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PROCESS AUDIT AT A GRINDING PLANT (CEMENT MILL) AT A CEMENT FACTORY - A CASE STUDY IN ROMANIA

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Abstract

The process audit is an analysis for the operation of an equipment, to establish its performance and to make proposals for measures to increase production, decrease consumption and improve product quality. The objective of the process audit is to establish the actual state of operation for the cement grinding plant (the degree of loading with grinding bodies, the air speed in the mill, the granulation of the material at the entrance and the exit, the wear of the shields, energy consumption) and is the basis for proposing measures for optimization. The audit from a grinding plant is carried out in the following situations: upon commissioning (to record the initial condition of the equipment) after modernization/modifications of the equipment in the composition of the grinding plant whenever there are deviations from the expected performance as a routine test, at least once a year, to appreciate the real condition of the equipment. The paper presents some determinations made at a cement mill from a Romanian cement factory, the sampling method to carry out analyses and recommendations for improving production.

Key words: *grinding ability, grinding chart, grinding efficiency, process audit, particle size analysis.*

INTRODUCTION

The audit process is intended to estimate whether the process requirements specified in operating instructions, procedures, and rules for the conduct of the manufacturing process are suitable for achieving quality objectives.

The audit can be performed by a person or team, depending on the complexity of the operation under examination and the need for skills outside the training of the technical staff on the production flow.

The technical audit is more important as it is one of the effective tools for reducing production costs (Ciobanu et al., 2020; Engin & Arı, 2005; Krishnamoorthy et al., 2018; Ramesh et al., 2013).

Cement plants and process technical managers are often asked to examine, "the big picture" in a production/operations environment.

The audit process is a procedure that helps technical staff determine not only what is wrong, but also what is right in an industrial activity.

The cement plant audits assess its performance against a criterion of corresponding reference, and after a detailed assessment, recommendations are made to optimize the plant through capital investments.

For example, an energy audit of the dry rotary kiln system operating in a cement factory in Turkey showed that approx. 40% of the total input energy is lost through the hot flue gases (19.15%), the cooling stack (5.61%), and the furnace casing (15.11%, convection plus radiation). Following the audit, some ways to recover heat losses were presented, and the findings noted that approx. 15.6% of the total input energy can be recovered (Engin & Arı, 2005; Garba et al., 2010).

The methods of carrying out the technical audit involve the monitoring of working, electrical and maintenance practices in different sectors of the cement factory, as well as of the exploitation operations, the condition of the instrumentation, environmental pollution control techniques, etc. (Khan et al., 2012; www.cementequipment.org).

For example, for the assessment of ball mills, maximum production, energy consumption, system air flow and material flow, separator performance, and the operational variables to be monitored include: temperature, at the inlet and outlet of the mill, the inlet pressure in the mill, the differential pressure, energy consumption, mill vibrations and other process parameters. In the paper are presented some determinations made at a cement mill from the formation of a cement factory in Romania, the method of sampling to carry out analyses and recommendations for improving production.

MATERIALS AND METHODS

The following methodologies and measuring devices were used to perform the mill audit:

a) The method was chosen to determine the specific surface area (SSB) of the grinding material (https://thecementinstitute.com).

The Blaine procedure is applicable to all cements defined in the standard SR EN 196-6: 2019.

The fineness of the cement shall be measured in the form of a specific surface, expressed in cm^2/g, which is based on determining the time of a fixed volume of air at known temperature to cross a layer of compacted cement, using the Blaine device.

b) A TESTO 920 type of device was used to measure the temperature at the main points of the installation.

c) The relative static pressures and flow rates at the main points of the grinding system were performed with the TESTO 400 to which a Pitot tube and a pressure transducer were connected.

d) For the chemical and granulometric analysis of the clinker, limestone + slag, gypsum and cement samples taken from the cement mill, an apparatus was used to perform the chemical analysis of the NovAA 400 grinding material.

The spectrometer is fully controlled by the PC for the flame and graphite technique, with transversely heated graphite furnace, single and double beam mode, and automatic turret with 6 lamps. Precise measurement of trace elements over a wide range of concentration is achieved by high precision at the high-performance optical drive, high-sample speed, and nucleus – transversely heated graphite furnace.

e) For the analysis of clinker granulometry, Mastersizer 2000E and CILAS - Delcita 715 are used (https://www.n8equipment.org.uk/).

There are three distinct ways to measure a sample with the Mastersizer 2000E:

1) The sample is prepared and dispersed to the correct concentration and then sent to the optical drive. Sample preparation is the most important step in making a measurement. If the sample is poorly prepared (unrepresentative or poorly dispersed) then the basic data will be incorrect.

2) Capture the spreading pattern from the prepared sample - measurement. The detector machine has a "snapshot" of the spreading pattern. Obviously, this snapshot only captures the scattering pattern in the particles passing through the analyser beam at that time. Taking a single snapshot may not get a representative view of the spreading pattern. Mastersizer takes many snapshots (known as snaps) and averages the result. Typically, more than 2000 snapshots are taken per measurement at a 1 ms interval.

3) Once the measurement is complete, the raw data is analysed by the machine's Malvern Software. After the data has been analysed, the information can be displayed in various ways.

The possibilities of investigation of the equipment are: Measuring the granulometric classes in the range of 1 ÷ 192 μm in a wet environment on any type of powdery material.

Interpretations of analyses:

- graphical presentation of the weight on 16 granulometric classes located in the range 1 - 192 μm;
- tracing the granulometric curve of the analysed powder;
- determination of the average diameter.

f) Optical microscopy apparatus Carl Zeiss AXIO IMAGER A1m and component determination by mineralogical analysis on natural raw materials: clay, marne, limestone, tiles, bushes and synthetic products such as cement clinker. It allows examination, both with transmitted light and reflected light (current 220 V, 15 A and frequency 50 Hz).

RESULTS AND DISCUSSIONS

The sampling and measurements necessary for the audit were carried out according to the schedule of determinations agreed with the factory representatives.

The cement produced was CEM II/A-LL 42.5R, with clinker, limestone, gypsum and dust from the furnace electrofilter (CKD). The grinding additive GTA 140 (dosage 300 g/t) was used for grinding, for increasing production, and SYNCRO 206 (dosage 600 g/t) for reducing chromium.

The cement mill was stopped for the purpose of evaluating the interior equipment and taking samples for drawing the grinding diagram.

The audit includes information about the main process parameters recorded in the factory control room and measurement results (sampling for chemical analysis, granulometric analysis of materials introduced in the cement mill, determination of the grinding fineness of the cement expressed by specific surface Blaine and determinations in the air flow of the ball mill).

The stages of the process audit are as follows:

1. Submission of observations on the process parameters of the ball mill;
2. Presentation of observations on grinding efficiency;
3. Measurements in the air flow of the ball mill (measurements of temperatures, pressures and flows), as well as observations from the measurements made;
4. Determinations on materials (clinker, slag and limestone, gypsum, mixture, cement);
5. Inspection of the interior of the mill (interior equipment of the mill) for determining the filling degrees and specific consumption of electricity;
6. Tracing and analysis of the grinding diagram;
7. Separation efficiency by sampling points of the dynamic separator: Separator supply, separator fine output, separator output grid, and Tromp selectivity curve drawing based on laser granulometric distributions.

The main process parameters, recorded in the control room, are summarized in Table 1, and the grinding efficiency is synthesized by the parameters expressed in Table 2.

Table 1. Process parameters in the control room

Characteristic	Value
Assortment of cement produced	II AS 32.5
Raw mixture, Dosage (wet), %	
Clinker	69.52
Slag + limestone	23.63
Gypsum	6.85
Moisture mixture at the entrance to the mill, %	1.29
Mill production: wet/dry	75.2/74.2
Specific electricity consumption (dry), kwh/t	
cement mill	32.5
factory	41.6
Cement characteristics	
specific surface, cm^2/g	3,174*
SO_3 content, %	3.33

*determinations mean in CEPROCIM laboratory

***Remarks**:*

- the mill production and the dosage of the mixture were calculated based on the hourly indications of the component meters (clinker, limestone + slag, gypsum);
- the moisture of the mixture was calculated weighted, based on the moisture of the components, determined in the factory laboratory;
- the specific surface of the cement represents the average of the determinations made by the CEPROCIM laboratory.

Table 2. Milling efficiency

Parameter	Val.	Observations
Production (dry), t/h	74.2	- low production
Cement grinding finesse, cm^2/g	3174	- appropriate finesse
Finesse filter dust, cm^2/g	3598	- possibility of increasing the air speed through mill
Electricity consumption (dry), kwh/t factory cement mill	32.6 41.6	- relatively good consumption
Recirculation coefficient	1.51*	- low value
Air speed above the charge, m/s	0.78	- speed outside the usual range (1-1.5 m/s)
Diameter max/min balls, mm, CI	90/60	- appropriate structure
CII	50/18	
Degree of filling, % CI	29.27	- degrees of filling calculated from H measured with material in the mill
CII	27.08	
Average ball weight in CI, kg	1.40	- relatively low weights
Average ball weight in CII, g	48.44	
Grinding chart, % $R_{2,5\ mm}$ at the mill wall	1.99	- good value (with a mill insufficiently loaded with material)
Mill speed, % of critical speed	76.40	- appropriate speed

*calculated from feed and grit flows

Determinations in the air flow

Using the portable equipment of CEPROCIM, measurements of temperatures, pressures and flows were made in the air flow. Thus, Table 3 shows the air temperatures and relative static pressures measured at the main points of the grinding plant, respectively the average air flow values, calculated based on dynamic pressure and temperature measurements.

Table 3. Process parameters on air flow

Measurement point	Air temperature, ºC	Relative static pressures, mm H_2O	Air flow, Nm^3/h
Mill outlet pipe	87-95	111-127	24,042
Fan inlet of separator	78-80	223-233	114,301
Entrance to the mill dedusting fan	78-80	242-212	33,315
Filter basket and attachments	64-65	0.2-2.6	25,489

Remarks*:*

- for the air flow of 24,042 Nm^3/h measured at the mill outlet, the maximum air speed through the mill (0% false air) is 0.97 m/s. Considering the false air infiltration at the exit of the mill of ca. 20%, the actual air speed through the mill becomes 0.78 m/s, value outside the range (1-1.5 m/s);
- the value of air infiltration on the mill outlet - mill deburnout filter basket is 9,273 Nm^3/h and represents approx. 27% of the air discharged to the basket.

Determinations on materials

During the audit, clinker, limestone + slag, gypsum and cement samples were taken, on which the following determinations were made:

✓ ***Clinker determinations (CEPROCIM determinations)***

The chemical analysis of clinker performed in the CEPROCIM laboratory is presented in Table 4.

Table 4. Chemical composition of materials

Chemical and modular composition	Clinker	Slag + limestone	Gypsum
Humidity*, %	0.01	4.06	4.72
Constitution water, %	0.72	4.02	13.6
SiO_{2total}, %	20.03	33.11	14.38
CaO, %	65.37	47.61	25.57
Al_2O_3, %	5.48	10.34	4.34
Fe_2O_3, %	3.83	1.18	1.26
MgO, %	1.41	2.0	1.6
SO_3, %	1.34	0.22	28.23
CaO_{free}, %	1.0	-	-
Insoluble residue, %	0.18	0.77	-
M_{Si}	2.13	-	-
M_{Al}	1.43	-	-
LSF	99.74	-	-
C_3S, %	65.02	-	-
C_2S, %	9.07	-	-
C_3A, %	8.04	-	-
C_4AF, %	11.65	-	-
CO_2, %	-	-	4.56
$CaSO_4 \cdot 2H_2O$, %	-	-	60.69
$CaCO_3$, %	-	-	10.37
Clay substances, %	-	-	23.22

*determination carried in the factory laboratory

Remarks*:*

- potential alite and belite contents favourable to obtaining cements with low energy consumption.

The granulometric analysis of the mean clinker sample, respectively slag + scale, is shown in Table 5.

Table 5. Granulometric characteristics of the materials

Parameter	Clinker	Slag + limestone	Gypsum	Mixture
R_{25mm}, %	14.87	0.8	32.85	12.77
$d_{80\%}$, mm	22.0	4.0	31.00	19.50
$d_{50\%}$, mm	11.9	2.5	16.50	6.50

Remarks*:*

- the particle size of clinker, gypsum and mix is well above the recommended value, while the particle size of the slag is very good compared to the recommended value (R_{25mm} < 5%).

Determination of cement

The grinding fineness of the cement expressed by the specific surface of Blaine, $R_{90\mu m}$, $R_{64\mu m}$ was determined in the CEPROCIM laboratory, and the results are presented in Table 6.

Table 6. Grinding finesse of cement

Hour	CEPROCIM residues		Specific surface area Blaine, cm^2/g	
	$R_{90\mu m}$,%	$R_{64\mu m}$,%	Factory	CEPROCIM
10	2.04	8.36	3,250	3,270
11	2.04	8.40	3,250	3,250
12	2.28	8.56	3,020	3,040
13	1.88	7.48	3,100	3,120
14	2.12	8.16	3,230	3,220
15	2.04	8.52	3,080	3,280
16	2.12	8.48	3,000	3,150
17	2.16	8.44	2,850	3,060
Average	**2.09**	**8.30**	**3,098**	**3,174**

Remarks*:* the specific surface values of the cement determined in the CEPROCIM laboratory are like those determined in the factory laboratory.

The proportion of limestone (dry) in cement was estimated by selective component determination on the average cement sample. The scale ratio is approx. 2.15%.

The proportion of slag in the cement was determined by optical microscopy on the Hourly samples.

The proportion of slag + scale calculated from the counters was 23.63% (wet) and 22.97% (dry), respectively. CEPROCIM determinations indicate an average slag value of 21.9% (dry) and 2.15% (dry), with total slag + limestone being 24.05% (dry), higher than the one calculated based on the metering of the supply flows of the mill. The measurements were made from hour to hour between 10:00 ÷ 17:00.

Temperature measurements on the mill input/output material are shown in Table 7.

Table 7. Mill inlet/outlet temperature

Temperature, ºC	Value
Clinker at mill inlet	80.0-86.5
Slag + limestone al mill inlet	27.6-33.0
Gypsum at mill inlet	7.7-8.4
Cement belt conveyor	73.0-78.5

Inspection of the interior of the mill

The inspection of the interior of the cement mill was aimed at:
- free height measurement (H), for determining the degree of filling with grinding bodies;
- assessment of the condition of the interior equipment of the mill;
- sampling to draw the grinding diagram; the samples were taken in three directions from 0.5 to 0.5 m.

The measurement of the free height (H) above the load with grinding bodies was done without emptying the material mill, and the initial structure of the load with grinding bodies is shown in Table 8.

Table 8. Cement mill - loading and filling grades (Cement II AS 32.5)

Mill	Production, t/h	Speed, rpm	Length, m	Inner diameter, m	Blaine, cm^2/g
MC	74	16.0	10.5	4.2	3174

Chamber	Length, m	Inner diameter, m	Balls density, $/m^3$	Critical speed, rpm	Mill speed, % of critical speed	H* measured, m
I	3.81	4.08	4.31	20.94	76.40	2.717
II	6.04	4.08	4.80	20.94	76.40	2.792

**measured with material in mill*

Based on the measurements of free H, the filling degree and the specific electricity consumption were calculated (relation Slegten), Table 9.

Table 9. The filling degree and the specific electricity consumption

Parameter	Chamber I	Chamber II	Total mill
Degree of filling, %	29.27	27.08	-
Specific electricity consumption, kWh/t	12.7	19.8	32.6

***Remarks**:* the specific electricity consumption of the mill is relatively good.

The internal equipment of the mill - Chamber I

Figure 1. Aspects at the entrance to the mill - material level and cascade armours for chamber I

***Remarks**:* armours in good condition.

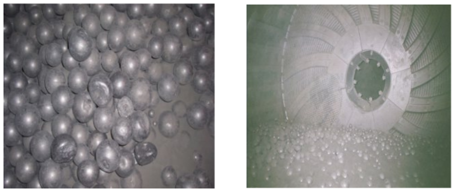


Figure 2. Broken balls, deformed balls (detail), respectively the partition wall, the ventilation ring, the material level and the cascade shields - chamber I

***Observation**:* Material below the ball level, missing material on the left side of the mill and broken and deformed grinding bodies and the presence of grinding bodies from chamber II.

Figure 3. Cascade shields (detail) and slots in the partition wall with ventilation ring (detail) - chamber I

***Observation**:* Field armour in good condition.

The internal equipment of the mill - Chamber II

Figure 4. Partition wall, self-sorting shields, the material level and the slots in partition wall (detail) - chamber II

Figure 5. Balls distribution and self-sorting shields (detail) - chamber II

Figure 6. The slots in the mill outlet wall (detail) and mill outlet grate (detail) - chamber II

Remarks: the shields in the partition wall and those at the mill outlet are in good condition, but the material is below the level of the balls. In addition, there are balls wedged between armours and slots partially blocked with balls.

The grinding diagram

To perform the grinding diagram, the cement mill was instantly switched off. Material samples were taken from 0.5 m in 0.5 m, in three directions along the mill, by CEPROCIM personnel. On the material samples, the residences were determined on the 5 mm, 2.5 mm, 1 mm, 200 µm, 90 µm sides of the eye, 64 µm and 32 µm and specific Blaine surfaces (room II) in the CEPROCIM laboratory and then the grinding diagram was drawn. The results are shown in Figures 7 and 8.

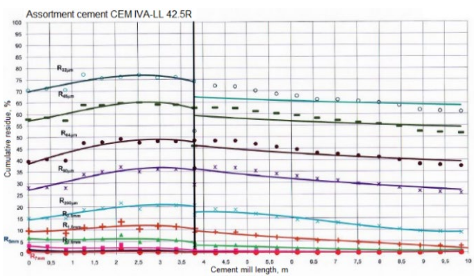


Figure 7. Cement mill. Milling diagram. Three-way sample average

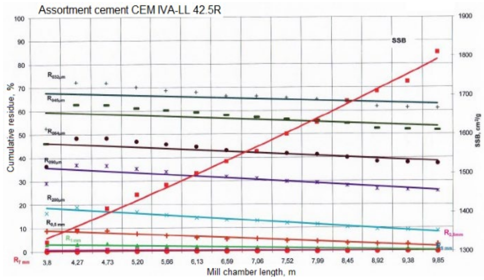


Figure 8. Cement mill. Residues evolution and Blaine specific surface area (SSB) in chamber II

The analysis of the grinding diagram highlights the following aspects:

Chamber I:

- ✓ well prepared material in room I - $R_{2.5mm}$ = 1.99% at the partition wall, in conditions of a mill insufficiently loaded with material.

Chamber II:

- ✓ active grinding along the entire length of the chamber;
- ✓ $R_{90\mu m}$ when leaving the mill (separator supply) cca 8%.

Efficiency of separation

For the characterization of the separation efficiency, samples were taken from the following grinding plant points:

- ✓ mill output material (separator supply);
- ✓ separator output for fine material;
- ✓ separator output for grout.

The following determinations were made on the materials taken:

- ✓ resided ($R_{90\mu m}$ and $R_{64\mu m}$);
- ✓ specific Blaine surfaces;
- ✓ laser granulometric distributions.

The values of the residuum and characteristic parameters of the grinding-separation process are shown in Table 10.

Table 10. Grinding-separation process parameters

Characteristics	Value
Recirculation coefficient, -	1.48
Fine material volume, %	67.65
Grit volume, %	32.35
Degree of fine material separation, %	75.34
Degree of grit separation, %	13.17
Separation eficiency, %	62.17

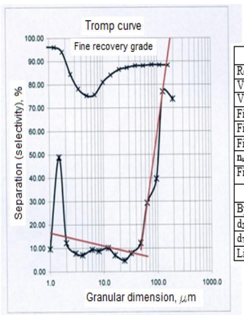
Remarks:

- R_a - the separator feed material resin – on the 90 µm and 64 µm sieve, %;

- R_g - the semolina resin - on the 90 µm and 64 µm sieve, %;
- R_F - the fin resin on the 90µm and 64µm sieve, % respectively;
- k - the recirculation coefficient;
- V_f - the volume of fine resulting from separation, %;
- V_G = the volume of semolina resulting from separation, %;
- f - the degree of separation of the fin (fine to fine), %;
- g - the degree of separation of the semolina (fine to fine), %;
- E - separation efficiency (f - g), %.

Have been found: good separation of the fin; poor separation of the semolina; relatively good separation efficiency; low value of recirculation coefficient.

The efficiency parameters of the separator were also calculated based on the laser granulometric distributions; the Tromp selectivity curve being drawn (Figure 9).



Separation characteristics			
Recirculation coefficient	1.24		
Volume of fine, %	80.7		
Volume of grist, %	19.3		
Fine efficiency at 30 µm, %	92.2	Grist in fine at 30 µm, %	65.1
Fine efficiency la 64 µm, %	89.7	Grist in fine at 64 µm, %	48.0
Fine efficiency la 90 µm, %	87.6	Grist in fine at 90 µm, %	34.9
n_s	0.90	$d_{R36.8\%}$, µm	25.4
Fine recovery grade, %	88.35		
Tromp curve characteristics			
Bypass, %	8.1		
d_{25}, µm	60.2	d_{50}, µm	97.7
d_{75}, µm	135.1	Imperfection, %	0.38
Limit of acuity, µm	34.8	Accuracy	2.2

Figure 9. Tromp curve. Characteristics of separation at the cement mill

It was found that the recirculation coefficient, calculated from the results of the laser granulometric analysis, was within the recommended range (2-2.5), with positive implications on production, but the degree of recovery of the fin (f) was relatively low (approximately 42%). However, the degree of wheat recovery (g) was very good (99.5%). Also now, the efficiency parameter values are characteristic of the third generation of separators.

Compared to the 2nd and 3rd generation separators, the WEDAG mill separator is presented in Table 11.

Table 11. Parameters of the cement factory separator

Separator parameters	Generation III	Generation II	WEDAG Separator
Coefficient of recirculation	>2	>2	1.23
Tromp curve characteristics			
By-pass, %	<10	10 - 35	8.30
imperfection, -	<0.310	0.30 - 0.45	0.40
acuity limit, µm	<15	15 -20	33.3
The slope of the RRS line, -	>1	0.85 - 1.0	0.90

It can be said that the efficiency parameters of the separator are favourable, located between those specific to the second and third generations of separators, under the conditions of low recirculation coefficients.

CONCLUSIONS

Following the audit of the mill, the following recommendations were proposed:

At the grinding:

- increasing the load of the mill with material, respectively increasing the degree of recirculation;
- increasing the degree of filling of the mill with grinding bodies to the maximum level allowed in both chambers, in order to increase productivity;
- increasing air speed through the mill by increasing aeration;
- increasing the weight of the average ball in room I;
- periodic inspection of the interior of the mill and intervention at the slots, diaphragm, wall exit mill, armour, etc.
- periodic cleaning of the bulkhead slots and the wall at the outlet of the stuffed ball mill, as well as the exhaust screen around the spray nozzle.

At the separation:

- periodic inspection of the interior of the separator;
- the value of the by-pass is within the range specified by the literature for the manufacture of this type of cement (5-15%);
- the slope of the RRS right indicates a narrower distribution of particle sizes in cement, which may be beneficial for the final strength of the cement. For this type of manufactured cement, the literature mentions the range of 0.85-1.15 for the slope of the RRS right.

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