 4, Figure 5, and Figure 6 show the schematic drawing and dimensions of the ball mill used for this research. Figure 5 is the cross-sectional view of the mill charge. Where D is the effective diameter of the compartment (m), L is the effective length of the compartment (m), V is the volume of the compartment (m^3), h is the center distance (h/D), H is the free height (m), q is the specific charge (%), *w is* the bulk weight (t/m^3), F is charge (t). There are some forces affecting the mill and its power consumption. Equations (1) to (8) show a mathematical relationship in the mills using dimensional analysis, [18, 19].

$$V = \frac{\pi}{4} \times D^2 \times L \tag{1}$$

$$H = h - \frac{D}{2} \tag{2}$$

$$\frac{h}{D} = \frac{H}{D} + \frac{1}{2} \tag{3}$$

$$H = \left(\frac{h}{D} - \frac{1}{2}\right) \times D \tag{4}$$

$$F = \frac{q}{100} \times W \times V \tag{5}$$

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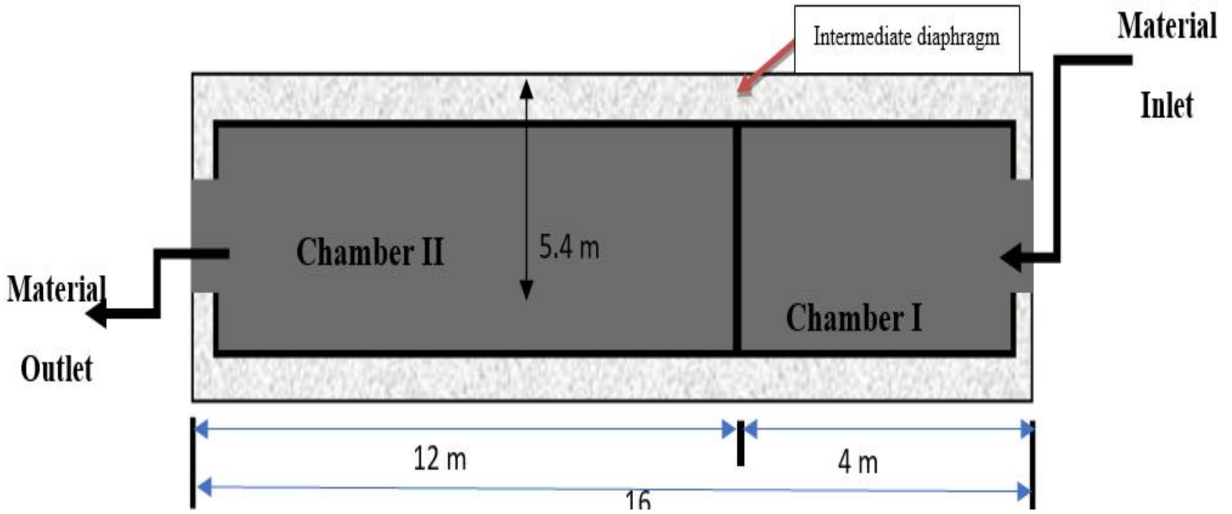

Figure 4: A schematic cross-sectional diagram of the ball mill

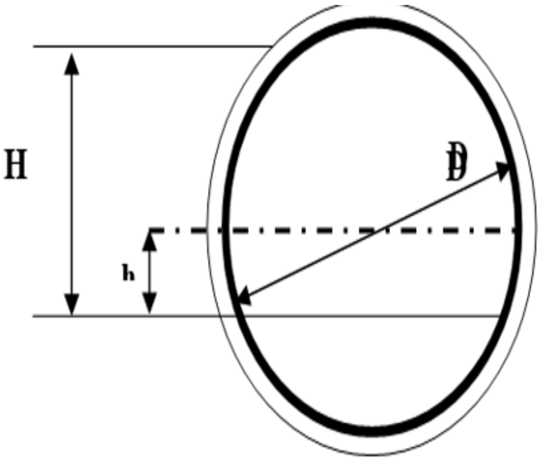

Figure 5: Cross-sectional view of the mill charge

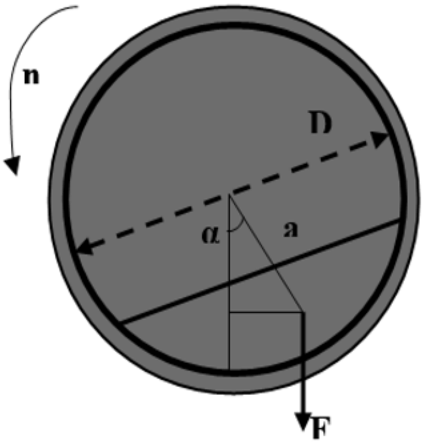

Figure 6: Forces acting inside the ball mill

$$N = F \times g \times D \times a \times \sin(\propto) \times \pi \times \frac{\pi}{60} \qquad (6)$$

where Sin (α) is the torque factor μ.

$$N = 0.514 \times F \times n \times \mu \times D \times a \qquad (7)$$

where: (a) is the arm of gravity in relation to mill diameter , (n) is the rotational speed of the mill rpm, (g) is the acceleration of gravity (9.81 m/s^2), (α) is the angle of displacement, (μ) is torque factor, (N) is power consumption by compartment at the mill shell, [18]

2.2 Critical Speed of a Ball Mill

The critical speed ball mill (n_c) is shown in Equation (8) and the centrifugal force at the mill lining is equal to the gravitational force

$$n_c = \frac{42.3}{\sqrt{D}} \qquad (8)$$

Normal mill speeds are 70 – 80% of critical speed [18, 19]

2.3 Heat Generation (Input and Output) in Cement Grinding

Production of OPC, it is assumed that the heat input consists of the grinding heat Q_g and the heat in clinker Q_{clk} as expressed in Equations (9) and (11) respectively, [19]. Cement grinding heat Q_g is a direct function of the installed motor power (N) where the clinker heat depends directly on its temperature, [19],

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$$Q_g = \frac{3.6\eta N}{G} \tag{9}$$

2.4 Clinker heat generation

The clinker heat generated in the process of grinding is shown in Equation (10) and (11) respectively,

$$Q_{PK} = C_{PK}\,(T_{clk} - T_O) \tag{10}$$

$$C_{PK} = (0.00046T_{clk} + 0.733) \tag{11}$$

where; *N* is motor power (kW) of the mill, *η* is mill drive efficiency (%), Cp_k is the specific heat value for clinker (kJ/kg °C),

T_{clk} is clinker outlet temperature (°C), *G* is mill output (t/h), T_o is ambient air temperature (°C). The heat loss with cement grinding outlet temperature is shown in Equations (12) and (13).

$$Q_C = C_{PC}\,(T_{cem} - T_0) \tag{12}$$

$$C_{PC} = (0.000_{cem} + 0.733) \tag{13}$$

where c_{Pc} is the specific heat capacity for cement (kJ/kg °C) and T_{cem} is the cement temperature (°C).

Heat loss due to radiation and convection which is the function of the surface of the mill and mill shell temperature is expressed in Equation (14).

$$Q_{r/c} = \frac{D_{0}\pi K\,({}^{D_d}/_{2} + L_i)}{1000G} \tag{14}$$

where, D_d is the nominal mill diameter (m), D_o is the mill outer diameter (m), L_l *is the* mill length (m), and *k* is the heat transfer factor (kJ/m^{2}h). The heat transfer factor (k) for grinding clinker varies with the mill diameters of the mill. For an open circuit mill heat transfer factor (k) is (4000 kJ/m^{2}h) for diameters greater than 2 meters but less than 3.5 meters. For a close circuit cement grinding mill with a diameter less than 3.5 m, the heat factor k is 8000 kJ/m^{2}h, close circuit cement grinding mill with a diameter greater than 3.5 m, the heat factor k is 12000 kJ/m^{2}h, [19-24].

Heat output due to venting air is expressed in Equation (15):

$$Q_a = [\,(Q_g + Q_c) - (Q_c + Q_{r/c} + Q_w)\,] \tag{15}$$

The heat output due to water evaporation is expressed in Equation (16):

$$Q_w = \frac{rw}{1000} \tag{16}$$

where; *w* is the water rate (including moisture content in feed material) (kg/t) *r* is the heat of evaporation of the water and has the value of 2500 kJ/kg, [19]. Heat generation output consists of the heat contained in the cement (Q_c), the heat lost by radiation and convection ($Q_{r/c}$), the heat removed by air (Q_a), and by evaporation of water (Q_w). Heat contained in cement depends only on the cement outlet temperature, [19]. The venting air volume (V_{air}) is dependent on the energy balance resulting from the heat input and heat generation during cement grinding (clinker, gypsum, and other additives). It is expressed in equation (17), [23]. Figure 7, shows a general overview of a cement grinding process

$$V_{air} = \frac{1000 \times G \times Q_a}{C_{pair}(t_{air} - t_0)} \tag{17}$$

The required water injection W is determined using Equation (18),

$$W = \frac{1000 \times Q_a}{r} \tag{18}$$

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Figure 7: Real-time data of a running cement grinding station

3.0 RESULTS AND DISCUSSION

Hot clinker leaving the cooler without proper cooling process, and the need for clinker at the cement grinding stations by the massive demand for OPC by consumers, has led to the continuous use of large volume water for hot cement quenching. Table 2, and Table 3 (see Appendix), shows some of the data used for this research from an existing running clinker cooler and a grinding cement station in Nigeria, the Cement mill is expected to trip/stop at a cement outlet exceed 125 °C.

Figure 8, shows the temperature for the clinker on the weigh-feeder and cement outlet temperature. Figure 9, shows the impacts of an inefficient clinker cooler: clinker outlet temperature ($T_{ck\text{-}outlet}$) leaving the clinker silo to the clinker weigh-feeder ($T_{wf\text{-}out}$) and its impact on the final products (OPC) leaving the cement mill (CM) with a cement mill outlet temperature ($T_{c\text{-}out}$). Table 3, shows the list of the operating parameters: clinker feed rate, limestone feed rate, cement mill outlet temperature, etc. The information was gathered at various intervals between August 26 and September 3rd, 2023.

Table 3: Real-time data obtained from a running cement plant

Date	Time	Clinker Outlet Temp silo $T_{ck\text{-}Out}$ (°C)	Gypsum Temp (°C)	Lime stone Temp. (°C)	Clinker Feed-rate (tons/hr) (80%)	Limestone Feed-rate (tons/hr) (15%)	Gypsum (5%)	Clinker weigh feeder Temp T_{wf} (°C)	Water Consump. CM1 (m³/hr)	CM1 Outlet Temp $T_{c\text{-}out}$ (°C)
26-Aug	9:30	130	30	32	136	45.9	8.5	85	7.3	119
26-Aug	11:30	172	30	32	136	45.9	8.5	92	7.3	120
26-Aug	1:30	160	30	32	136	45.9	8.5	94	7.3	121
26-Aug	3:30	152	30	32	136	45.9	8.5	94	7.3	121
27-Aug	9:30	270	30	32	136	45.9	8.5	85	7.3	119
27-Aug	11:30	171	30	32	136	45.9	8.5	92	7.3	120
27-Aug	1:30	173	30	32	136	45.9	8.5	92	7.3	121
27-Aug	3:30	165	30	32	136	45.9	8.5	85	7.3	119
28-Aug	9:30	195	30	32	136	45.9	8.5	85	7.3	119
28-Aug	11:30	173	30	32	136	45.9	8.5	92	7.3	120
28-Aug	1:30	170	30	32	136	45.9	8.5	92	7.3	121

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28-Aug	3:30	280	30	32	136	45.9	8.5	90	7.3	119
2-Sep	9:30	190	30	32	136	45.9	8.5	92	7.3	121
2-Sep	11:30	172	30	32	136	45.9	8.5	92	7.3	120
2-Sep	1:30	170	30	32	136	45.9	8.5	92	7.3	121
2-Sep	3:30	210	30	32	136	45.9	8.5	88	7.3	119
3-Sep	9:30	184	30	32	136	45.9	8.5	87	7.3	119
3-Sep	11:30	171	30	32	136	45.9	8.5	92	7.3	121
3-Sep	1:30	172	30	32	136	45.9	8.5	92	7.3	121

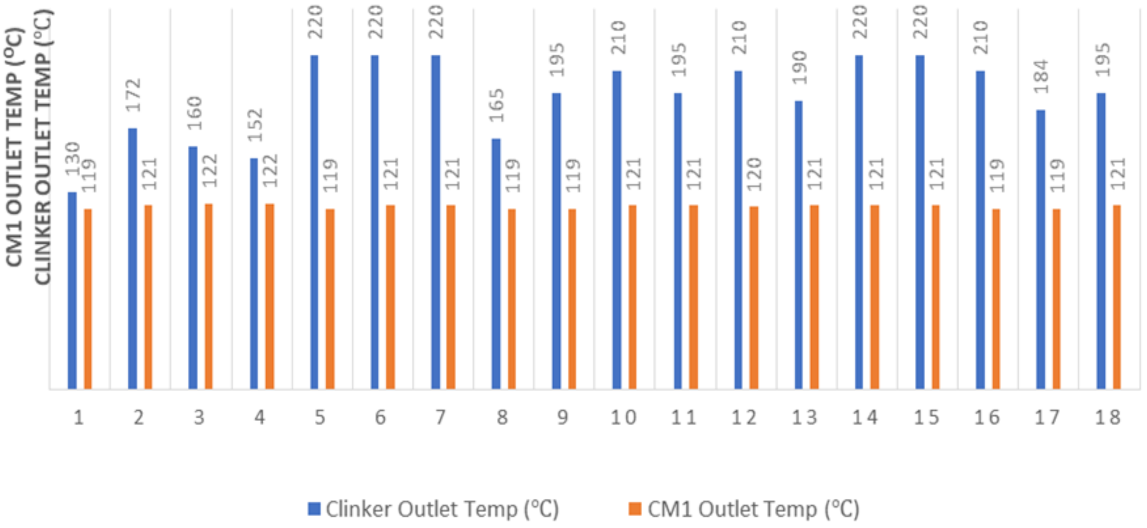

Figure 8: Bar Chart of CM1 clinker weigh feeder temperature (°C) and CM1 cement outlet temperature (°C)

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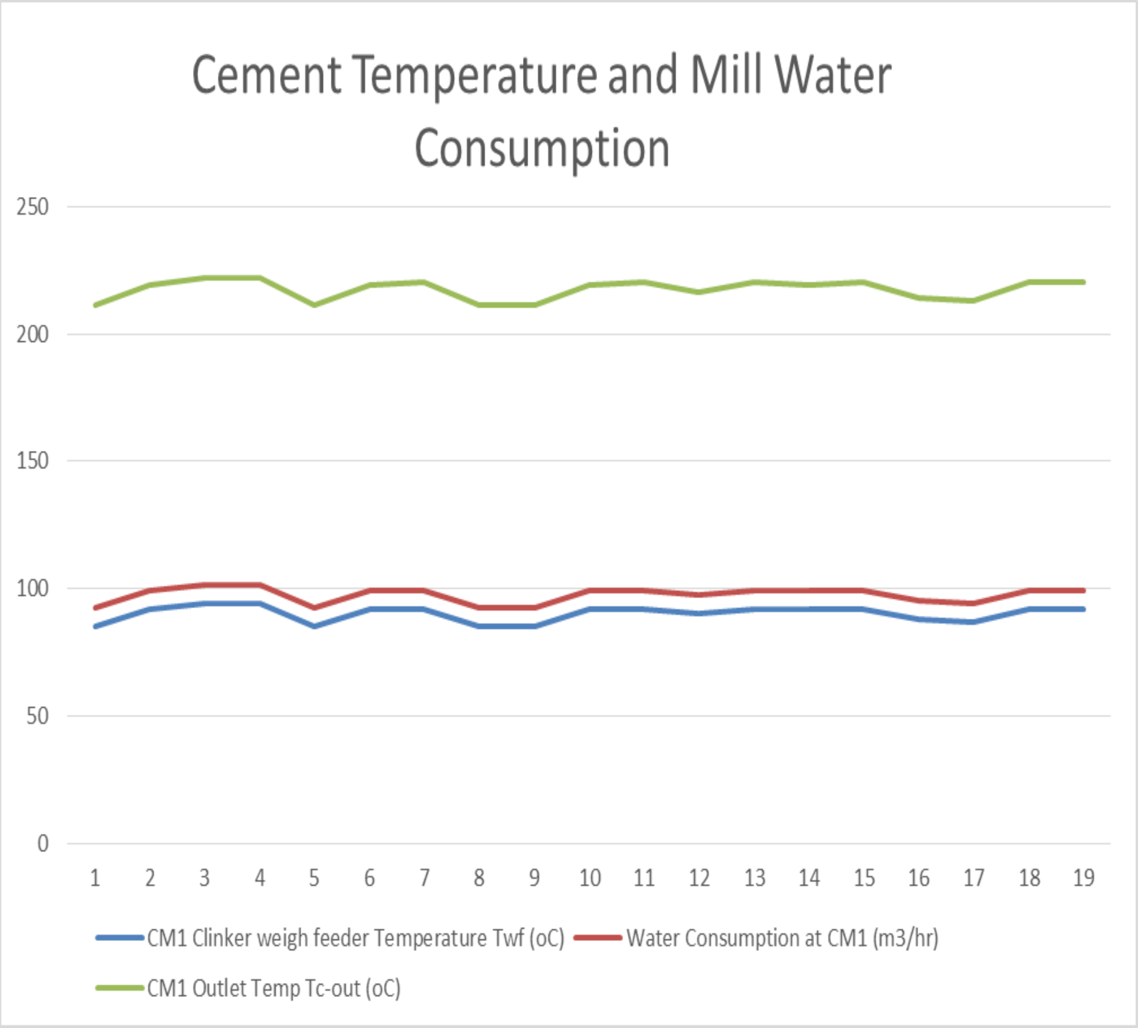

Figure 9: A graph of CM1 clinker weigh feeder temperature water consumption and CM1 outlet temperature

Figure 8 and Figure 9 shows the relationships between hot clinker and constant use of water. The continuous use of hot clinker leaving an inefficient clinker cooler will always results in the continuous demand of high volume of water, in most cases the water temperatures used are less than 35 °C. The water used were injected into the mill at chamber II using a water injection pump. The increases the material temperature are due to fractional forces (reactions) and impact force activities taking place inside ball mills as shown in Figure 6. These inner reactions inside the ball increase the temperature of the materials (clinker) entering from 92 °C to 121 °C (material outlet temperature).

The mill was consuming an average 7.3 m^3/hr of water. The excessive water usage is to keep the cement mill running, maintain a cement outlet temperature of less than 123 °C, and to avoid gypsum dehydration. This were illustrated in Figure 7, this shows the ball mill running with a real-time data, it also shows the variation in mill inlet and mill outlet temperature and percentage water opening or water injection into the mill. The impacts of using the hot clinker and the excessive use of large quantities is as followings:

- Caked cement formation inside cement silo;
- Premature stoppages on the ball mills for mill diaphragms cleaning;
- Continuous damage and replacement of bag filters;
- Increase in environmental pollution; and
- Negative impacts on human health

Figure 9 and Figure 10 shows some impact of excessive use of water on ball mills;

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Figure 9: Cement silo (caked cement) cleaning

Figure 10: High cement dust emissions

It was also observed [15-19], that high cement temperature (above 123 °C) causes quicker cement setting time and poor products workability by the end users.

4.0 CONCLUSION

The efficiency of any clinker cooler plays a vital role in the performance of any ball mill grinding station. The continuous use of hot clinker at the cement mill grinding station and the excessive use of water to quench cement outlet temperature has the following negative effects:

- ✓ economical losses due to wasted man-hours on repairs, compensation claims and revenue loss due to poor quality.
- ✓ cement cake and lumps formation inside cement silos.
- ✓ inability to operate the ball mills optimum capacity and
- ✓ often times loss of human life in the process of cleaning the cement silos, as shown in Figure 9.

It is very important to ensure that the existing clinker cooler operates at it optimal level with clinker outlet temperature from the cooler below 68 °C, [21]. Operators and engineers operating the existing clinker coolers should ensure that both the recoverable efficiency and energy efficiency does not drop below 70% and 80% respectively[23, 24], this will directly improve cement grinding process and water consumption at the cement grinding station.

4.1 Recommendations

[18, 20] recommended, that clinker cooler recoverable energy was 49.2%, energy efficiency was 59.2% and the average clinker temperature leaving the clinker cooler was 250 °C, this indicate an inefficient clinker cooler, [18, 20]. The low efficiency of the clinker cooler is large responsible for the high material temperature inside the ball mills and high volume of water consumption at the cement grinding plant.

[23-25], recommended that optimizing clinker cooler bed height to 600mm can improve the energy recovery efficiency from inside the clinker cooler: recoverable energy is 49.2% and energy efficiency 59.2% and the modeled clinker cooler recoverable energy and energy efficiency are 70% and 80.7% respectively and also reducing the clinker outlet temperature from 250 °C to 68 °C.

REFERENCES

[1] Guangchao, S. Changzhong, Wu. Hengshuai, G. Liang, W. Guitao, W. and Mingpeng, Z. “Design of Three-chamber Ball Mill”, *Journal of Physics*, 1750 (2021), pp. 1-7, 2021. doi:10.1088/1742-6596/1750/1/012065

[2] Aga, T. Anyadika, C. Mbajiorgu, C. and Ogwo, V. “Assessment of the Effect of Cement Industry Effluent Discharge on Water Quality of NGO River in Benue, Nigeria”. *Nigerian Journal of Technology*, 39(3), pp. 918-924, 2020. doi:10.4314/njt.v39i3.34

[3] Artanti, L. Mustofa, B. Sari, R. and Rutama, D. “Comparative Study of the use of ordinary Portland Cement (OPC), Portland

Composite Cement (PCC) and Hydraulic cement (HC) types in High Quality Concrete with an Independent Compaction System", *International Seminar of Science and Applied Technology: Natural Resources Management for Environmental Sustainability*. 479, pp. 1-9, 2024. doi:10.1051/e3sconf/202447907019

[4] Oyepata, J. "Energetic and Exergetic Analytical Approaches in Optimizing Grate Clinker Cooler Performances: A Case Study of a Cement Plant in Nigeria", *Journal of Engineering Research and Reports*, 25(6), pp. 96-108, 2023. doi:10.9734/JERR/2023/v25i6926

[5] American Society for Testing Materials - ASTM C441/C441M-17. "Standard Method for Effectiveness of Pozzolans or Ground Blast-Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction", *International, West Conshohocken, Philadelphia USA*, 2018.

[6]Sutar, S. Patil, V. and Chavan, V. "Ordinary Portland Cement", *Study and Review of ordinary Portland Cement*, 1(3), pp.153-160, 2021. doi:10.17509/ajse.v1i3.37973

[7]Iryna, K. and Dmytro, S. "Improvement of the structure of a ball mill with the purpose of Increasing the efficiency of material crushing", *Technology Audit and Production Reserves*, 65(3), pp. 6-11, 2022. doi:10.15587/2706-5448.2022.260278.

[8]Tianming, G. Lei, S. Ming, S. Litao, L. and Fengnan, C. "Analysis of material flow and Consumption in cement production process", *Journal of Cleaner Production*, 112 (20), pp. 555-565, 2016. doi:10.1016/j.jclepro.2015.08.054

[9]Ziya, S. Zuhal, O. and Hikmet, K. "Mathematical Modeling of Heat Recovery from a Rotary Kiln", *Applied Thermal Engineering*, 30(9), pp. 817-825, 2010. doi:10.1016/j.applthermaleng.2011.04.024

[10] Madlool, N. Saidur, R. Rahim, N. and Kamalisarvestani, M. "An overview of energy savings measures for cement industries", *Renewable Sustainable Energy Review*, 19 (13), pp. 18- 29, 2013. doi: 10.1016/j.rser.2012.10.046

[11] American Society for Testing Materials - ASTM C688-14. *Standard Specification for Functional Additions for Use in Hydraulic Cements International, West Conshohocken, Philadelphia USA.*, 2018.

[12] American Society for Testing Materials - ASTM C1565-19. *Standard Test Method for Determination of Pack-Set Index of Portland and Blended Hydraulic Cements International, West Conshohocken, Philadelphia USA*, 2018.

[13] Frauke, S. Ioanna, K. Bianca, M. Scalet, S. and Luis, D. "Best Available Techniques (BAT), Reference Document for the Production of Cement, Lime and Magnesium Oxide for the Cement Industry", *Integrated Pollution Prevention and Control* 3(12), pp. 39-42, 1999. doi:10.2788/12850

[14] Kumar, S. Kumar, J. Mahesh, M.. *Quantum Nanostructures (QDs)*, 1, pp. 58 – 88, 2018. https://doi.org/10.1016/B978-0-08-101975-7.00003-8

[15] Bian, X., Wang, G., Wang, H., Wang, S., and Lv, W. "Effect of lifters and mill Speed on particle behavior, torque, and power consumption of a tumbling ball mill: Experimental study and DEM simulation", *Minerals Engineering*, 105 (17), pp. 22–35, 2017. doi:10.1016/j.mineng.2016.12.014

[16] Sinnott, M. Cleary, P. and Morrison, R. "Combined DEM and SPH simulation of overflow ball mill discharge and trommel flow", *Minerals Engineering*, 108(7), 93–108., 2017. doi:10.1016/j.mineng.2017.01.016

[17] Peter *del* Strother. *Lea's Chemistry of Cement and Concrete*, 5th Edition, Butterworth-Heinemann, Oxford, U.K, pp. 2-34., 2019.

[18] FLSmidth. *Comminution Manual.* Copenhagen, Denmark, pp. A.1-E.13, 2007.

[19] Holderbank, (2000b). "Process Technology, Mill Ventilation and Cement Cooling" *Holderbank Financière Glaris Ltd Publication,* Glaris Germany, pp. 1-35, 2000.

[20] Rasoul P and Kianoush, B. "The effect of ball size distribution on power draw, charge motion and breakage mechanism of tumbling ball mill by discrete element method (DEM) simulation", *Physicochemical Problems of Mineral Processing*, 54 (2), pp. 1-15, 2017. doi:10.5277/ppmp1811

[21] Oyepata, J. Baba, N. Idowu, E. and Adediran, A. "Impacts of Clinker Storages Heat Transfer, Its Effect on Vertical Roller Cement Performances: A Case Study of Cement Grinding Operations in Nigeria". *Journal of Engineering Research and Reports*, 25(7), pp. 66- 81, 2023. doi:10.9734/jerr/2023/v25i7939

[22] Mohsen M. "Simulation of a Laboratory Scale Ball Mill via Discrete Element Method Modelling". *Advances in Materials Physics and Chemistry*, 11(10), pp. 167-175, 2021. doi:10.4236/ampc.2021.1110016

[23] Oyepata, J. Dahunsi, O. Yaru, S. and Idowu, E. "Modelling of Clinker Cooler and Evaluation of Its Performance in Clinker Cooling Process for Cement Plants". *Nigerian Journal of Technology*, 39(4) pp. 1093-1099, 2020. doi:10.4314/njt.v39i4.16

[24] Oyepata, J. Dahunsi O. Yaru, S. and Idowu, E. "Effect of Clinker Bed Height on Clinker Cooling Process on Clinker Grate Coolers Used in Cement Plant", *Journal of Engineering,* 12(11) pp. 25-37, 2022. [Online]. Available: https://iosrjen.org/Papers/vol12_issue11/C1211012537.pdf

[25] Oyepata, J. Dahunsi, O. Yaru, S. and Idowu E. "Effect of clinker bed height on energetic and exergetic in clinker coolers used in cement plant", *Journal of Mechanical Engineering Research,* 13(1), 1-11, 2026. doi:10.5897/JMER2022.0567

https://dx.doi.org/10.4314/njt.v45i1.17