UNIVERSITY **POLITEHNICA** OF BUCHAREST
Faculty of Biotechnical Systems Engineering
Department of Biotechnical Systems

Eng. Cristian-Bogdan CIOBANU

Summary PhD Thesis

RESEARCHES ON THE PROCESS OF CLINKER GRINDING IN CEMENT PLANTS IN ORDER TO DECREASE DUST EMISSIONS

Scientific coordinator:
Prof. Dr. Eng. Gheorghe VOICU

Bucharest (2023)

Content

FOREWORD

The paper ” *Researches on the process of clinker grinding in cement plants in order to decrease dust emissions*” presents the authors' experimental research on the clinker crushing process and the effects of different design and functional parameters on the mode of operation.

The main objective of the experimental research within in this paper is the analyze the process of grinding clinker, using a laboratory ball mill, the grinding being part of the technological process of obtaining different types of cement .

A part of the research was carried out within Be Entrepreneur project.

In the **Chapter 1**, of the work, some general considerations regarding the cement manufacturing process and aspects regarding environmental protection in cement plants are presented, as well as the importance of the topic and the objectives of the doctoral thesis.

Chapter 2 presents aspects regarding the physical properties of the raw materials used in the cement industry (the physical characteristics of the raw and auxiliary materials for clinker obtaining, the factors that influence the process of clinker obtaining, different types of cement-manufacturing recipes of different cement plants in Romania and their use).

In the **Chapter 3**, the technologies and the equipment are presented on the flow of clinker production (general technological scheme for clinker production), technological schemes and equipment for clinker production, construction - component parts and operation of ball mills for grinding clinker, as well as the technological regime of clinker mills.

In the **Chapter 4**, entitled: "The current stage of research on the working process of ball mills in the cement industry" aspects of theoretical research are described (the theoretical bases, the current stage of theoretical studies and the synthesis of the theoretical models used in the analysis of the process of ball mills balls) and experimental ones, the work process on a global scale and the parameters of ball mills in the cement industry.

Chapter 5, entitled: "Theoretical aspects and contributions regarding the crushing of clinker in ball mills" firstly describes theoretical aspects regarding the crushing of clinker in ball mills. All numerical integrations were carried out by an explicit Runge-Kutta method, calculating the ball trajectories as a function of the ball filling surface of the cement mill. To simulate the grinding of clinker in a laboratory ball mill, the professional simulation program EDEM 2022.0 from the company Altair Engineering, Eng was used.

In the **Chapter 6** entitled: "Experimental research on the clinker crushing process" the equipment and working methods of the experimental determination are firstly introduced. Then the material subject to grinding is presented with the initial characteristics and the method of obtaining. We proceed actually to the experimental determinations regarding the crushing of clinker with the help of the laboratory mill, of the vibrations of the laboratory ball mill in different working variants and experimental determinations in the laboratories of cement plants in Romania regarding the crushing process and the characteristics of the material, following the crushing of the clinker.

Reference is also made to the evaluation parameters of the crushing process carried out as a result of research (degree of crushing, crushing time, specific surface of the grinder, specific energy consumption, concentrations of particles in suspension due to clinker crushing, etc.) and of the correlations between the parameters that describe the grinding process.

Chapter 7 of the paper is assigned to the General Conclusions of the paper and individual contributions to the optimization of the clinker grinding process. In addition, relevant aspects related to this theme are also highlighted, which can be further discussed by other researchers. The author appreciates this paper which is about the use of tubular ball mills, a relatively modest contribution to the optimization of the clinker grinding process.

List of symbols and notations

Chapter 1 – The importance of the topic and the objectives of the doctoral thesis

WBCSD	World Business Council for Sustainable Development
HG	Government Ordinance
APM	Environmental Protection Agency
CEN	European Committee for Standardization
ISO	International Organization for Standardization
SA 8000	Social Accountability (Social responsibility)
BAT-AEL	The best technology available (BAT- Best Available Techniques); Levels of Associated Issue (AEL- Associated Emission Levels)

Chapter 2 – Aspects regarding the physical properties of raw materials used in the cement industry

C_3S	Tricalcium silicate (allite)
C_2S	Dicalcium silicate (belite)
C_4AF	Tetracalcium alumino-ferrite (celite 1)
C_3A	Tricalcium aluminate (celite 2)
K	Portland cement clinker
S	Granulated blast furnace slag
Q	Calcined natural pozzolana (pozzolanic materials)
V	Siliceous fly ash

Chapter 3 – Technologies and machinery on the clinker production stream

D, L	Inner diameter and length of drum (Ø,m)
G_b	The weight of the grinding bodies (kN)
P	Engine power (kW)
Q_m	Mass flow (t/h)
ρ_v	Bulk density of grinding bodies (kg/m^3)
ε_g	Goal percentage
σ_{rc}	The compressive strength of the fed material
ω	Angular speed of rotation of the drum (s^{-1})
φ	Degree of filling

Chapter 4 – The current state of research on the working process of ball mills in the cement industry

SEC	Specific Energy Consumption
MIGO	Constrained Integral Gain Optimization
PID	Proportional Integral Derivative
E_s	Specific energy consumption for grinding the material

L_1	The mechanical work consumed by the machine;
L_2	The mechanical work consumed in the grinding process
E_c	The kinetic energy of grinding
E	Young's modulus (N/m^2)
V	Material feed volume (m^3)
d_{bo}	The optimal diameter of the ball
x	Grain size
δ_N	Normal particles overlap
k_v	The finished product (cement)
S_{res}	The residual error

Chapter 5 – Aspects and theoretical contributions regarding the crushing of clinker in ball mills

X	The subset of independent input variables (x_1,x_2 , ...x_n) which characterize the system
Y	Subset of output dependent variables (y_1,y_2,...y_n) which characterize the system
F	The subset of functions
B	The vector of fuel flows whose elements b_i ndicate the fuel flow inserted into the device i

Chapter 6 – Experimental research on the clinker crushing process

SSB	Blaine Specific Surface Area;
w	The specific energy consumption of the industrial mill;
c_1	Grindability index;
w_1	Specific energy consumption;
τ	Correlation coefficient;
R_{009}($R_{90\mu m}$)	Residue obtained on the 90 µm sieve;
R	The residue of the finished product;
W_z	Zeisel index of grindability;

CHAPTER 1. THE IMPORTANCE OF THE TOPIC AND THE OBJECTIVES OF THE DOCTORAL THESIS

1.1. The importance of approached topic. General considerations regarding the cement manufacturing process

The crushing process in the current stage of cement technology is one of the biggest consumers of energy. In the technological flow of cement manufacturing, the grinding processes occur in two of its phases, namely: during the preparation of raw materials and at cement obtaining in ball mills. Considering the technological importance of the grinding processes and the energy implications on which they bring, by the present work was sought to deepen the physics of these processes (determining the energy consumption of the laboratory mill, determining the specific surface area, determining the vibrations of the ball mill, etc.).

The process of grinding or to decrease the size is based on probabilistic studies. Both the feed to machine and the resulting product are defined using a particle size distribution function, which expresses the probability of the presence of particles of a certain size in a sample of ground material. The grinding process must be carried out in such a way that there must not be undesirable changes in the processed material, such as impurities or excessive heating.

A simplified classic cement manufacturing flow is shown in the fig.1.1

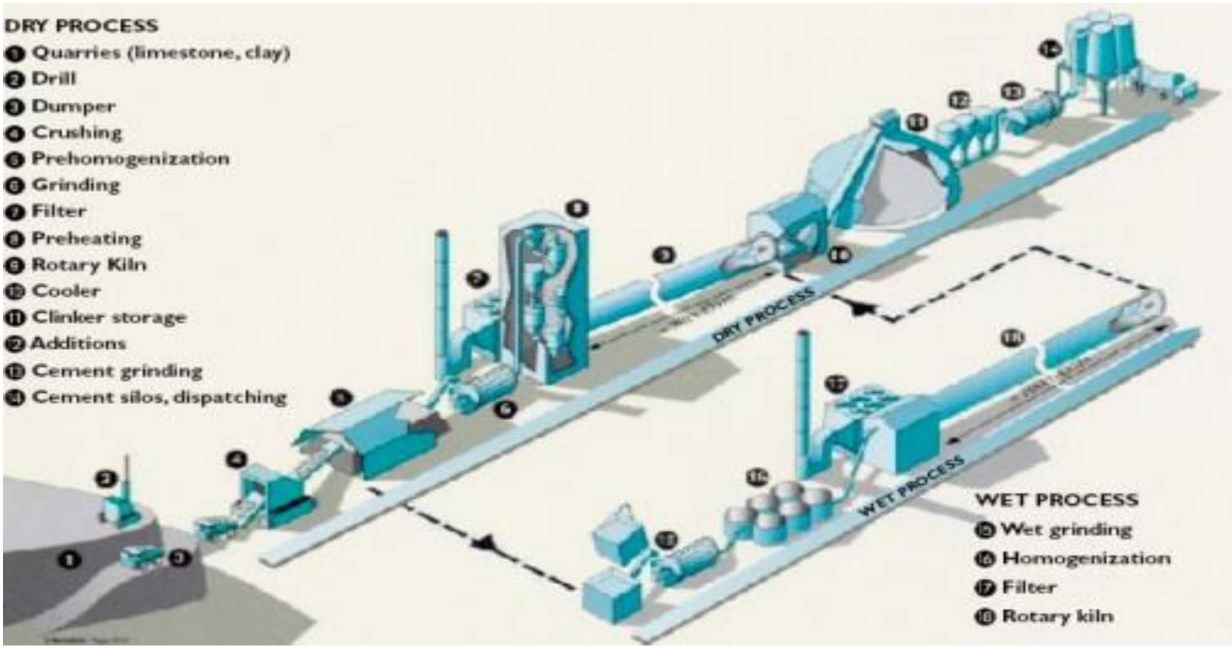

Fig.1.1 The general flow of cement manufacturing, [78]

The main operations (phases of the technological process) in order to manufacture cement are the following:

a) extraction of the raw materials;
b) loading and transporting the demolished material;
c) arrangement and storage of raw materials;
d) grinding and homogenization of raw materials;

e) burning the raw mixture, clinker obtaining;
f) clinker burning;
g) storage and grinding of the clinker.

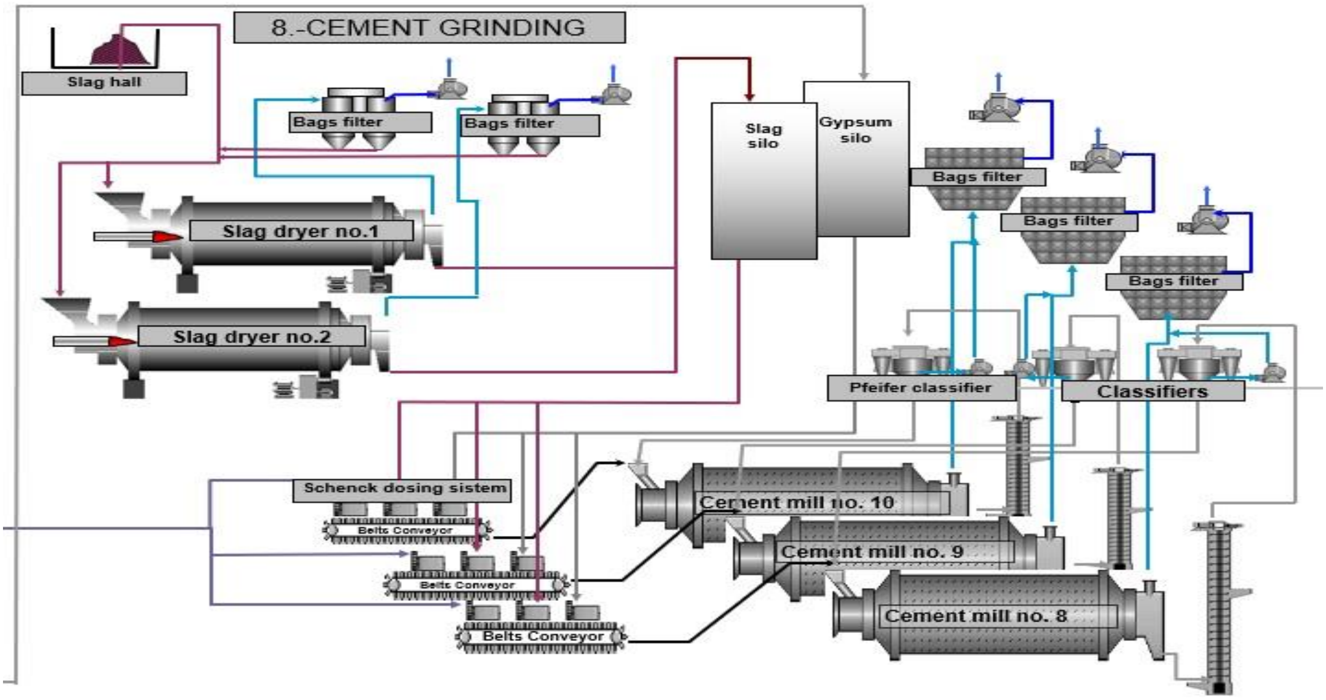

Fig.1.2 Flow of clinker grinding

h) packaging and delivery of cement
The shipment of cement from the silos can be loaded directly in bulk as well as bagged. Bagging is done with automatic rotary machines, after which the bags are arranged with the palletizing machine and wrapped with polyethylene film , [112].

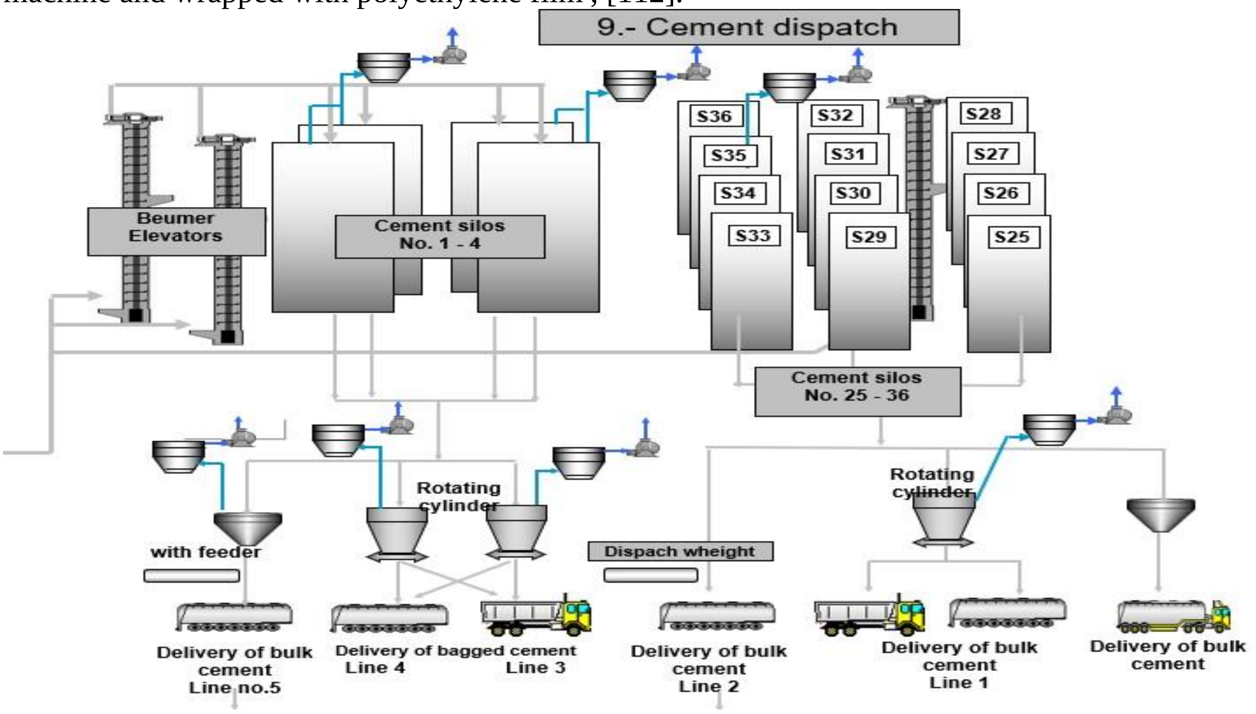

Fig.1.3 Flow of cement packaging and delivery

1.2. Aspects regarding environment protection in cement plants

Environment protection represents an absolute priority for Romanian cement producers, who are active members of the World Business Council for Sustainable Development (WBCSD), [107].

Significant investments were made to comply with Romanian legislation regarding all environment aspects such as air, water, soil, waste, etc. [107].

Environment protection in a cement plant requires compliance with the following steps:

- environment management;
- monitoring and reporting of environmental factors (emissions, immissions, waste waters, soil, etc.);
- reduction of dust emissions - dedusting of production equipment;
- improvements and modernizations of combustion facilities.

Environment management consists of the following activities:

a) *Implementation and certification in the plant of an integrated Quality - Environment - Occupational Health and Safety management system and a social responsibility management system according to: ISO 14001, ISO 9001 :2015, ISO 45001 :2018, SA 8000, etc., [112].*

b) *Implementation of internal and external audits according to annual planning or upon request in order to assure and improve the quality of the activity;*

c) *Informing and consulting external partners with whom the cement plant has concluded contracts in order to implement - modernize - assure the maintenance or purchasing of new equipment / machines in order to increase the productivity and reduce the emissions*;

d) *Raising awareness of staff and subcontractors regarding environment protection;*

e) *Efficient waste management.* These are classified and divided according to: waste type, code, origin and storage method. Attached is a description of an efficient waste management model (table 1.1)

Table 1.1 Waste management model, [95]

No. crt	Type of waste	Code compliant HG.856/2002	Source	Storage mode
1.	Waste paper (torn bags)	15 01 01	Shipment of cement	Waste paper warehouse
2.	Plastic waste (foil)	15 01 02	Shipment of cement	Storage boxes
3.	Wood waste (pallets)	15 01 03	Shipment of cement	Specially arranged spaces
4.	Conveyor belt waste	07 02 99	Maintenance and demolitions	Waste rubber platform
5.	Used tires	16 01 03	Maintenance	Waste rubber platform
6.	Ferrous waste	17 04 05	Maintenance and demolitions	Storage boxes

1.2.1. Monitoring and reporting of environment factors

This monitoring consists of:

- the fixing of gas analyzers for efficient combustion control;
- continuous monitoring of dust emissions: kiln, cement mills, grate cooler, coal mills;
- permanent monitoring of emissions of: NOx, SO_2, CO, O_2, HF, HCl, NH_3, C_6H_6, COT.

The automatic measurement system is checked at least once by parallel measurements applying reference method.

1.2.2. Decreasing of dust emissions

In the cement industry, emissions occur throughout the technological process, from quarrying to delivery. The sources of direct pollution in a cement plant are monitored according to the type and content of emissions, as shown schematically in fig.1.7.

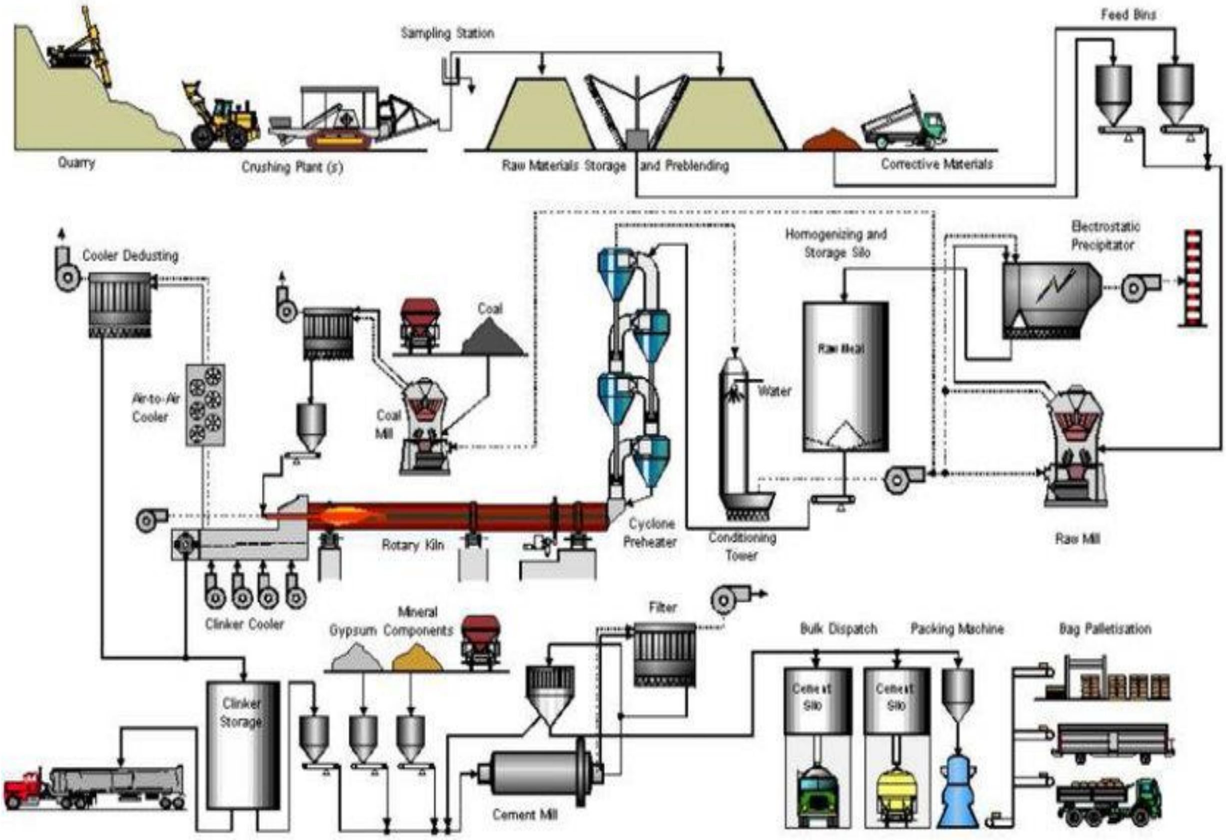

Fig.1.7 Identification of sources of emissions into the atmosphere and control method specific to a cement manufacturing plant, [114]

1.2.3. Arrangements and upgrades

The arrangements and upgrades at the cement plants consist of the following activities:

- arranging of green spaces;
- systematization of car loading of bulk cement;
- the purchase of new dust removal equipment used in production, transport and storage processes, in order to reduce the amount of dust released into the atmosphere and of the emissions of combustion gases;
- keeping of non-renewable resources (minerals and fossil fuels) by introducing alternative fuels into the cement production process;

1.3. The objectives of the doctoral thesis

Grinding ensures the correct functioning of the physical-chemical processes induced by the formation of the product, [114]. In this respect, the **main objective** of the thesis is the research on the clinker crushing process in ball mills, in order to reduce dust emissions.

The secondary objectives of the paper are:

- recognition of the factors that determine the process of clinker obtaining;
- analysis of the construction and operation of ball mills for clinker crushing;
- theoretical study of the technological working regime of clinker mills (degree of filling, speed, flow rate, yield, energy consumption, granulometry, etc.);
- the study on the current state of research on the working process of ball mills in the cement industry (summary of theoretical and experimental researches at global level concerning the operation and parameters of ball mills from cement industry);
- modeling and simulation with finite element of the working process of ball mills;
- development of methodology and experimental equipment;
- experimental laboratory determinations regarding the clinker crushing process in order to establish the influence of the different amounts of clinker/grinding media in the mill on the degree of grinding and the specific energy consumption for different amounts of clinker and balls in the mill;
- experimental determinations regarding the determination of grinding ability in the laboratory mill and on Zeisel laboratory apparatus;
- experimental determinations regarding the vibrations of the laboratory ball mill in different working variants;
- experimental determinations regarding the grinding process and the characteristics of crushed material in cement plants in Romania (determinations regarding the degree of grinding, Blaine specific surface of the grinder, specific energy consumption, the concentrations of the particles in suspension due to the grinding of the clinker);
- establishing concordances between the parameters of the grinding process of ball mills, in order to increase its quality (correlation of the specific energy consumption with the degree of grinding for different amounts of clinker and balls in mill);
- establishing correlations between the degree of grinding with the finest grinding categories (the connection between the degree of grinding and the particles quantity smaller than 1 micron, 5 microns and 10 microns);
- aspects regarding the monitoring of dust emissions from stationary emission sources (monthly measurements of dust carried out at the chimney of the ball cement mill - mill exit and separator exit) from a cement plant in Romania;
- experimental determinations regarding clinker crushing using PULVERISETTE 19 laboratory micro-mill and the quantitative analysis of the solid particle size by dry sieving with the Analysette 3 Spartan sieve classifier.

CHAPTER 2. ASPECTS REGARDING THE PHYSICAL PROPERTIES OF THE RAW MATERIALS USED IN THE CEMENT INDUSTRY

2.1. Brief history of Portland cement

The first who discover Portland cement was the English builder, **Jozef Aspdin**. In 1822, in Portland City (England), he obtained a binder material from a mixture of lime and clay burned until the carbon dioxide was completely removed. In 1824 he was offered a certificate for obtaining the first adhesive material, later recognized as a type of cement, which still exists today.

Portland cement is produced by burning in a rotary kiln at temperatures of 1400-1500 °C, a mixture made up of lime, iron, silicone and alumina (aluminum oxide), which is chemically transformed. The resulting clinker, mainly composed of calcium and aluminum silicate compounds, is ground with small amounts of calcium sulfate in order to obtain a powder with a sufficient grinding fineness. At the same time, the quality of the cement improves, the strength index increases, the assortment is diversified, different types of cement are produced for various branches of industry.

2.2. Physical-chemical and mineralogical characteristics of the raw and auxiliary materials for clinker production

Portland cement is the final result of burning a mixture of raw materials until it partially melts. Its ingredients include limestone, alumina clay, iron oxide and aluminum oxide.

Fig.2.1 Clay, [115]

Fig.2.2 Limestone, [115]

Fig.2.3 Marl, [115]

For different products, the kiln mixes a mixture or a paste of meal in the raw materials. This process is called preparation and takes place in three stages:

- preparation of the raw mixture;
- clinker burning;
- grinding cement clinker with additives such as gypsum or kiln slag to produce the desired type of cement.

2.2.1. Chemical composition of clinker

The normal oxide composition of a Portland cement is contained within the following limits:

Table 2.1 Composition/notation of oxides in the cement industry [115]

Oxide	Composition percentage	Notațion
CaO	60 – 67%	C
SiO_2	19 – 24%	S
Al_2O_3	4 – 7%	A
Fe_2O_3	2 – 6%	F
MgO	4 – 5%	M
SO_3	Max 3%	S

In order to achieve the specified composition, used raw material should be a proportion of 75 ÷ 80% $CaCO_3$ and 25 – 30% SiO_2, Al_2O_3, Fe_2O_3.

2.2.2. Mineralogical composition of clinker

The mineral composition of Portland cement clinker can be described by the following relationships:

$$C_3S + C_2S \quad = 75\% \tag{2.1}$$

$$C_3A + C_4AF = 25\% \tag{2.2}$$

2.2.3. Physical-chemical characteristics during thermal processing of clinker

The quality of clinker depends on its chemical and mineralogical composition. The chemical composition is characterized by the content of different oxides in the clinker, and the mineralogical composition by the ratio of minerals obtained after burning.

Among the physical and mechanical properties of cement, the most significant are:

a) **Density**: it is between 3 ÷ 3.2 g/cm^3. Determined by the pycnometer method using petroleum ether as the working fluid.

b) **Setting time**: Start and end of the set are terms used to distinguish cements in terms of setting speed.

c) **Water of normal consistency**: The water added to cement to make mortar or concrete must give the mixture the necessary fluidity.

d) **Volume variation**: Cement stone exhibits contraction and expansion phenomena during hardening. The high content of 3CaO*SiO_2 (C_3S) reduces cement shrinkage.

e) **Mechanical strengths**: The compressive strength is calculated in a standardized way on granular sand-cement mixtures.

2.3. Manufacturing recipes

In order to obtain quality concrete, it is necessary to check the quality of used materials, especially the quality of the aggregates, by purchasing from certified, reliable sources.

Table 2.3 shows the usual types of cement used.

Table 2.3 Types of cement. Classification according to EN 197-1, [118]

Cement type	*Rating of the 27 products (types of common cements)*		*Composition (percentage by mass) – Main components: Clinker K*	*Composition (percentage by mass) – Main components: Additions*
CEM I	Portland cement	CEM I	95-100	-
CEM II	Portland cement with slag	CEM II/A-S	80-94	Blast furnace slag, S: 6-20
		CEM II/B-S	65-79	Blast furnace slag, S: 21-35
	Portland cement with ultrafine silica	CEM II/A-D	90-94	Ultrafine silica, D: 6-10
	Portland cement with pozzolana	CEM II/A-P	80-94	Natural pozzolana, P: 6-20
		CEM II/B-P	65-79	Natural pozzolana, P: 21-35
		CEM II/A-Q	80-94	Calcined natural pozzolana, Q: 6-20
		CEM II/B-Q	65-79	Calcined natural pozzolana, Q: 21-35
CEM II	Portland cement with fly ash	CEM II/A-V	80-94	Siliceous fly ash, V: 6-20
		CEM II/B-V	85-79	Siliceous fly ash, V: 21-35
		CEM II/A-W	80-94	Calcined fly ash, W: 6-20
		CEM II/B-W	65-79	Calcined fly ash, W: 21-35
	Portland cement with calcined shale	CEM II/A-T	80-94	Calcined shale, T: 6-20
		CEM II/B-T	65-79	Calcined shale, T: 21-35
	Portland cement with limestone	CEM II/A-L	80-94	Limestone, L: 6-20
		CEM II/B-L	65-79	Limestone, L: 21-35
		CEM II/ALL	80-94	Limestone, LL: 6-20
		CEM II/BLL	65-79	Limestone, LL: 21-35
	Composite Portland cement	CEM II/A-M	80-94	S,D,P,Q,V,W,T,L,LL: 6-20
		CEM II/B-M	65-79	S,D,P,Q,V,W,T,L,LL: 21-35
CEM III	Kiln cement	CEM III/A	35-64	Blast furnace slag, S: 36-65
		CEM III/B	20-34	Blast furnace slag, S: 66-80
		CEM III/C	5-19	Blast furnace slag, S: 81-95
CEM IV	Pozzolanic cement	CEM IV/A	65-89	D,P,Q,V,W: 11-35
		CEM IV/B	45-64	D,P,Q,V,W: 36-55
CEM V	Composite cement	CEM V/A	40-64	S: 18-30 P,Q,V: 18-30
		CEM V/B	20-38	S: 18-30 S,P,Q,V: 31-50

2.4. The factors that influence the process of clinker obtaining

The most important factors that influence the process of clinker obtaining are:

- material temperature that must be maintained between 1450-1500 °C, and the flame temperature that must be~2000 °C.
- the fuels used in the cement industry in Romania are: fuel oil, coal, petroleum coke, natural gas, and alternative fuels resulted from waste, [107].

2.5. Conclusions

At the base of cement manufacturing process is clinker obtaining by decomposition of raw materials (including decarbonation of limestone) up to calcium, silicone, iron and aluminum oxides and their mineralization in the form of clinker. The formation of clinker is a complex, intensively energy-consuming process.

This process inherently emits CO_2 (greenhouse gas), resulting from both the decarbonation of limestone and the burning of various fuels (traditional and alternative) in the clinker kiln in order to obtain the necessary thermal energy. Other greenhouse gases such as methane and nitrous oxide may be emitted during cement production, but their importance is low compared to that of CO_2. They can result from incomplete combustion, fugitive emissions or other outgassing, or even side reactions, especially with nitrogen in the air. Each additional molecule of CH_4 or N_2O from atmosphere blocks more infrared radiation than one molecule of CO_2. However, the average residence time in the atmosphere also varies with each gas, with that of a methane molecule being, for example, shorter than that of CO_2, particularly as it can be oxidized. The clinker is then crushed together with gypsum and transformed into Portland cement. In the European Union, the cement is mainly produced by modern "dry process" technology. This consumes about 50% less energy than burning the clinker in a kiln using the "wet process".

Cement manufacturers have expanded the use of mineral compounds in cement by developing a wide range of composite cements with increasingly diverse applications. Their use in concrete brings multiple benefits, among which we mention:

- for hardened concretes – increasing of final strengths, decreasing of hydration heating and implicitly of the tendency of their cracking, increasing of concretes durability.
- improving the properties of fresh concrete (workability, reduction of segregation, etc.)

CHAPTER 3. TECHNOLOGIES AND EQUIPMENT ON THE FLOW FOR CLINKER OBTAINING

3.1. General technological scheme (technological flow) for cement obtaining

By reviewing the analysis of the entire cement manufacturing process, starting from the quarry and ending with the way of delivery, the equipment and machinery specific to each operation were identified, as shown in Table 3.1

Table 3.1. Equipment and machinery related to technological processes

<table>
<tr><th>No. Crt</th><th>Technological phase</th><th colspan="2">Equipment and machinery used</th></tr>
<tr><td>1</td><td>Extraction of raw materials</td><td colspan="2">Excavators; Bulldozers
Perforators; Drills</td></tr>
<tr><td>2</td><td>Primary grinding</td><td colspan="2">Crushers: jaw, hammer, impact, rotary, roller</td></tr>
<tr><td>3</td><td>Fine grinding</td><td colspan="2">Grinding plants with material recirculation
Wet grinding plants without recirculation
Dry grinding facilities
Rotary drum mills, tubular bar mills, roller mills</td></tr>
<tr><td>4</td><td>Drying facilities</td><td colspan="2">Drum dryer, vertical dryer, fluidized bed dryer</td></tr>
<tr><td rowspan="2">5</td><td rowspan="2">Clinker plants</td><td>Installations for the wet and semi-wet process</td><td>With internal heat exchangers;
With external heat exchangers
With heat exchangers in stages</td></tr>
<tr><td>Installations for the dry and semi-dry process</td><td>With rotary kiln and rolling grrate - Lepol in fluidized layer;
With heat exchanger in suspension;
With kiln with gas suspension heat exchanger and heat exchanger</td></tr>
<tr><td>6</td><td>Cooling installations</td><td colspan="2">Rotary coolers; planetary coolers; grate coolers; mixed</td></tr>
<tr><td>7</td><td>Packaging and delivery facilities</td><td colspan="2">Bulk cement delivery facilities;
Cement bagging installations;
Linear and rotary bagging machines.</td></tr>
</table>

3.2. Technological schemes for clinker obtaining

There are four main cement production processes: dry, semi-dry, semi-wet and wet. The selection depends on the state of the raw materials (wet or dry).

a) DRY PROCEDURE

The mixture is introduced into short rotary kilns with external heat exchangers where the material is first suspended in air.

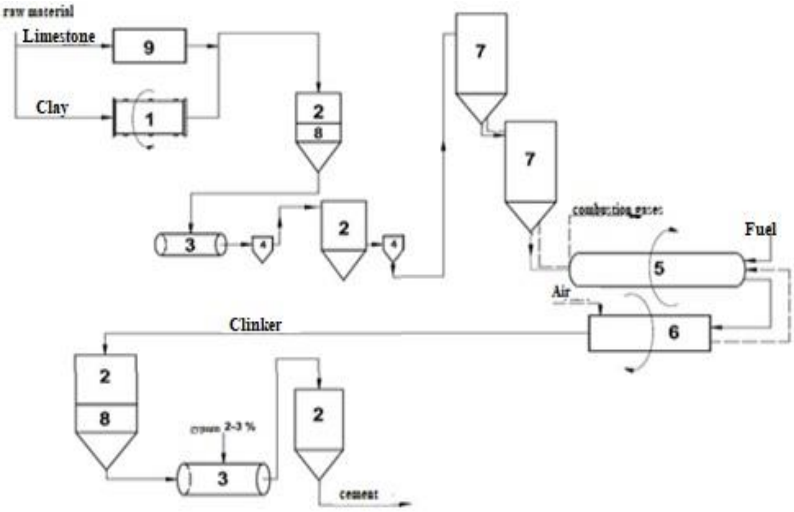

Fig.3.15 Technological scheme for the manufacture of Portland cement after the dry process, [121] where: 1. dryer; 2. silo; 3. ball mill; 4. compressor; 5. kiln; 6. cooling drum; 7. cyclone tower; 8. weighfeeder; 9. crusher with hammers

In the dry process, in order to reduce the consumption of methane gas by 30 ÷ 35%, a precalcining station was attached to the combustion kiln where the temperature of the raw materials reaches up to 150º, consuming lower coals with a calorific value of 1500 ÷ 1800 kcal/kg (1 kcal = 4,186 kJ).

b) WET PROCEDURE

Wet grinding of raw materials in order to obtain a mixture of slurry of raw materials with a water mixture of 30-50%. The kiln used for clinkering is serviced with the resulting paste during the grinding process.

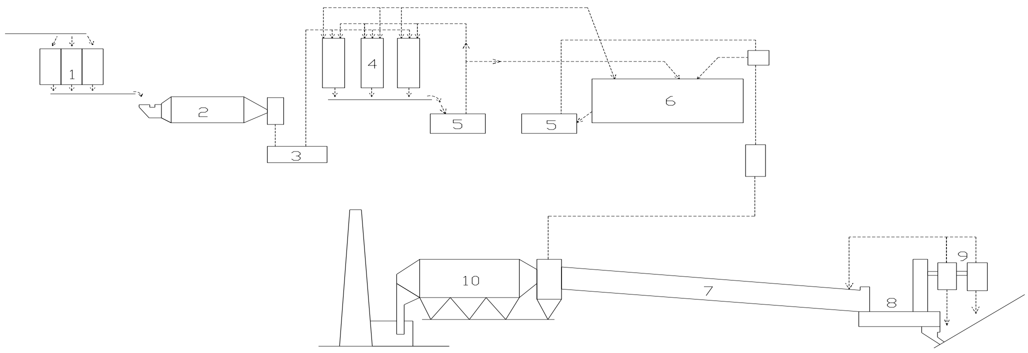

Fig.3.16 Technological flow for wet process, [122]

where: 1. raw material supply bins; 2. slurry mill; 3. slurry pumps; 4. slurry basins; 5. pumping station; 6. slurry homogenization basin; 7. rotary kiln; 8. clinker cooler; 9. multicylon type dust removal; 10. dust removal installation.

c) SEMI-DRY PROCESS

The raw material is prepared according to a technique similar to the dry process. The raw meal is mixed with 8-12% water and the resulting granules are sent to the kiln. The raw mixture is fired in a kiln with grate cooler. This process can be used when dry process conditions are met and the meal has good granulation properties.

d) SEMI-WET PROCESS

The raw material is crushed in the same way as at the wet process. Filter the resulting slurry to remove excess water. The resulting cake with a moisture content of 18 ÷ 20% is granulated and placed in a clinker kiln. This procedure is used when the suspension has good filterability.

3.3. Equipment used in the technological flow for clinker obtaining

3.4. Construction and operation of ball mills for clinker crushing

3.4.1. Construction of ball mills in the cement industry

Ball mills, also known as rotary drum mills, are used for fine and ultrafine grinding of soft, medium-hard, brittle and hard materials. They essentially consist of a cylindrical or sometimes cylindrical-conical drum, which rotates around its horizontal axis. The grinding media together with the material to be crushed occupy between 20 and 40% of the useful volume of drum mills.

The operating principle of the cement mill is as follows:

- ✓ The material is fed uniformly into the first chamber of the ball mill (made of steel or cast iron alloy of high quality in the proportion of approx. 30%) by the feeding device through the hollow shaft. The first chamber has stepped liner or corrugated liner (armors) which is filled with steel balls of various specifications.

✓ After the material reaches coarse grinding in the first chamber, it enters in the second chamber through the single layer transfer slot. The second chamber is incorporated with a flat liner with steel balls inside in order to crush the material. The powder is released through the exhaust pipe.

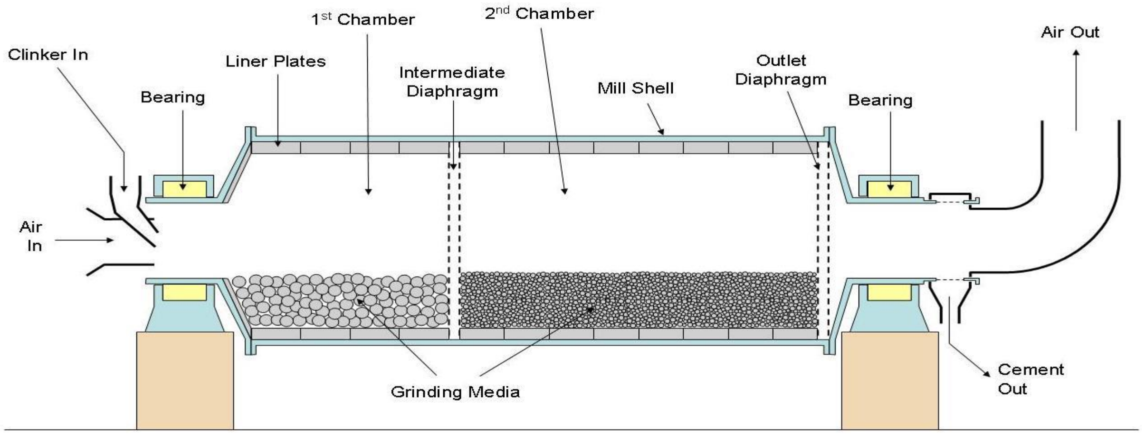

Fig.3.49 Scheme of the ball mill used to grind clinker in cement manufacturing, [40, 22]

Grinding technology is based on the following remarks:

- the particle size fraction from 3 to 30 microns is ideal for developing cement strength;
- the particle size fraction below 3 microns contributes only to the initial resistance; this particle fraction hydrates quickly and after a day results the highest compressive strengths;
- the fraction over 60 microns hydrates slowly and contributes to cement strength;
- tubular mills are generally equipped with sensors (of various types) that indicate the degree of filling in each chamber.
- ventilation of the mill is necessary for its dust removal and cooling;
- during grinding, the temperature of the materials and the friction between the bodies in the mill lead to an increase of inside temperature.

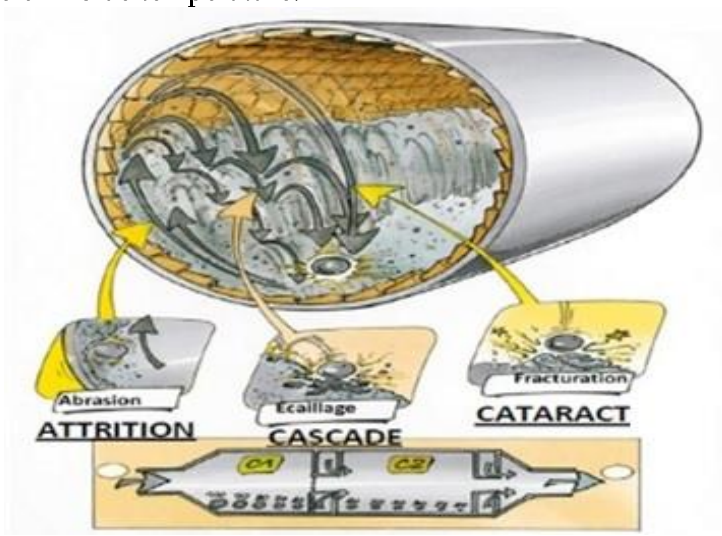

Fig.3.50 Grinding of clinker and additives, [22, 76]

That is why the most important thing in grinding is the importance of the degree of filling of the mill. The evacuation of the crushed material (cement) is done through the partition wall located between the two rooms but also through the wall at the exit of the mill, these being provided with slots of different sizes (fig. 3.51). The crushed material, reached the appropriate granulometry, passes from one chamber to another and exits the mill through these slots and through the ventilation ring.

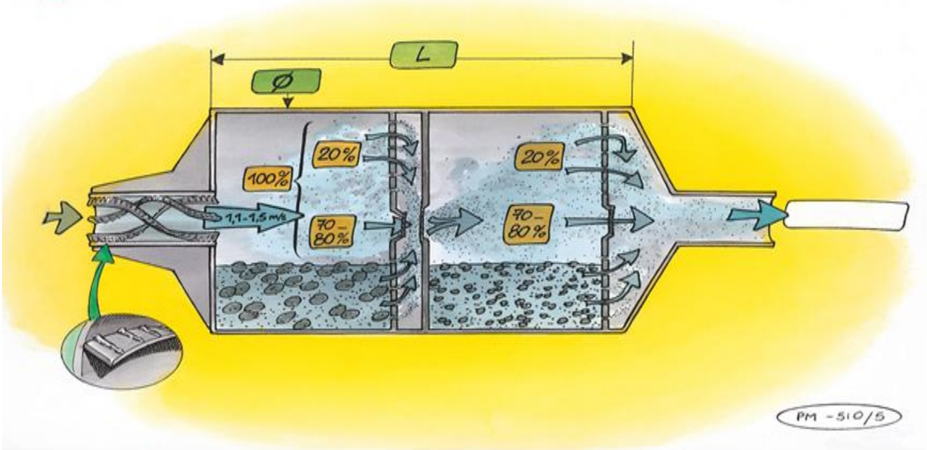

Fig. 3.51. Evacuation of crushed material (cement), [22,76]

The mill is continuously fed, it works in a closed circuit. The retention time of the material in the mill differs depending on the crushing degree of the materials which entering the mill (how easily they are crushed), the fineness of grinding (fineness of the finished product, cement).

At the mill exhausting, the material is taken over by a pneumatic chute and transported to a vertical elevator that, through a pneumatic chute, feeds the dynamic separator, where the fine particles are separated from the coarse ones (fig. 3.52). The tail is the coarse part of the material at the exit of the separator. The meal is the best part of the material leaving the separator, in this case the finished product, i.e. cement.

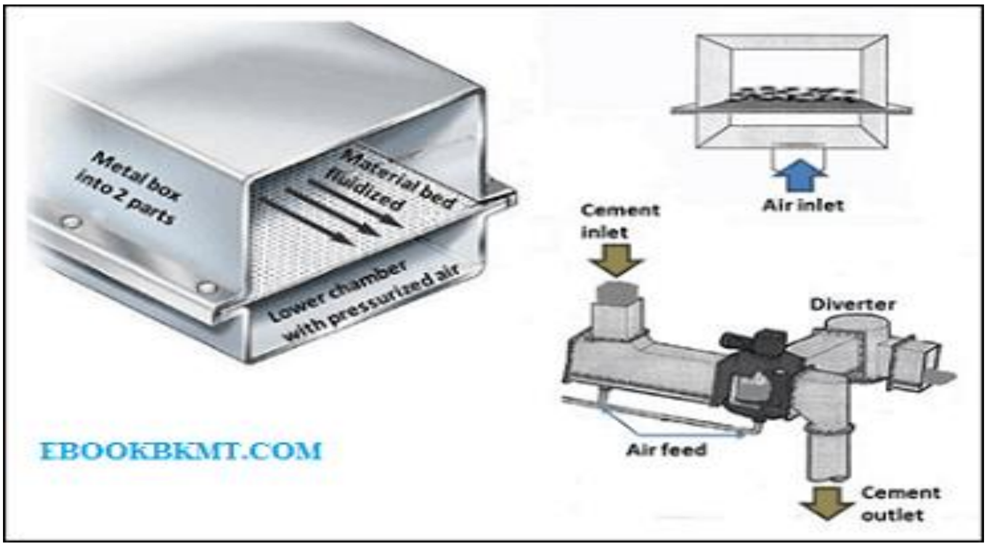

Fig. 3.52. Dynamic separator, [138]

where: 1.lower room; 2. support room; 3.fabric with membrane; 4. feeder

3.4.2. Technological regime of clinker mills

The behavior of the grinding media in the crushing drum is defined by two quantities: the filling degree in which the grinding media fill the drum and the rotation of the drum. Depending on the values of these two operating regimes, the ball mill works as follows:

- cascade operation mode (low speed operation);
- operating mode cataract (high speed, operation with falling balls).

In cascade operation, the balls rise to a certain height along concentric trajectories in the drum, then roll into the lower parallel layer of the drum (Fig. 3.53 a).

In the operative state of cataract (with falling balls), the balls are introduced into the drum along concentric circular trajectories up to a certain height, from where they fall, following a parabolic trajectory, to the lower part of the drum (fig. 3.53b). In practice, the most used is the operating regime in cataracts.

When the mill drum rotates, the balls rise to a certain height together with the material to be crushed, and then by falling, impact grinding takes place.

If a grinding body of mass m is at radius r in rotation, then the centrifugal force acts on it $F_c = mr\omega^2$ and own weight $G = mg$ (fig.3.55). At the detachment point A, the balance of forces is given by the relationship:

$$F_c = G\cos\alpha \Rightarrow mr\omega^2 = mg\cos\alpha \qquad (3.2)$$

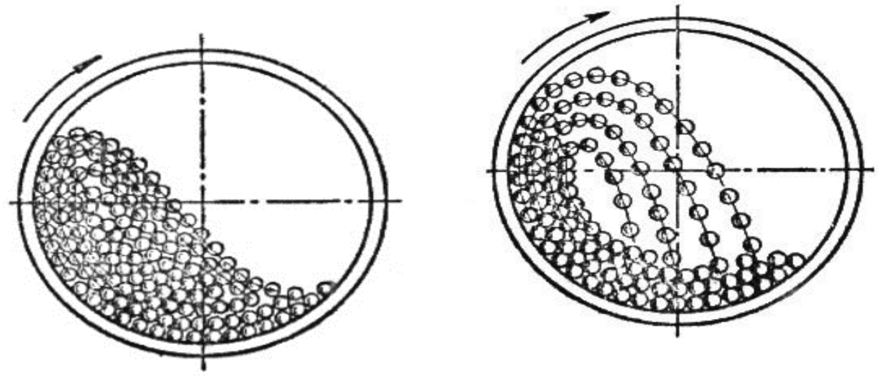

Fig. 3.53 Modes of operation of ball mills a) in cascade, b) in cataract, [37**]**

from which it follows: $\omega = \sqrt{\frac{g\cos\alpha}{r}}$ (3.3)

If it is assumed that the detachment of the grinding body from the surface of the drum is done at point E, of maximum height, where $r = \frac{D}{2}$, then the value of the critical angular velocity is obtained.

$$\omega_{cr} = \sqrt{\frac{2g}{D}} \qquad (3.4)$$

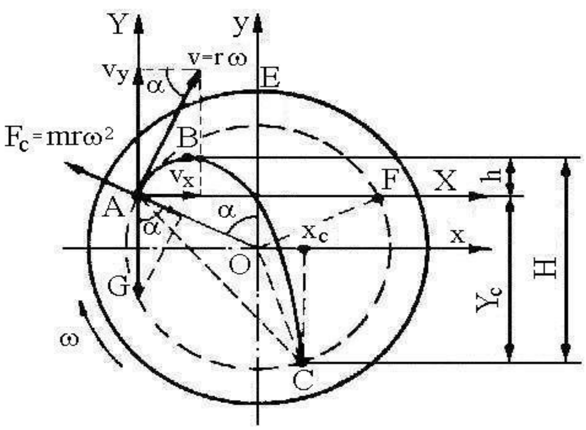

Fig.3.55 Decomposition of the forces of a grinding media, [37]

The influence of the filling degree of the mill on the process

The filling degree of the mill, φ, influences the regime speed, according to the relationship:

$$n = \frac{8}{\sqrt{D}}(5\varphi + 2) \quad (3.5)$$

where: *D* - diameter, in m;

n – the revolution, in rot./min.

Its value ,φ is chosen so that there is no interference between the material that goes up on the arch CA and the one that falls after the parabola ABC (fig. 3.56) because this would cause an increased consumption of energy without increasing the efficiency.

The filling degree is defined by the formula:

$$\varphi = \frac{V_u}{V} = \frac{4M}{\rho_v(\pi D^2 L)} \quad (3.6)$$

where: $\rho_v = \rho(1 - \varepsilon_g)$ is the bulk density of the grinding media; ε_g - gaps percentage;

Influence of mass and balls dimensions on the process

The dimensions of the grinding bodies (balls) are taken according to the maximum dimensions *Dmax* of the pieces subject to grinding. In the case of balls, the following is calculated:

- *the lower limit of the ball diameter* d_{bmin} ,

$$d_{b,min} = D_{max}\sqrt{\frac{\sigma_{rc}^2}{1{,}28E\rho_b gD}} \quad (3.7)$$

where: σ_{rc} - the compressive strength of the fed material; *E* – the modulus of elasticity; ρ_b - ball density; *D* – inner diameter of the drum.

- *its upper limit* d_{bmax},

$$d_{b,max} = \frac{D}{18} \div \frac{D}{24} \quad (3.8)$$

- ***The influence of the mill diameter on the process***

The flow of the mill depends on a series of factors: the diameter and the length of the drum, the number of compartments, the construction of the diaphragms, the speed, the shape and dimensions of the grinding media, the mechanical characteristics of the material to be crushed, the degree of grinding, the degree of filling with grinding media and material to be processed, etc.

The mass flow of the mill is determined with the relation:

$$Q_m = \frac{1}{\sigma_{rc}} LDM_m[10 + 0{,}35(x - 10)]\left(\frac{t}{h}\right) \quad (3.9)$$

where: *D* şi *L* are in meters; M_m - mass of grinding media, in tons; *x* – percentage of residue.

The relationship for determining the required power is:

$$P_n = k \cdot M_b \cdot D \cdot \omega \quad (3.10)$$

where: k – constant; M_b - the mass of the grinding bodies.

If the angular speed of rotation is the optimal one, is obtained as follow:

$$P_n = k \cdot G_b\sqrt{D}\ (kW) \quad (3.11)$$

where: G_b - weight of grinding bodies, in [kN]; D - drum diameter, in (m); k - constant which depends on the filling degree and the nature of the grinding media

3.4.3 The power requirement for driving tubular ball mills

Power output necessary for mill is:

$$N = G \cdot r \cdot \omega = G \cdot R_0 \cdot \omega \cdot sin\alpha \qquad (3.12)$$

where G is the weight of grinding load, R_0 is the radius which define the position of centre of gravity, and ω is angular rotation speed of the drum.

3.5. Conclusions

The manufacture of cement is an energy-intensive process that involves the proper dosing of components according to the manufacturing recipe (clinker, slag and limestone, gypsum) and their crushing in tubular ball mills. During the final crushing, which must meet the requirements for average particle size and specific surface area, well-defined proportions of furnace dust are added, as well as the filter dust obtained during the crushing and separation process.

Because cement can be produced in three ways (dry, wet and combined), the equipment is purchased separately for each of them. Therefore, one must first decide what technology is applied in order to produce the cement, and then the equipment are purchased. In our country, all cement plants operate using the dry process. The dry method is good because less coal is needed. For this simple reason it becomes more and more widespread.

CHAPTER 4. THE CURRENT STATE OF RESEARCH ON THE WORKING PROCESS OF BALL MILLS IN THE CEMENT INDUSTRY

4.1. Synthesis of theoretical research on the working process of ball mills in the cement industry

4.1.1. Theoretical basis of material grinding in ball mills

For almost a century, grinding processes have been studied in terms of the energy consumed during grinding. This way of looking at the matter is correct and logical, because the grinding, as has been shown, is a decisive factor in determining the cost price of cement manufacture, and the energy consumed for this is largely due to the crushing processes.

The Russian academician **Rebinder** developed a general formula of the relationship regarding the distribution of mechanical work in the grinding process. Therefore, according to Rebinder's theory, the specific energy consumption (expressed, for example, in kgf.m/cm^3) of the crushed material can be expressed as, [141]:

$$E_s = L_1 + L_2 \qquad (4.1)$$

where: L_1 – the mechanical work consumed by the machine; L_2 – the mechanical work consumed in the grinding process.

Each of the two terms can be decomposed:

$$L_1 = L_{11} + L_{12}$$
$$L_2 = L_{21} + L_{22} \qquad (4.2)$$

where: L_{11}- the mechanical work provided to the machine for the elastic deformation of the elements that compose it; L_{12}, L_{22} - the mechanical work consumed for the generation of new surfaces, at the active elements of the machine; L_{21}- represents the mechanical work necessary for the elastic deformation of the piece of material, until it breaks;

For the L_2 value belonging to the material, it can be written as:

$$L_{21} = N \cdot k_{21} \cdot \frac{\sigma_r^2}{2E} \quad (4.3)$$

$$L_{22} = k_{22} \cdot \Delta A \cdot \alpha \quad (4.4)$$

Size α is defined as:

$$\alpha = \left(\frac{A_2}{A_1}\right)^n \quad (4.5)$$

This leads to the generalized law of fragmentation:

$$E_s = L_1 + N \cdot k_{21} \cdot \frac{\sigma_r^2}{2E} + k_{22} \cdot \Delta A \cdot \alpha \quad (4.6)$$

In relation (4.6) the degree of grinding can be found in the size α, and the conditions under which the grinding operation takes place in the size *N* and the exponent *n*.

The physical yield of grinding is:

$$\eta_f = \frac{\sigma \cdot \Delta A}{E_{ef}} \quad (4.7)$$

The most important part of the quantity E_{ef} comes from the deformation of the individual particles and the mechanical work of deformation, which is crsuhed

The technical yield is:

$$\eta_f = \frac{\sigma \cdot \Delta A}{E_{totală}} \quad (4.8)$$

Thus, $\eta_t \approx 0{,}01 \div 0{,}1\%$.

Charles-Walters developed a general theory to calculate useful grinding energies, valid for any material to be crushed, [141]:

$$\frac{dE}{dx} = -\frac{C}{x^m} \Rightarrow dE = -\frac{C}{x^m} dx \quad (4.9)$$

The useful grinding energy will be:

$$E_s = \int_0^E dE = -\int_D^d \frac{C}{x^m} dx \quad (4.10)$$

For the value *m* = 1 the above relation is integrated and thus the law is obtained ***Kick-Kirpicev:***

$$E_s = C_1 \left[lg\left(\frac{1}{d}\right) - lg\left(\frac{1}{D}\right) \right] \quad (4.11)$$

<u>According to the Kick-Kirpicev law</u>, the energy required to shred identical and homogeneous bodies varies directly proportional to the *volumes* or *weights* of these bodies

Kirpicev's law was controlled experimentally and a connection was found in the case of large-sized materials but significant errors in the case of small-sized materials, [141].

For the value *m = 2* from the relationship (4.10) is obtained ***the Rittinger law***:

$$E_s = C_2 \left(\frac{1}{d} - \frac{1}{D}\right) \quad (4.12)$$

<u>According to Rittinger's law,</u> the useful crushing energy is proportional to the increase in surface *area*

For the value m = 1,5 from the relationship (4.10) is obtained ***Bond law***:

$$E_s = C_3 \left(\frac{1}{\sqrt{d}} - \frac{1}{\sqrt{D}}\right) \quad (4.13)$$

<u>According to Bond law</u>, useful grinding energy is equal to the difference between the *energies* contained in the material after and before grinding. The constant C_3 can be put in the form:

$$C_3 = W\sqrt{100} \tag{4.14}$$

If the relationship is replaced (4.13) in the (4.14) is obtained :

$$E_s = W\left(\frac{1}{\sqrt{d}} - \frac{1}{\sqrt{D}}\right) \cdot \sqrt{100} = W\left(\frac{\sqrt{D}-\sqrt{d}}{\sqrt{D}}\right) \cdot \sqrt{\frac{100}{d}} \tag{4.15}$$

or:

$$W = E_s\left(\frac{\sqrt{D}}{\sqrt{D}-\sqrt{d}}\right) \cdot \sqrt{\frac{d}{100}} \tag{4.16}$$

The Bond Act has wider applicability than the **Kirpicev and Rittinger** Acts. Introducing the specific surface, A, is inversely proportional to the square of the particle size, relation (4.9) becomes, [141]:

$$\frac{dA}{dE} = C_1 \cdot x^{\alpha} \tag{4.17}$$

Tatsuo Tanaka proposes a detailed version of the relationship mentioned above, [141]:

$$\frac{dA}{dE} = K \cdot (P_c) \cdot (P_\sigma) \cdot (P_a)x^{\alpha} \tag{4.18}$$

where: P_c- the probability of particle collisions; P_σ- the probability that the breaking strength of the material will be exceeded.

Djingenzhian's thermodynamic theory follows from the following point of view: the sum of the kinetic energy required to crush the material and the internal caloric energy of the crushed material, which is transformed into useful work, is a constant, according to the relationship, [141] :

$$E_c + Q_{int} = k \cdot Q \tag{4.19}$$

where: E_c - the kinetic energy of grinding; Q_{int} - internal caloric energy transformed into useful mechanical work; Q - the heat generated during grinding; k - thermodynamic constant that characterizes the material subjected to grinding.

Carey and Stairmand's theory of free grinding begins with the idea that during grinding, an external force is applied to the particles subject to grinding, resulting in a particle size distribution, of the resulting fragments, characteristic of the material, which can be called a "natural distribution". [141].

The theory of free grinding can be transposed into the relationship:

$$E_p - E_m = \eta \cdot E_c \tag{4.20}$$

where: E_p- the energy of the grinding product; E_m- raw material energy; E_c- he energy consumed by the grinding machine; η - the energy yield of the machine.

Andreasen's model theory starts from the idea that one can quantitatively determine the variation of a certain property of the material for grinding when the size ratio changes, [141].

4.1.2. The current stage of theoretical studies on the working process of ball mills

The grinding operation is evaluated by the degree of grinding defined by the relation, [141]:

$$i = \frac{D}{d} \tag{4.21}$$

where: D - the average size of the fed material; d - average size of grinding material.

The synthesis of theoretical research on the working technology of ball mills was compiled from the translation of several research papers published in specialized magazines and websites (World Cement, ZKG, Cemento Hormigon, Revista Română de Materiale, Minerals Engineering, Researchgate.net , Energies etc) and includes information about:

4.3.Conclusions

The grinding theories have a more or less empirical character, a rather approximate range of validity, and none of them can be considered as a general law of the process.

They are based on simplifying assumptions regarding the real phenomenon of grinding, disregarding one or more of the findings known or highlighted by practice. Confirmed or unverified by experiments, supported or disputed by various authors, some or others from these empirical theories can still be used to study the mechanism of grinding;

CHAPTER 5. ASPECTS AND THEORETICAL CONTRIBUTIONS REGARDING CLINKER CRUSHING IN BALL MILLS

5.1. Mathematical modeling of the working process of ball mills

The description, design and operation of a technological system, therefore also the system that defines a cement manufacturing plant (fig. 5.1), can be done by modeling it.

Considering the whole installation as a system, three subsystems can mainly be defined, for the definition of which it is necessary to specify very clearly the boundary surface separated from the environment and/or system and the interactions between them.

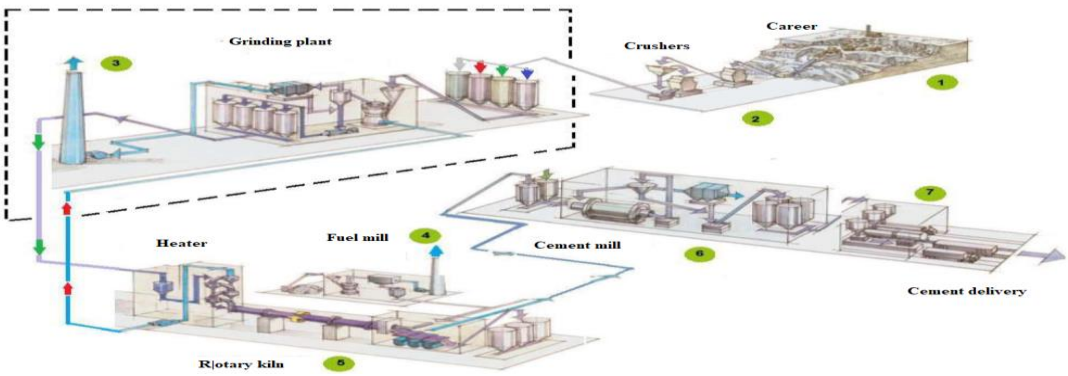

Fig.5.1 Cement manufacturing systems: hot gas flow mixed with material particles collected from the cyclone tower; material flow, [443]

5.1.1. Technical implementation

All numerical integrations are performed by an explicit Runge-Kutta method. Ball trajectories must also be calculated as a function of the surface of fill with balls of the cement mill.

5.1.2. Parameters of the cement mill

a) Rotation speed: in the mathematical model, the rotation speed of the mill can be changed in order to obtain different results (eg: different trajectories, different kinetic energies of the balls).

b) Suspension volume: in the case of the mathematical model, this parameter seems not to be important for the energy of the balls hitting the surface of the mill.

c) Balls volume: An increase in the number of balls would reduce the number of flying balls, but the problem that can arise is that the filling could become too heavy.

5.1.3. Definition the material circulation matrix

According to the law of mass conservation, the sum of all the matter entering the system in a given time interval and the sum of the matter present at the initial time must be equal with the material released in the same time interval and the material remaining in the system.

5.1.4. Material balance for the grinding plant

The relation for the conservation of mass and which is expressed by the balance equation of the respective quantity, has the following general form:

$$\frac{\text{accumulations in the system}}{\text{unit of time}}=\frac{\text{inputs in the system}}{\text{unit of time}}-\frac{\text{outputs in the system}}{\text{unit of time}}+\frac{\text{products in the system}}{\text{unit of time}}-\frac{\text{consumption in system}}{\text{unit of time}}$$

Taking into account the complexity of the system through the existing interactions between the components, an accessible way is to calculate global material balances using matrix calculation relationships. The balance of materials for an apparatus *i* of the grinding plant is represented schematically in fig. 5.4.

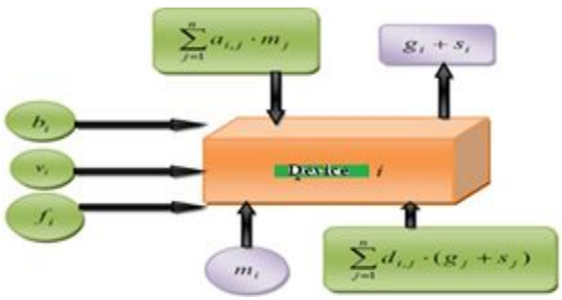

Fig.5.4. Material balance diagram for device *i*, [40]

In order to perform the mathematical modeling of the cement grinding process using ball mills, cement samples were brought from a Romanian cement plant of a certain type (CEM II/A-LL 42.5R). It were obtained the following results, shown in the table 5.1.

Table 5.1 Resulting cement values by granulometric classes, [53]

No. Crt	Granulo-metric classes (sieve diameter)	Cumulative Passes [%]														
		Sample code														
		85	86	87	88	89	95	96	97	98	113	114	115	116	117	118
1	<1 µm	4.9	1.2	1.2	0.4	0.4	4.6	0.4	0.4	0.4	0.4	4.9	0	0	0.4	0.4
2	<1.5 µm	5.7	3.4	2.0	0.8	0.9	5.0	1.2	0.8	0.8	0.8	5.7	0.8	0.4	1.2	0.8
3	<2 µm	6.5	4.7	3.1	1.2	1.3	5.4	2.2	2.0	1.6	1.9	5.7	2.6	1.2	1.8	1.6
4	<3 µm	9.1	6.3	4.3	1.6	1.8	6.6	3.8	3.2	2.4	2.3	6.9	4.2	2.1	2.6	2.4
5	<4 µm	107	8.1	5.1	2.0	2.5	9.6	5.4	4.0	3.2	2.7	7.8	5.4	3.3	3.4	3.2
6	<6 µm	15.2	10.5	6.6	2.8	3.8	13.3	9.2	5.5	4.4	4.1	10.2	7.5	4.9	4.8	4.3
7	<8 µm	20.6	12.7	8.2	3.6	5.5	16.6	12.9	7.5	6.1	5.3	14.7	10.0	6.9	6.4	5.5
8	<12 µm	29.2	16.9	10.5	5.7	8.0	23.7	18.4	11.1	8.9	8.4	24.1	15.0	11.1	9.8	8.0
9	<16 µm	35.8	21.6	14.0	9.8	10.5	30.7	23.4	17.0	12.1	11.7	30.6	21.7	15.1	14.2	11.1
10	<24 µm	40.6	30.0	21.0	15.1	15.6	41.5	31.7	25.3	17.8	16.4	44.0	32.5	22.5	20.6	16.7
11	<32 µm	55.1	38.5	28.0	20.8	20.6	54.5	40.9	32.9	23.1	21.8	57.5	41.6	29.9	26.2	22.2
12	<48 µm	69.6	50.3	38.6	29.0	27.4	74.5	54.7	43.2	31.6	31.7	73.8	55.8	40.9	33.8	31.0
13	<64 µm	79.4	58.8	49.1	36.3	35.0	85.3	63.8	52.6	39.7	39.3	83.6	67.5	50.3	41.6	38.1
14	<96 µm	94.6	70.1	60.4	46.1	43.4	98.6	74.7	61.0	48.6	46.3	97.0	78.8	60.5	50.7	45.7
15	<128 µm	98.8	80.4	66.6	53.8	47.6	99.4	86.0	67.3	53.4	50.4	97.8	86.7	69.1	56.7	51.6
16	<192 µm	99.1	84.6	70.1	57.1	50.6	99.8	91.8	71.3	56.7	53.5	97.8	91.7	73.6	60.1	55.6
Residue*																
17	>192 µm	1.25	15.4	29.9	42.9	49.4	0.2	8.2	28.7	43.3	46.5	2.2	8.3	26.4	39.9	44.4
Statistical parameters																
18	$D_{50[\mu m]}$	27.4	47.7	66.1	118.8	174.9	28.9	42.1	59.3	104.9	127.7	27.25	40.7	64.1	94.0	118.5

Note: The sieving time at the CILAS - Delcita laser granulometric analysis machine or at the Mastersizer 2000E laser machine was 60 seconds per sample.

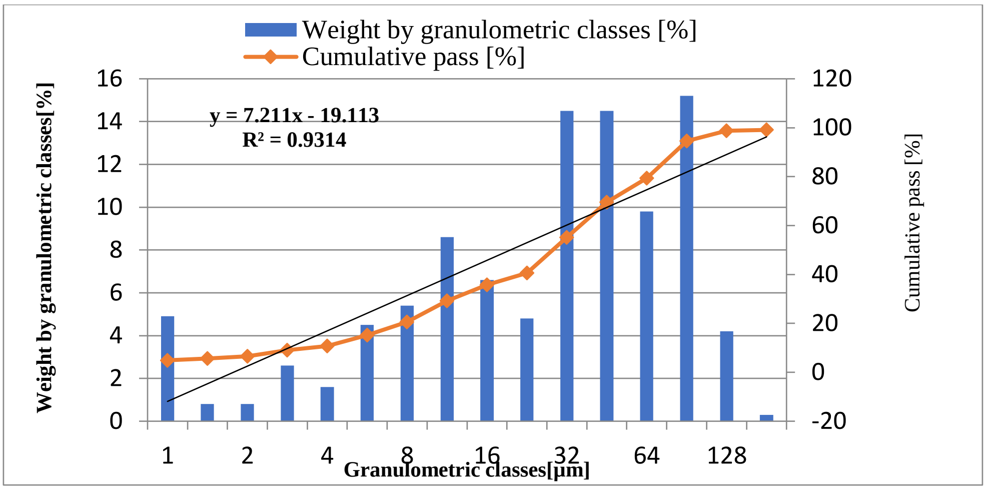

Fig.5.5 Weight by grain size classes sample 85

The modeling of the cement grinding process using ball mills was carried out using MATLAB, that uses the Symbolic Math Toolbox, which is a set of symbolic mathematical tools for creating and manipulating symbolic mathematical expressions.

Thus, the cumulative passage on the site was obtained from the samples analyzed (fig. 5.11)

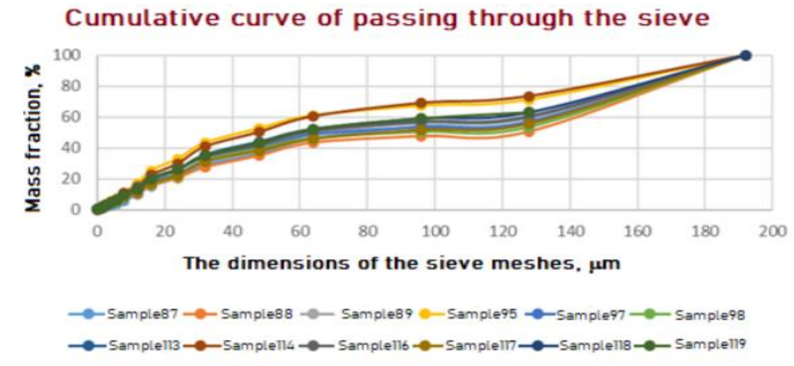

Fig.5.11 Cumulative passage on the site, [53]

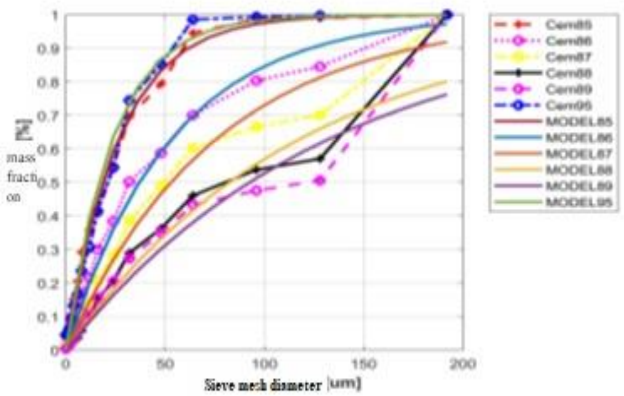

Fig.5.12 Mass fraction according to the sieve mesh diameter

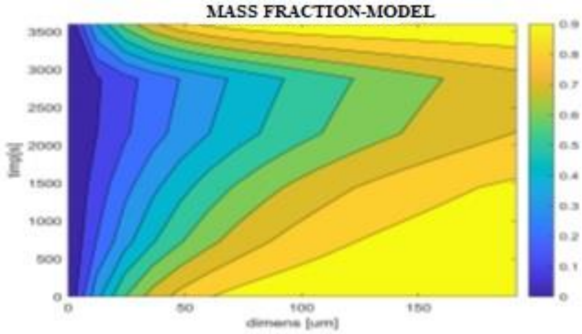

Fig.5.13 Mass fraction model of particle sizes over time

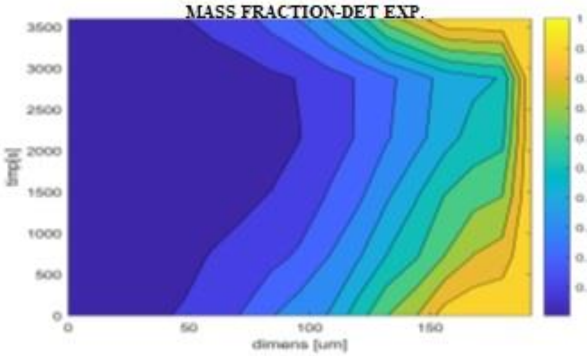

Fig.5.14 Experimental values of mass fractions

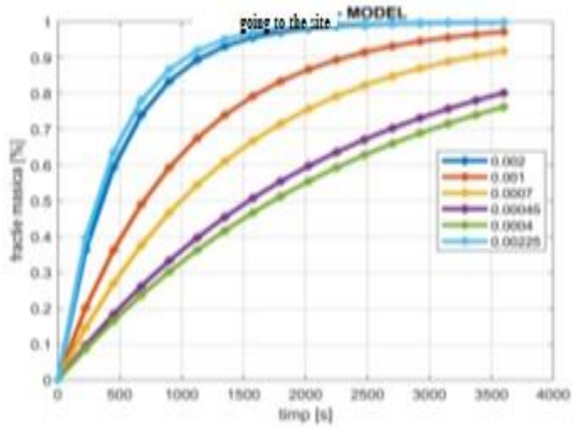

Fig.5.15 Sieve pattern as a function of time of the mass fraction

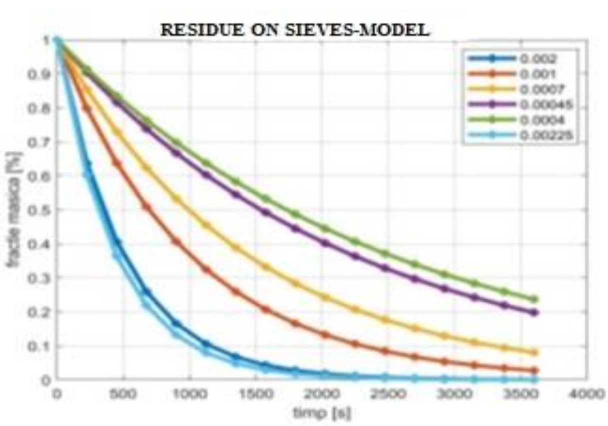

Fig.5.17 Model of the residue on sieves as a function of time of the mass fraction

5.2. Finite element simulation of the working process of ball mills

5.2.1. Proposals of mathematical models that appreciate the grinding process

One of the most widely used particle size distribution laws recommended for the characterization of the particle size distribution of cement, obtained in ball mills and sorted by fractions in flat sieve compartments, is the Rosin-Rammler law, which can be expressed by one of the following relations, [64]

$$R = \exp\left[-\left(\frac{x}{p}\right)^{n}\right] \qquad (5.7)$$

5.2.2. Mathematical models describing the correlation between clinker crushing process parameters

Mathematical modeling of cement manufacturing was used by considering their compositional and quality parameters: chemical, physical and mechanical.

In the thesis, the DEM approach was applied in a highly sampled way to investigate the process of crushing with balls, including the trajectory, velocity and distribution of powder particles and balls inside the mill.

- ✓ ***DEM simulation results***

To simulate clinker crushing in a laboratory ball mill, the professional simulation program EDEM 2022.0 from the company Altair Engineering, Eng was used.

The stages of building a model are: cleaning the geometry (adding the components that will be simulated with their characteristics: balls, clinker), import geometry; setting the dynamics of the model elements; setting the parameters of the model elements; setting the parameters of bulk materials.

Furthermore, the computer-aided design (CAD) geometry used for the DEM simulations is shown in Fig. 5.20

The geometry shows the characteristic regions of charge motion and the stochastic variability of the particle flow pattern. Thus, the particles are coloured according to their speed. Fig. 5.21 illustrates the different stages of particle breaking. The particle size distribution is mainly concentrated near the mill wall due to the high centrifugal accelerations caused by the drum motion.

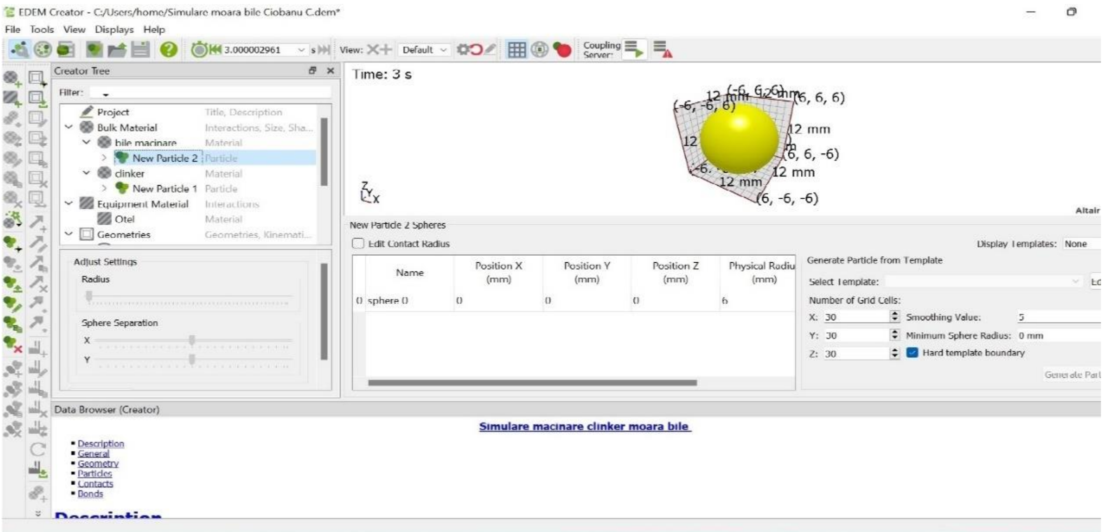

Fig. 5.20 Computer Aided Design Geometry, [19]

Fig. 5.21 Different stages of particle breaking, [19]

However, it means that the particles and balls are well mixed. Fig.5.21 shows particles moving at high speed, which produce high energy impacts during the grinding process. Figure 5.22 demonstrates a reduction in the number of collisions and an increase in their magnitude.

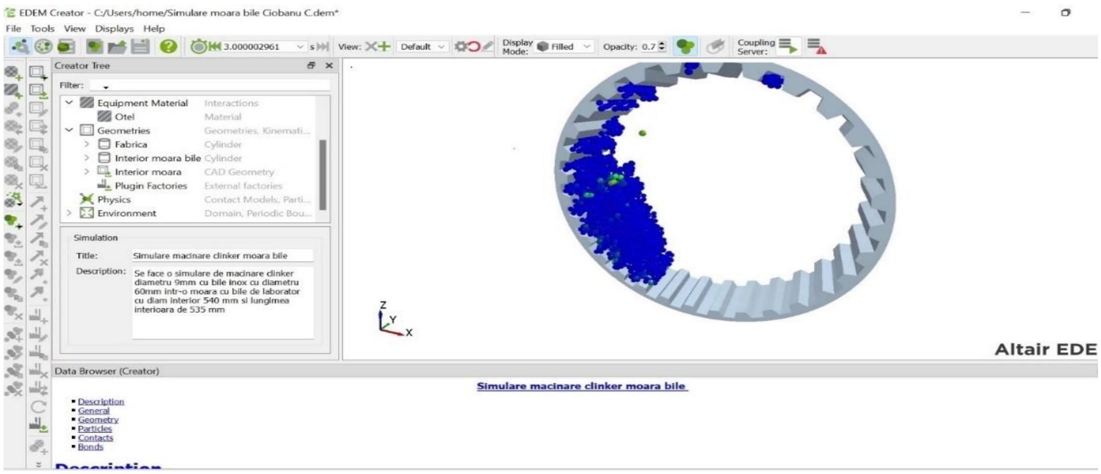

Fig. 5.22 Decreasing the number of collisions, [19]

At the end of the simulation (the time set for the simulation) the program stops when it reaches 100% (fig. 5.23).

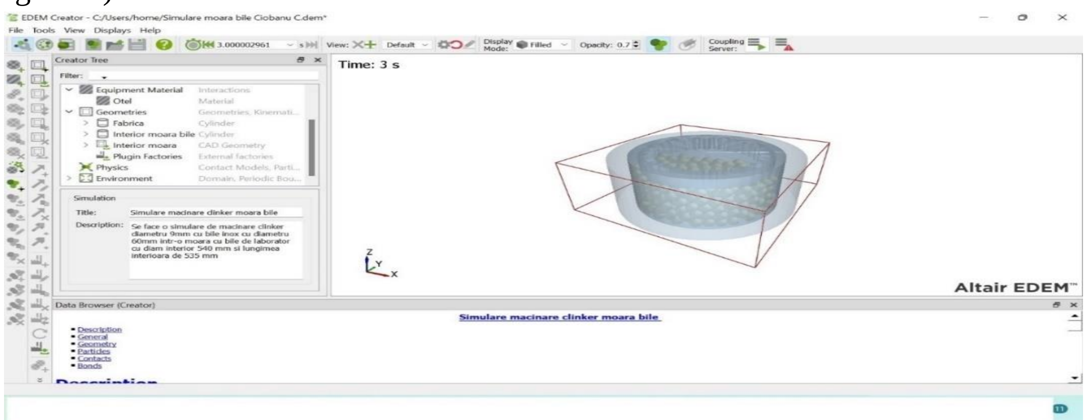

Fig. 5.23 End of simulation

5.3. Conclusions of theoretical researches

The Matlab program was used to calculate the trajectories of the different concentric layers in the cement mill considering the number of layers, the speed of the mill, the total mass of the balls. Different speeds lead to different trajectories and different kinetic energies of the balls, so it can be concluded that for a lower kinetic energy of the balls when they touch the surface of the material it is good to use more balls and a smaller volume of material.Material balance equations were established based on a scheme designed for a grinding apparatus, and also equations for the fractions resulting from disintegration within the apparatus as a function of initial particle sizes and time.

These results could be used to further develop synthesis performance, predict reaction and reduce wear in dry milling reactions.

CHAPTER 6. EXPERIMENTAL RESEARCHES ON THE CLINKER CRUSHING PROCESS

6.1. Objectives of experimental researches

The general objective of the work is represented by researches on the clinker crushing process in order to reduce dust emissions.
The partial objectives of experimental research are:

- elaboration of the experimentation methodology;
- experimental determinations regarding the clinker crushing process;
- identifying the mathematical models that describe the correlation between the parameters of the clinker crushing process;
- establishing the correlations between the degree of grinding and specific energy consumption, with the finest grinding categories (1 micron, 5 microns and 10 microns);
- aspects regarding the monitoring of dust emissions from stationary emission sources (monthly measurements of dust carried out at the chimney of the ball cement mill - mill exit and separator exit) from a cement plant in Romania.

6.2. Methodology and apparatus of experimental research

6.2.1. Experimental research methodology

<u>Determination of grindability</u>

2 working procedures were used:

<u>a) CEPROCIM S.A. procedure</u> which is based on the grinding of a batch of material in a laboratory mill with a rotating horizontal drum in two stages:

- First stage with load of balls;
- The second stage with a load of biconical bodies.

Periodically, the fineness of the material is determined by the residue R_{009} and, in the case of cement, the specific surface area. The first stage is considered completed when R_{009} is ~35% rezidue (R_{009}-rezidue on the sieve of 90μm). The energy consumption is determined between the moments when the fineness of the material is performed, using a wattmeter (in this case, the consumption was read directly from the meter). These consumptions are accumulated from the beginning of the determination and are related to the mass of the load, calculating the specific energy consumption w_{li}. Grindability index is the specific energy consumption w_1 corresponding to a reference fineness, [166].

$$c_1 = \frac{w}{w_1} \tag{6.1}$$

Experimentally, a diagram of the correlation coefficient with industrial mills was drawn, where the specific energy consumption of the industrial mill was noted with w, in the assumption of the drive through the pinion-crown toothed final group and speed reducer, including the losses from the electric motor. Reference fineness is characterized by R_{009} =10% in the case of raw materials and s = 2500 cm^2/g in the case of cement.

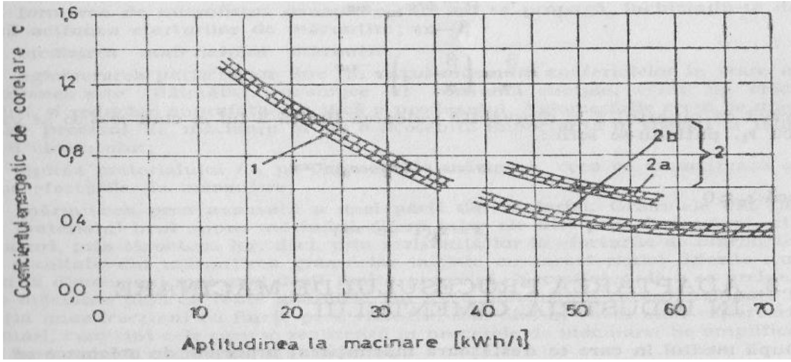

Fig.6.1 Correlation coefficient of grindability with industrial tubular mills, [166]

b) Zeisel process presents a number of advantages over other laboratory processes (small amount of material, simple utilization, fast execution).

Zeisel grindability index is the total specific energy consumption required in order to obtain a certain specific surface area of the material.

$$W_z = \sum W_i \quad (6.2)$$

Determination of energy consumption

These consumptions were accumulated from the beginning of the determination and related to the mass of the slag (20 kg of clinker/plant from 2 plants and 20 kg of slag), calculating the specific energy consumption w_{1i} in the unit of time set by 10 minutes.

$$\text{Energy consumption} = \frac{\text{Counter difference[KWh]}}{\text{batch mass[kg]}} \quad (6.3)$$

Curves $R_{009} = f\,(w_{li})$ and $s = f\,(w_{li})$ were drawn. Grindability index is the specific energy consumption w_1 corresponding to a reference fineness.

Determination of Blaine specific surface area

The Blaine specific surface area was calculated according to the relation (6.4) and is conventionally expressed in cm^2/g, as:

$$S = \frac{K}{\rho} \cdot \frac{\sqrt{e^3}}{(1-e)} \cdot \frac{\sqrt{t}}{\sqrt{10 \cdot \eta}} \quad (6.4)$$

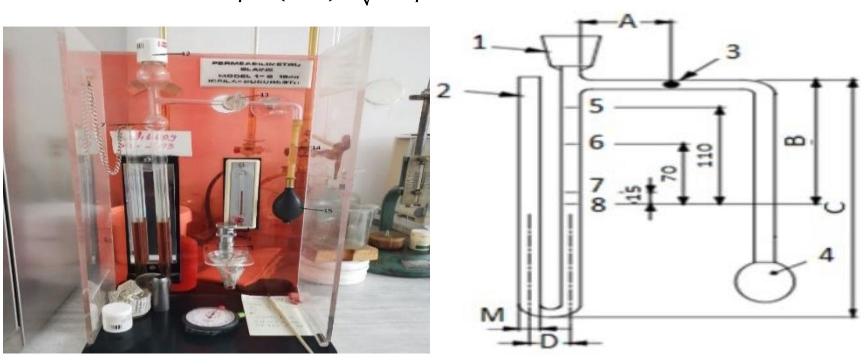

Fig.6.2 Blaine permeability meter, [18, 151]

<u>Determination of ball mill vibrations</u>

In order to determine the vibrations of the laboratory ball mill, after mounting the sensor at the measuring point, the dedicated software for vibration determination with the settings of the manufacturer Banner was installed according to the configuration instructions of the vibration sensor QM42VT1:

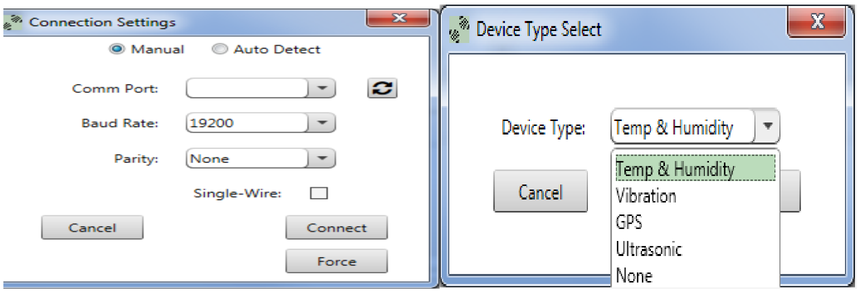

Fig.6.3 QM42VT1 sensor configuration, [146]

<u>Laser particle size analysis and chemical analysis</u>

The following analysis methods were used for performed determinations:

- for laser granulometric analysis: ISO 13320:2009; SR ISO 9276-1:2001 [148,149]
- for complete chemical analysis: SR EN 196-2:2013 [148].

<u>Methodology for determining the concentrations of total dust emissions</u>

The powder measurement method is based on the isokinetic sampling of a volume of gas from the residual gas flow and the deposition of particles on the filter elements (stainless steel cartridge filled with quartz wool) and the gravimetric measurement on an analytical balance according to SR EN 13284- 1:2018, [140].

6.2.2. Apparatus and equipment used in experimental clinker crushing research

The devices and equipment presented below were used to carry out the experimental determinations regarding the clinker crushing process.

Apparatus for crushing the material subject to crushing *- jaw crusher Retsch BB100 for crushing the clinker in order to pass completely through the sieve of 7 mm.*

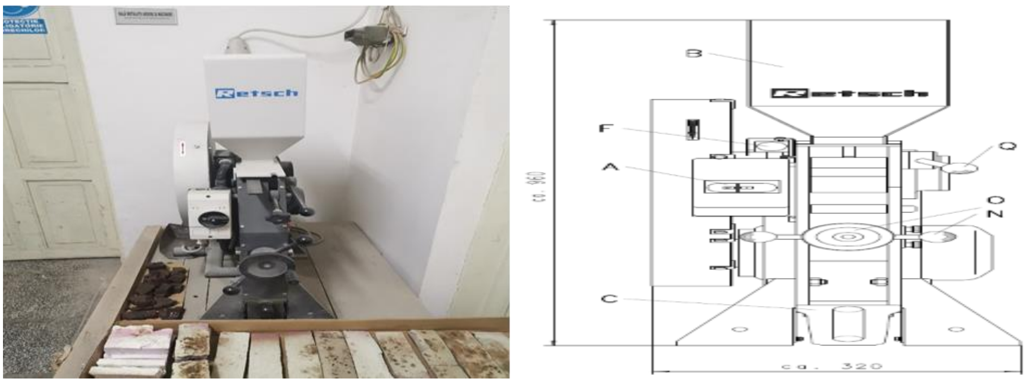

Fig.6.6 Jaw crusher Retsch BB 100, [19]

Fig.6.7 Grinding sieve of diameter Ø=7 mm

Crushing sieves are used in the laboratories of cement plants and in research institutes when preparing samples for grinding material of a certain grain size in laboratory mills.

- ***Laboratory ball mill***

The crushing was carried out in the laboratory mill, without recirculation, belonging to CEPROCIM S.A.

Fig.6.8 Laboratory ball mill, [19, 21]

1. mill body; 2. mill bearings; 3. mill supports; 4. attack pinion; 5. toothed crown; 6. attack pinion bearing; 7-8. wheels for trapezoidal belts; 9. trapezoidal belts; 10. bearing support for the attack pinion; 11. engine

- ***The system for determination energy consumption at the ball mill***

Used counter was an electromechanical meter of the watt-hour type and the determination of energy consumption in the ball mill was made by reading directly from the meter the consumption of electrical energy consumed in relation to the mass of the clinker batch or crushed slag.

Fig.6.10 Electromechanical meter

- ***Apparatus for determining the specific surface area (SSB) the Blaine permeameter***

To determine the specific surface area (SSB) of the crushed material, the Blaine permeameter method was chosen. The Blaine procedure is applicable for all cements defined in the EN 196-6 :2018 standard, [151].

- ***Apparatus for chemical analysis of crushed material NovAA 400***

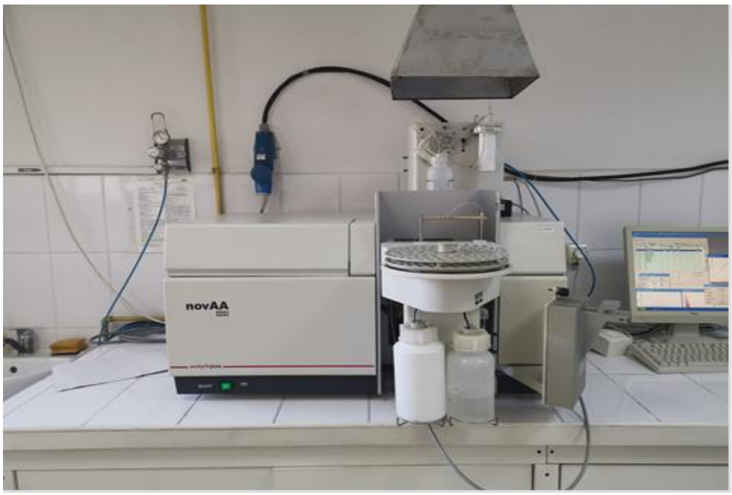

Fig.6.17 NovAA 400 clinker chemical analysis apparatus

- ***Devices for measuring clinker granulometry Mastersizer 2000E and CILAS – Delcita 715***

Fig.6.18 Mastersizer 2000E laser granulometric analysis device, [18,152]

Fig.6.19 CILAS - Delcita 715 laser granulometric analysis device

- ***Optical microscopy device Carl Zeiss AXIO IMAGER A1m***

Fig.6.20 Optical microscopy apparatus Carl Zeiss AXIO IMAGER A1m

Optical microscope for transmitted and reflected light Carl Zeiss AXIO IMAGER A1m for the determination of components through mineralogical analysis on natural raw materials: clays, marls, limestones, sandstones, tuffs and synthetic products such as cement clinkers.

Apparatus for determining the concentrations of total dust emissions in cement mills

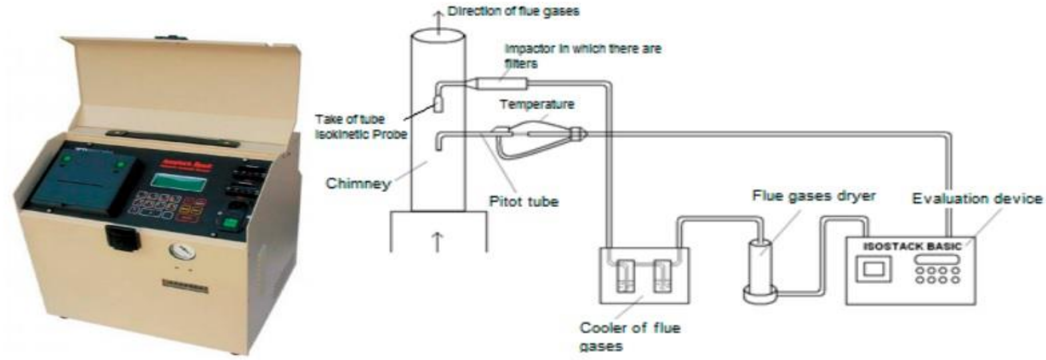

Fig.6.21 ISOSTACK BASIC HV-TCR TECORA automatic sampler, [16,17]

System for determination of mill vibrations during crushing

To determine the vibrations of the mill during crushing, the vibration and temperature sensor model: QM42VT1 from the company Banner was used connected to a laptop in order to register the accelerations (G) of the mill during the crushing of the samples.

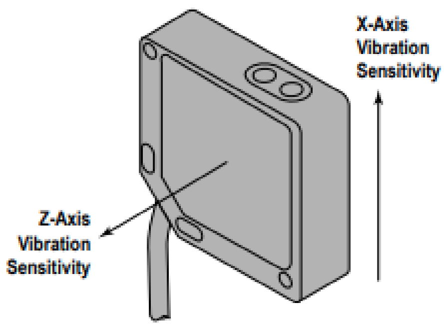

Fig.6.22 Sensor assembly QM42VT1, [146]

Fig.6.23 Sensor QM42VT1, [146]

- ***Determining the grindability on the Zeisel laboratory device***

Fig.6.24 Zeisel Apparatus for grindability determination

Press type ZD 10/90 (fig.6.26.), for slow compression.

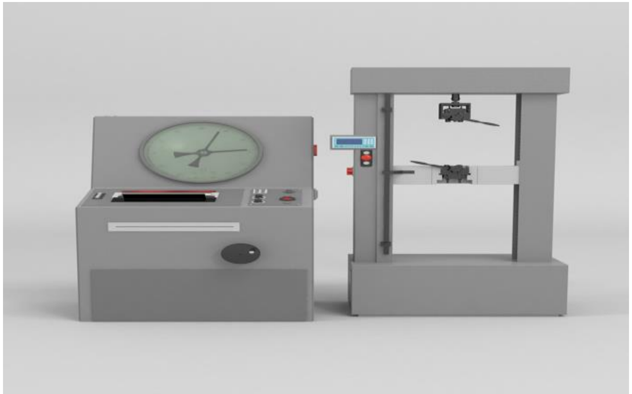

Fig.6.26 Press type.ZD 10/90, [151]

- ***Quantitative analysis of the size of solid particles by dry sieving***

For the quantitative analysis of the size of all types of solid particles and suspensions by dry or wet sieving with a rectangular test sieve, the ANALYSETTE 3 SPARTAN sieve classifier from the Fritsch company was used (fig. 6.27).

Fig.6.27 Classifier with site Analysette 3 Spartan, [162]

- ***Sieving and grinding in one unit for crushing and homogenizing of small amounts of sample***

Pulverisette 19 ULVERISETTE 19 is a powerful, low-speed universal cutting mill for fast, reproducible grinding of hard, elastic and temperature-sensitive materials and plastics, with a maximum feed size of 120 x 85 mm and a flow rate of up to at 85 l/h with a low rotation speed of 50-700 rpm and a three-phase motor of 2.8 kW.

Fig.6.28 Micro vibrating mill PULVERISETTE 19

6.3. Material subject to grinding, initial characteristics and method of obtaining

6.3.1. The method of obtaining the material subject to processing

6.3.2. Initial characteristics of the material subjected to grinding

The material that will be crushed in the 2 work installations (laboratory mill type CEPROCIM and Zeisel device) must have a particle size between 0-7 mm, according to the methodology for determining the grindability. [166]

During the doctoral internship, several experimental researches were carried out where several types of materials were used, namely:

a) For the experiment no. 1 - clinker and slag grinding using the laboratory ball mill according to the CEPROCIM method

To carry out the experiments, the following materials were used: clinker from two cement plants in Romania marked with Clincher A and Clincher F and granulated blast furnace slag. At the initial moment of carrying out the determinations, the samples were chemically characterized according to the requirements of SR EN 196-2:2013 - Test methods of cements. Part 2: For chemical analysis of cement [139], the final clinker used to produce type cement: CEM I 42.5 R, which is a high initial strength Portland cement.

b) ***For the experiment no. 2 - clinker grinding using the laboratory mill with balls of different sizes according to different amounts of material***

To carry out the experiments, a clinker from a single cement plant in Romania was used as material. The clinker is used for the production of cement type: CEM I 52.5 R.

c) For the experiment no. 3 – clinker grinding using the laboratory ball mill and Zeisel apparatus in order to determine the grindability

To carry out the experiments, a clinker from a single cement plant in Romania was used as material.

d) For the experiment no. 4 - clinker grinding using the industrial cement mill in order to determine the degree of grinding in the mill of the cement plant

To carry out the experiments, cement type CEM I 42.5 R from a single cement plant in Romania was used as material.

e) For the experiment no. 5 - clinker grinding using the PULVERISETTE 19 laboratory micro-mill and quantitative analysis of the size of solid particles by dry sieving with the Analysette 3 Spartan sieve classifier

To carry out the experiments, clinker material from a single cement plant in Romania was used

6.3.3. Initial processing of the material subject to grinding. Experiment

According to the CEPROCIM method, the batch with grinding media, for the first experiment, for the first stage of grinding (coarse) is:

Table 6.3 Grinding media load

Ø[mm] grinding balls	65-75	55-65	45-55	Total
G[kg] grinding balls	76.90	38.55	28.85	~144.3

Fig.6.29 Grinding balls of different sizes, [19]

The final grinding (second phase - fine) is the (coarse) crushing stage carried out with the equivalent biconical load of ~144.3 kg.

Fig.6.30 Bicones, [19]

After the crushing is finished, the clinker from both samples is within the norms for the production of CEM I 42.5 R type cement (having the Blaine specific surface area around 3800 cm^2/g), the energy consumption for each sample being about 100 KWh/ t.

<u>*a) Experimental steps for the first experiment:*</u>

1. Clinker A (20kg.) was sieved on the Ø = 7 mm sieve, then the material remaining on the sieve was crushed in the Retsch jaw crusher (fig. 6.6);
2. The same operation as in point 1 was carried out for clinker F (20kg.);
3. The obtained content was homogenized and the granulometric curve was determined;

Table 6.4 The amount of material (pass percentage) rejected on sieves of different sizes - clinker F

Sieve [mm]	Residue on sieves		T [%]	R[%]
	p[g]	p[%]		
5	140.38	12.79	87.21	12.79
3	215.73	19.66	67.55	32.45
1	204.66	18.65	48.90	51.10
0	536.65	48.90	-	48.90
Total material	**1097.42**		-	

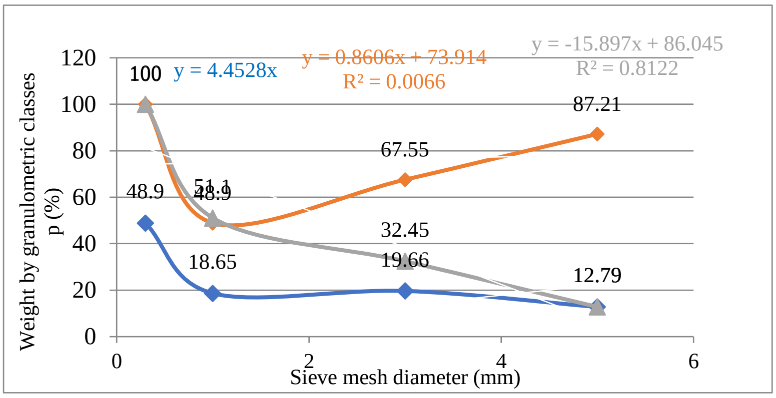

Fig.6.31 Granulometric curve related to the amount of material-clinker F

4. After finishing the individual crushing of the samples (clinker F, clinker A) with bicones in the laboratory mill, about 50g clinker F and 50g were taken from each ground sample - the average sample (represents 7.5 kg of crushed clinker obtained from each sample) clinker;
5. Each sample of ≈50 g was crushed in a pestle and delivered to the laboratory for chemical analysis and microscopy by Laser granulometric analysis;

b) Experimental steps for the second experiment:

The load with grinding media, for the second experiment in the first phase of crushing (coarse) was:

Table 6.6 Grinding media load

Ø[mm] grinding balls	70-65	60	70-65-45	Total
G[kg] grinding balls	44	44	44	~132

Different amounts of clinker were ground: 5 kg, 10 kg, 13.5 kg, 17 kg and 20 kg. Initial experimental steps:
1. They were sieved on the Ø=7 mm sieve, then the material remaining on the sieve was crushed in the Retsch jaw crusher (fig. 6.4).
2. Obtained content was homogenizat and the granulometric curve was determined.

Table 6.7 The amount of material (percentage pass) sieved on the sieves of different sizes

Sieve [mm]	Residue on sieves		T [%]	R[%]
	p[g]	p[%]		
5	399.13	20.50	79.50	20.50
3	599.37	49.60	29.90	70.10
1	230.91	13.20	16.70	83.30
0	245	16.70	-	16.70
Total material	**1474.41**		-	

3. After completion the crushing of the samples with balls of different sizes (Ø70+ Ø65; Ø60; Ø70+ Ø65+ Ø45) mm, but with the constant mass of 44 kg in the laboratory mill, ≈ 50g of clinker was taken;
4. The sample of ≈50 g was crushed in a pestle and delivered to the laboratory for chemical analysis and microscopy by Laser granulometric analysis;

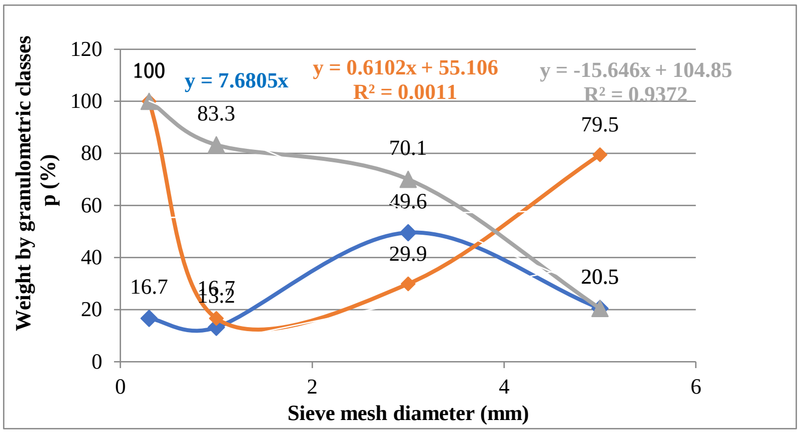

Fig.6.33 Granulometric curve for Ø ≤ 7mm Clinker A

c) Experimental steps for the third experiment:

In the case of determination clinker grindability in the laboratory with Zeisel machine, a batch of material is of 30 g. During the laboratory work, a quantity of material (clinker) with a grain size between 0.7-1 mm was prepared according to the methodology work of Zeisel device.[166]

d) Experimental steps for the fourth experiment

To carry out the experiments (granulometric determination by the laser method with the CILAS – Delcita 715 device) cement type CEM I 42.5 R from a single cement plant in Romania was used as material and the components were determined by mineralogical analysis with the Carl Zeiss device AXIO IMAGER A1m. 24 samples (25 g/sample) were analyzed.

e) Experimental steps for the fifth experiment

To carry out the experiments, clinker material from a single cement plant in Romania was used.

6.4. Experimental determinations of clinker crushing using the laboratory ball mill

6.4.1. Experimental determinations of energy consumption in crushing clinker

The energy consumption for crushing the clinker between the moments when the fineness of the material is determined (it was expressed by the refusal R (%), with the precision of 0.1%, on the sieve with the mesh diameter of 90 μm, according to ISO 565) was read directly on the meter. These consumptions were accumulated from the beginning of the determination and related to the mass of the slag (20 kg of clinker / plant from 2 plants), calculating the specific energy consumption w1i in the preset time unit of 10 minutes.

$$Energy\ consumption = \frac{Difference\ counter\ [KWh]}{batch\ mass\ \ [kg]} \tag{6.15}$$

Thus, the following energy consumptions were recorded:

a) for Clinker A:

Table 6.9 Energy consumption related to crushing time - clinker A, [19]

Nr.crt.	Crushing time [min]	Resulting energy consumption [kWh/kg]	Cumulative energy consumption [kWh/kg]
1	10	10.7	10.7
2	20	10.9	21.6
3	30	10.6	32.2
4	40	11	43.2
5	50	11.1	54.3
6	60	11.4	65.7
7	70	11.05	76.75
8	80	11.25	88.00

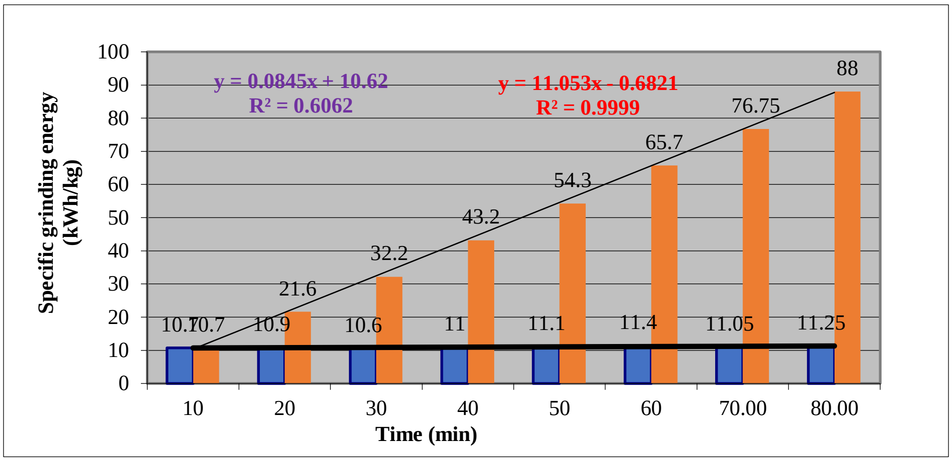

Fig.6.34 Variation of the specific clinker crushing energy A, [19]

6.4.2. Experimental determinations of the specific surface area when crushing clinker

Blaine Specific Surface Area (SSB) for different grinding times and different degrees of loading with balls and material it was calculated according to the relation (6.9). Specified porosity e = 0.500 and the test temperature 20±2°C,SSB it was calculated according to the relation (6.12). Thus the following Blaine Specific Surfaces (SSB) were registered:

a) For the first experiment, grinding clinker and slag using the laboratory ball mill according to the CEPROCIM method:

➢ <u>For Clincher type A</u>:

Table 6.17 SSB values and energy consumption per time unit, [19]

Nr.crt.	Crushing time [min]	Consumption meter indicator [kWh]	Grinding media	$R_{90\mu m}$ ball [%]	SSB bicones [cm²/g]
0	0	0	0	0	0
1	10	240	Grinding balls	51.68 %	-
2	20	221	Grinding balls	33.6%	-
3	30	214	Bicones	-	2250
4	40	218		-	2650
5	50	212		-	2830
6	60	220		-	3180
7	70	222		-	3520
8	80	228		-	3590
9	90	221		-	3700
10	100	225		-	3870

After determining the energy consumption at the crushing of clinker type A, the variation of the specific Blaine surface area (SSB) in the unit of time was graphically represented.

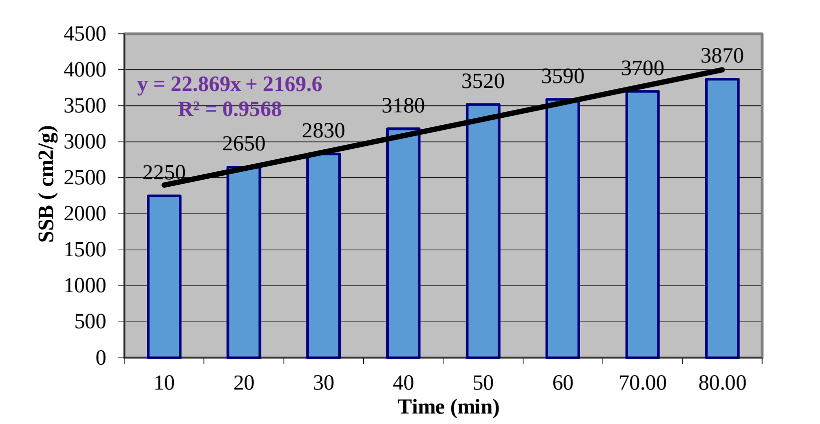

Fig.6.40 Variation of the Blaine Specific Surface Area when crushing clinker A with a bicone mill, [19]

A linear increasing variation of SSB with a slope of 228.7 cm2/g/min is found.

6.4.3. Experimental determinations regarding the determination of grindability in CEPROCIM S.A. laboratory mill and on Zeisel laboratory apparatus

A) Determination of the grindability in CEPROCIM S.A. laboratory mill.

The load with grinding bodies, in the first stage of crushing (coarse) for this experiment is:

Table 6.20 Mill load with grinding bodies

Ø[mm] grinding balls	65-75	55-65	45-55	Total
G[kg] grinding balls	73.47	36.75	27.77	~137.77

In the second stage of experiments with the structure of the load with bicones Ø 25 x 30 mm ~137.77 kg, the granulation of the material at the feed of the mill was between 0...7 mm according to the way of working in CEPROCIM SA type laboratory mill. After each stage, R009 and SSB were determined. For experiments in the laboratory, 11 material samples (clinker: 95%; gypsum: 5%;) from a single cement plant in Romania were prepared, as follows:

- ***Sample (batch) 1***- *standard clinker whose particle size distribution is detailed in table 6.21 and fig. 6.46.*

Table 6.21 Particle size distribution of standard clinker and pressed clinker (20MPa), [21]

Sieve mesh size	**Standard clincher**		**Clincher pressed at 20 MPa**	
	partially	**cumulative**	**partially**	**cumulative**
(mm)	**(%)**	**(%)**	**(%)**	**(%)**
25	8	-	5	-
15	21	8	15	5
10	8	29	16	20
7	11	37	14	36
5	22	48	10	50
3	12	70	11	60
1	9	82	11	71
<1	9	91	18	82

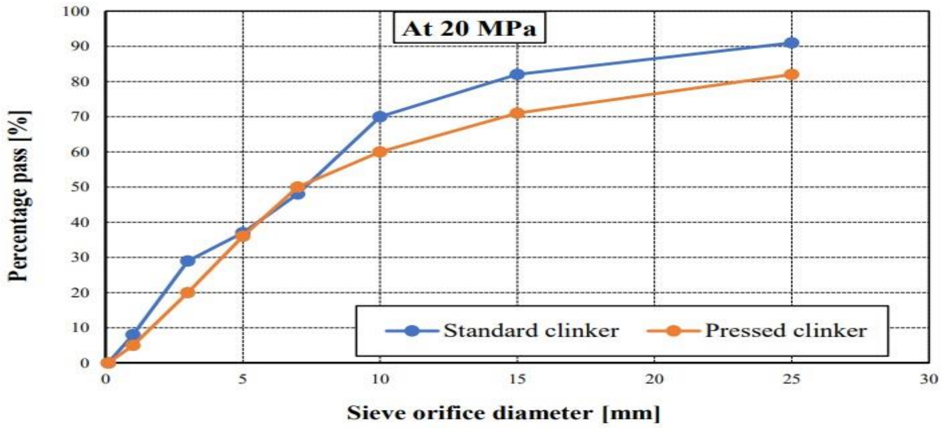

Fig.6.46 Particle size distribution of the standard clinker compared to the pressed clinker (20 MPa),[21]

Table 6.23 Particle size distribution of the reference clinker and the twice pressed clinker (100 MPa)

Sieve mesh size	Standard clinker		Pressed clinker	
	partially	cumulative	partially	cumulative
(mm)	(%)	(%)	(%)	(%)
>25	1.1	1.1	0.1	0.1
15	8.3	9.4	2.8	2.9
10	13.3	22.7	5.7	8.6
7	13.9	36.6	8.7	17.3
5	14.6	51.2	7.0	24.3
3	18.5	69.7	16.2	40.5
1	16.5	86.2	23.3	63.8
<1	13.8	100	36.2	100

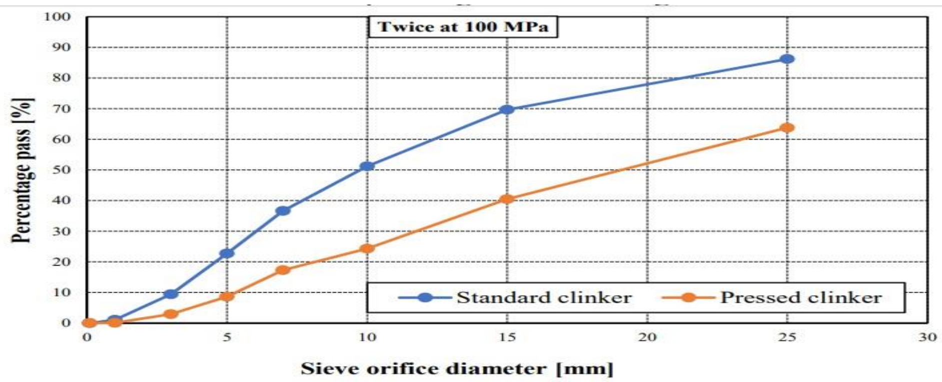

Fig.6.48 Particle size distribution of the reference clinker compared to the clinker pressed twice (100 MPa)

These results confirm the statements in the specialized literature that at low pressures the influence of pressure is not noticeable as there is a minimum of 50 MPa at which it must be achieved.

Determination of grindability in the laboratory with Zeisel apparatus

During the experiments, a quantity of material (clinker) was prepared from a cement plant in Romania with a granulometry between 0.7-1 mm according to the working methodology of Zeisel device (presented earlier in subchapter 6.2.1.). The grindability was determined with Zeisel apparatus on 7 samples (lots).

Table 6.35 Grindability by Zeisel process of uncrushed clinker

	No. rotations		Counter registration		Mechanical work	Specific electricity consumption	The specific surface area SSB
	partially	cumulative	Partially (kWh)	Cumulative (kWh)			
	rotații	rotații			Kg·m (J)	KWh/t	cm^2/g
Sample 1 Uncrushed clinker	200	200	18.5	18.5	43.682	7.9297	1619
	200	400	14.7	33.2	78.391	14.2307	2358
	100	500	7.0	40.2	94.920	17.2311	2520
	300	800	21.1	61.3	144.741	26.2754	3164
	200	1000	14.7	76.0	179.451	32.5763	3465
	300	1300	22.8	98.8	233.286	42.3492	3730
	200	1500	15.7	114.5	270.357	49.0788	4016
Sample 2 Uncrushed clinker	200	200	17.7	17.7	41.793	7.5868	1730
	200	400	14.7	32.4	76.502	13.8878	2290
	200	600	14.2	46.6	110.031	19.9744	2644
	200	800	14.8	61.4	144.977	26.3182	3023
	300	1100	22.5	83.9	198.104	35.9626	3480
	300	1400	22.8	106.7	251.940	45.7355	3760
	300	1600	15.5	122.2	288.538	52.3793	4006
Sample 3 Crushed clinker	200	200	16.9	16.9	39.904	7.2439	1688
	200	400	13.4	30.3	71.544	12.9876	2143
	200	600	13.3	43.6	104.948	17.6885	2514
	200	800	13.7	54.3	128.213	23.2749	3096
	200	1000	14.2	66.5	157.019	28.5043	3306
	100	1100	7.0	73.5	173.548	31.5047	3500
	300	1400	22.1	95.6	225.730	40.9776	3770
	100	1500	7.4	103.0	243.203	44.1495	3870
	150	1650	11.3	114.3	269.885	48.9931	4110
Sample 4 Clincher pressed at 100 MPa (assortment:5 -7 mm)	200	200	16.6	16.6	39.195	7.1153	1805
	200	400	14.1	30.7	72.488	13.1591	2358
	100	500	6.9	37.6	88.781	15.1167	2520
	200	700	14.2	51.8	122.310	22.2033	3000
	100	800	7.5	59.3	140.019	25.4181	3200
	200	1000	15.2	74.5	175.909	31.9334	3565
	300	1300	23.2	97.7	230.689	41.8777	3916
	100	1400	7.6	105.3	248.634	45.1354	4000
Sample 5 Clincher pressed at 100 MPa (assortment:5 -7 mm)	200	200	18.1	18.1	42.737	7.7583	1805
	200	400	14.5	32.6	76.975	13.9735	2390
	100	500	7.1	39.7	93.739	16.0168	2590
	200	700	14.2	53.9	127.268	23.1035	2956
	200	900	14.6	68.5	161.742	29.3616	3250
	200	1100	15.4	83.9	198.104	35.9626	3630
	200	1300	15.4	99.3	234.467	42.5635	3850
	100	1400	7.6	106.9	252.412	45.8212	3956
Sample 6 Clincher pressed twice at 100 MPa (assortment:5 -7 mm)	200	200	16.8	16.8	39.668	7.2010	1665
	200	400	13.6	30.4	71.780	13.0305	2310
	100	500	6.9	37.3	88.072	13.8016	2517
	200	700	14.1	51.4	121.365	22.0319	2870
	100	800	7.0	58.4	137.894	25.0323	2960
	300	1100	21.8	80.2	189.368	30.3766	3480
	300	1400	22.7	102.9	242.967	40.1066	3950
Sample 7 Clincher pressed twice at 100 MPa (assortment:5 -7 mm)	200	200	16.6	16.6	39.668	7.101	1730
	200	400	13.5	30.1	71.075	13.000	2350
	100	500	6.8	36.9	87.128	13.750	2575
	200	700	13.9	50.8	119.004	22.031	2910
	100	800	7.0	57.8	136.477	24.932	3055
	300	1100	21.7	79.5	187.715	30.475	3560
	200	1400	22.5	102.0	740.842	40.950	3985

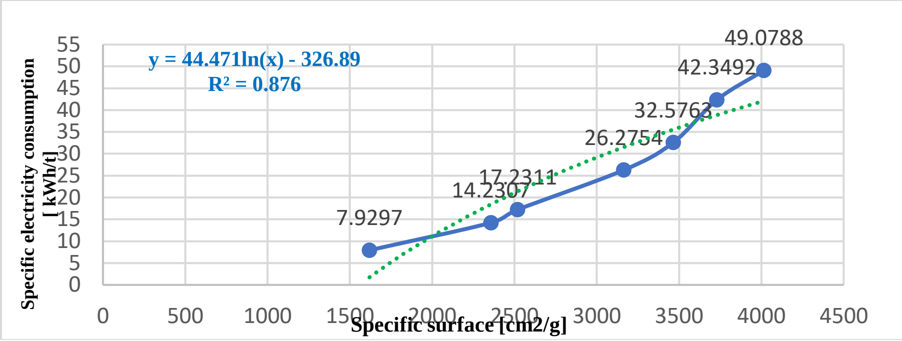

Fig.6.60 Grindability by Zeisel process of uncrushed clinker (sample 1)

It is found that to reach a SSB of 4016 cm2/g for uncrushed clinker (sample 1), 49.078 kWh/t is consumed, at a mill rotation of 1500 and a mechanical work of 270.35 kg·m (J). The variation of energy consumption follows a logarithmic increase, as shown in fig.6.60.In table 6.36, the grindability evaluated by the specific consumption of electricity, both for laboratory conditions and for industrial conditions, of the standard clinker, crushed or pressed, was summary presented.

Table 6.36 Summary table for the grindability by Zeisel method on clinker

No. puncture	Specific reference surface	Specific electricity consumption in the laboratory				Specific consumption of industrial electricity			
		standard	crushed	pressed to 100 MPa	pressed twice at 100 MPa	standard	crushed	pressed to 100 MPa	pressed twice at 100 MPa
1	2500	17.50	17.68	15.56	13.77	19.25	19.09	18.12	16.66
2	3000	26.29	23.27	22.65	22.03	25.30	25.01	23.73	21.82
3	3500	34.26	31.504	31.50	30.37	31.88	31.49	29.89	27.48
4	4000	50.72	48.99	45.47	40.52	38.85	38.56	36.60	32.65

6.4.4. Experimental determinations after crushing clinker in ball mills regarding their mineralogical composition by chemical analysis and laser granulometry

For the clinker categories subjected to the experimental crushing tests, analyzes were also carried out regarding their mineralogical composition. Thus, the results of these analyzes are presented in table 6.37.

Table 6.37 The results of mineralogical composition analyzes for the clinker A and clinker F sample

Determination	M.U.	Sample code Clinker A	Uncertainty of extended measurement	Sample code Clinker F	Uncertainty of extended measurement
Loss on ignition – LOI	%	0.53	± 0.06	0.96	± 0.10
SiO_2	%	21.20	± 0.32	20.88	± 0.31
Al_2O_3	%	5.66	± 0.20	5.04	± 0.18
Fe_2O_3	%	2.99	± 0.05	3.80	± 0.06
CaO	%	66.34	± 0.70	66.78	± 0.71
MgO	%	1.20	± 0.16	0.80	± 0.10
SO_3	%	0.83	± 0.03	0.74	± 0.03
Na_2O	%	0.21	± 0.03	0.12	± 0.02
K_2O	%	0.50	± 0.03	0.34	± 0.02
CaO_{free}	%	0.31	± 0.00	0.92	± 0.01
Insoluble residue HCl – Na_2CO_3	%	0.15	± 0.03	0.17	± 0.04

The expanded measurement uncertainty was obtained by multiplying the compound standard uncertainty by the expansion factor k = 2, which gives a confidence level of 95 %.

Assuming the clinkers to be placed in the thermal equilibrium subsystem $C_3S - C_2S - C_3A - C_4AF$ $(MA_i > 0{,}64)$, Robert H. Bogue established the following calculation formulas for mineralogical constituents: [9]

$$\%C_4AF = 3{,}04\%\ Fe_2O_3 \tag{6.16}$$

$$\%C_3A = 2{,}65\%Al_2O_3 - 1{,}69\%Fe_2O_3 \tag{6.17}$$

$$\%C_3S = 4{,}07\%CaO - 7{,}60\%SiO_2 - 6{,}72\%Al_2O_3 - 1{,}42\%Fe_2O_3 \tag{6.18}$$

$$\%C_2S = 8{,}60\%SiO_2 + 5{,}06\%Al_2O_3 + 1{,}07\%Fe_2O_3 - 3{,}05\%CaO \tag{6.19}$$

It is observed that C_2S clinker A > C_2S clinker F (11.48 > 6.8) which results that clinker A requires additional energy consumption at crushing because it has a higher C_2S content.

For the second experiment, the results and interpretations of the chemical and granulometric Laser analyzes of the material subject to crushing (clinker) were as follows:

Table 6.45 Resulting cement values by granulometric classes

Nr. Crt	Granulometric classes (µm)	Cumulative passes [%]														
		Sample code														
		85	86	87	88	89	95	96	97	98	113	114	115	116	117	118
1	<1	4.9	1.2	1.2	0.4	0.4	4.6	0.4	0.4	0.4	0.4	4.9	0	0	0.4	0.4
2	<1.5	5.7	3.4	2.0	0.8	0.9	5.0	1.2	0.8	0.8	0.8	5.7	0.8	0.4	1.2	0.8
3	<2	6.5	4.7	3.1	1.2	1.3	5.4	2.2	2.0	1.6	1.9	5.7	2.6	1.2	1.8	1.6
4	<3	9.1	6.3	4.3	1.6	1.8	6.6	3.8	3.2	2.4	2.3	6.9	4.2	2.1	2.6	2.4
5	<4	10.7	8.1	5.1	2.0	2.5	9.6	5.4	4.0	3.2	2.7	7.8	5.4	3.3	3.4	3.2
6	<6	15.2	10.5	6.6	2.8	3.8	13.3	9.2	5.5	4.4	4.1	10.2	7.5	4.9	48	4.3
7	<8	20.6	12.7	8.2	3.6	5.5	16.6	12.9	7.5	6.1	5.3	14.7	10.0	6.9	6.4	5.5
8	<12	29.2	16.9	10.5	5.7	8.0	23.7	18.4	11.1	8.9	8.4	24.1	15.0	11.1	9.8	8.0
9	<16	35.8	21.6	14.0	9.8	10.5	30.7	23.4	17.0	12.1	11.7	30.6	21.7	15.1	14.2	11.1
10	<24	40.6	30.0	21.0	15.1	15.6	41.5	31.7	25.3	17.8	16.4	44.0	32.5	22.5	20.6	16.7
11	<32	55.1	38.5	28.0	20.8	20.6	54.5	40.9	32.9	23.1	21.8	57.5	41.6	29.9	26.2	22.2
12	<48	69.6	50.3	38.6	29.0	27.4	74.5	54.7	43.2	31.6	31.7	73.8	55.8	40.9	33.8	31.0
13	<64	79.4	58.8	49.1	36.3	35.0	85.3	63.8	52.6	39.7	39.3	83.6	67.5	50.3	41.6	38.1
14	<96	94.6	70.1	60.4	46.1	43.4	98.6	74.7	61.0	48.6	46.3	97.0	78.8	60.5	50.7	45.7
15	<128	98.8	80.4	66.6	53.8	47.6	99.4	86.0	67.3	53.4	50.4	97.8	86.7	69.1	56.7	51.6
16	<192	99.1	84.6	70.1	57.1	50.6	99.8	91.8	71.3	56.7	53.5	97.8	91.7	73.6	60.1	55.6
Residue*																
17	>192	1.25	15.4	29.9	42.9	49.4	0.2	8.2	28.7	43.3	46.5	2.2	8.3	26.4	39.9	44.4
Statistical parameters																
18	D_{50}	27.4	47.7	66.1	118.8	174.9	28.9	42.1	59.3	104.9	127.7	27.25	40.7	64.1	94.0	118.5

As an example, the weights by granulometric classes for sample 85 were represented.

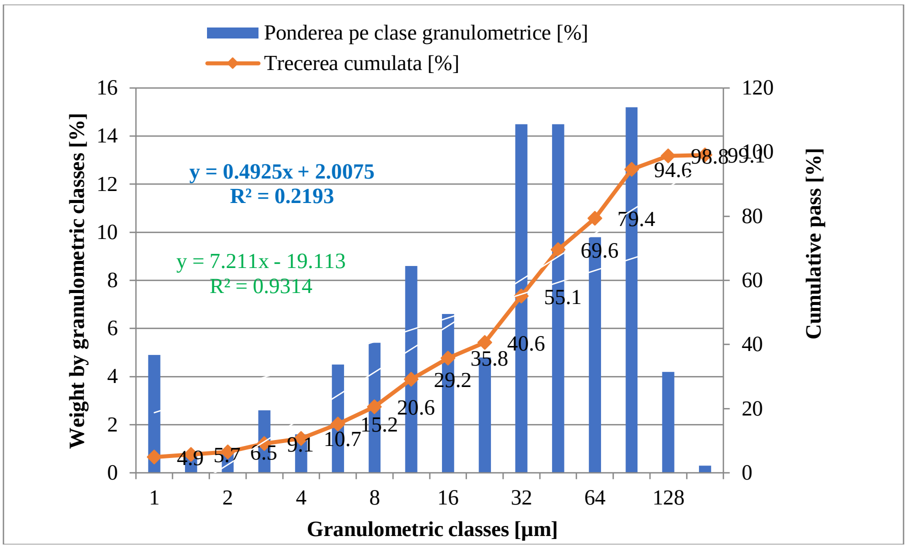

Fig.6.72 Weight by grain size classes sample 85

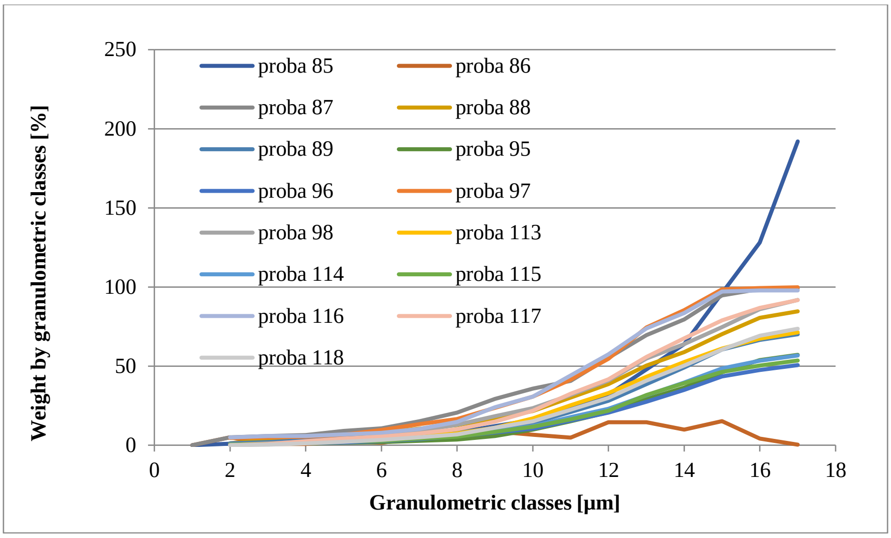

Fig.6.73 Graphical representation by granulometric classes for all samples from table 6.45

Both from the data table and from shown graph, it is found that about 50% of the material has values below 27.5 µm, 50% having higher values.

6.4.5. Experimental determinations after crushing the clinker using laboratory micro-mill PULVERISETTE 19 and quantitative analysis of the solid particle size by dry sieving with Analysette 3 Spartan sieve classifier

To carry out the experiments, clinker material from a single cement plant in Romania was used. The experiments were carried out in the Biotechnical Systems Engineering Faculty of the Polytechnic University of Bucharest.

Table 6.47 Amount of material (percentage passing) sieved on different screen sizes with Analysette 3 Spartan screen classifier

Sieve [mm]	Residue on sieves		p[g]	T [%]	p[g]	R [%]
	p[g]	p[%]				
6.3	794.9	15.1	573.06	14.9	221.99	84.9
5	584.4	4.3	498.4	19.2	86	80.6
3.15	730.0	10.5	563.02	29.7	166.91	70.1
2	761.2	12.2	518.27	41.9	242.94	57.9
1	637.2	7.9	458.64	59.6	178.55	40.2
0.5	608.1	9.0	500.45	68.7	107.66	31.1
0.2	650.3	11.8	537.85	80.5	112.42	19.3
0	894.1	19.3	510.6	99.8	383.4	0.0
Total material	-	-	-	-	**1499.87**	-

where: *p* – weight by granulometric classes (%), (g) ; *T* - cumulative pass (%); *R* – material remaining on the sieve (%).

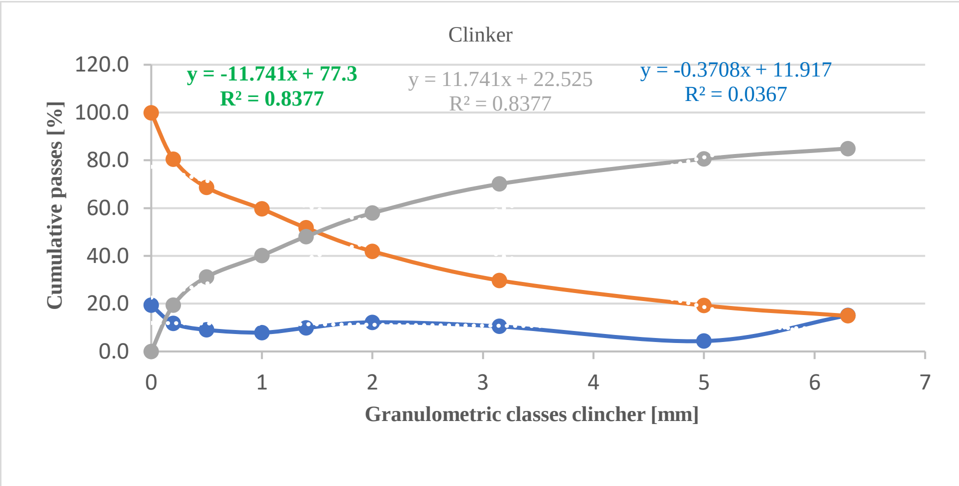

Fig.6.74 Weight by granulometric classes of ground clinker

From fig. 6.74 and table 6.47, it can be seen that the clinker was crushed very finely, a fact resulting from the cumulative T(%) passing of 99.8%, a passage of 80.5% through the 0.2 mm sieve and a residue percentage of 19.3% on the same sieve of Analysette 3 Spartan Sieve Classifier. The most residue remained on the sieve 6.3 in proportion of 84.9, on the 5 sieve of 80.6 and the sieve 3.15 of 70.1.

6.5. Experimental determinations of ball mill vibrations in different working variants

The vibration determinations were carried out according to the methodology from subchapter 6.2.1, where it was aimed to:

- determination of RMSAcc and PeakAcc values for each experiment (per 10 minutes) performed;
- in making graphs of vibrational acceleration over time.

5 vibration measurements were carried out for crushing samples, the data were recorded and the mentioned graphs were drawn.

Table 6.55 Summary table for vibration acceleration at clinker A crushing

Nr.crt	**Hour**	**RMSAcc2 [G]**	**RMSAcc3 [G]**	**RMSAcc4 [G]**	**RMSAcc5 [G]**	Timp [s]	**PeakAcc2 [G]**	**PeakAcc3 [G]**	PeakAcc4 [G]	**PeakAcc5 [G]**
1	10:22:42	0,006	0,006	0,006	0,006	1	0,059	0,063	0,071	0,062
2	10:22:43	0,006	0,006	0,006	0,006	2	0,059	0,063	0,071	0,062
3	10:22:44	0,006	0,006	0,006	0,006	3	0,059	0,063	0,071	0,062
4	10:22:45	1,558	3,007	1,703	1,384	4	21,049	15,042	13,829	14,443
5	10:22:46	1,558	3,007	1,703	1,384	5	21,049	15,042	13,829	14,443
6	10:22:47	1,558	3,007	1,703	1,384	6	21,049	15,042	13,829	14,443
7	10:22:48	1,558	1,95	2,823	1,384	7	21,049	12,89	18,001	14,443
8	10:22:49	2,528	1,95	2,823	1,415	8	16,654	12,89	18,001	16,317
9	10:22:50	2,528	1,95	2,823	1,415	9	16,654	12,89	18,001	16,317
10	10:22:51	2,528	2,645	2,576	1,415	10	16,654	14,528	18,343	16,317
11	10:22:52	2,184	2,645	2,576	2,704	11	16,278	14,528	18,343	19,364
12	10:22:53	2,184	2,645	2,576	2,704	12	16,278	14,528	18,343	19,364
13	10:22:54	2,184	2,944	1,225	2,704	13	16,278	13,128	14,356	19,364
14	10:22:55	1,502	2,944	1,225	2,905	14	19,631	13,128	14,356	18,969
15	10:22:56	1,502	2,944	1,225	2,905	15	19,631	13,128	14,356	18,969
16	10:22:57	1,502	2,058	3,026	2,905	16	19,631	14,583	19,974	18,969
17	10:22:58	2,66	2,058	3,026	1,645	17	20,258	14,583	19,974	13,936
18	10:22:59	2,66	2,058	3,026	1,645	18	20,258	14,583	19,974	13,936
19	10:23:00	2,66	2,041	2,896	1,645	19	20,258	14,616	17,517	13,936
20	10:23:01	2,43	2,041	2,896	2,643	20	18,916	14,616	17,517	18,181
21	10:23:02	2,43	2,041	2,896	2,643	21	18,916	14,616	17,517	18,181
22	10:23:03	2,43	3,127	2,896	2,643	22	18,916	14,667	17,517	18,181
23	10:23:04	1,382	3,127	1,425	3,075	23	16,935	14,667	12,196	17,781
24	10:23:05	1,382	3,127	1,425	3,075	24	16,935	14,667	12,196	17,781
25	10:23:06	1,382	3,127	1,425	3,075	25	16,935	14,667	12,196	17,781
26	10:23:07	2,393	2,71	2,731	2,151	26	17,135	14,051	18,714	14,428
27	10:23:08	2,393	2,71	2,731	2,151	27	17,135	14,051	18,714	14,428
28	10:23:09	2,393	2,71	2,731	2,151	28	17,135	14,051	18,714	14,428
29	10:23:10	2,393	1,911	3,255	2,151	29	17,135	10,989	18,746	14,428
30	10:23:11	2,814	1,911	3,255	2,061	30	18,468	10,989	18,746	16,988

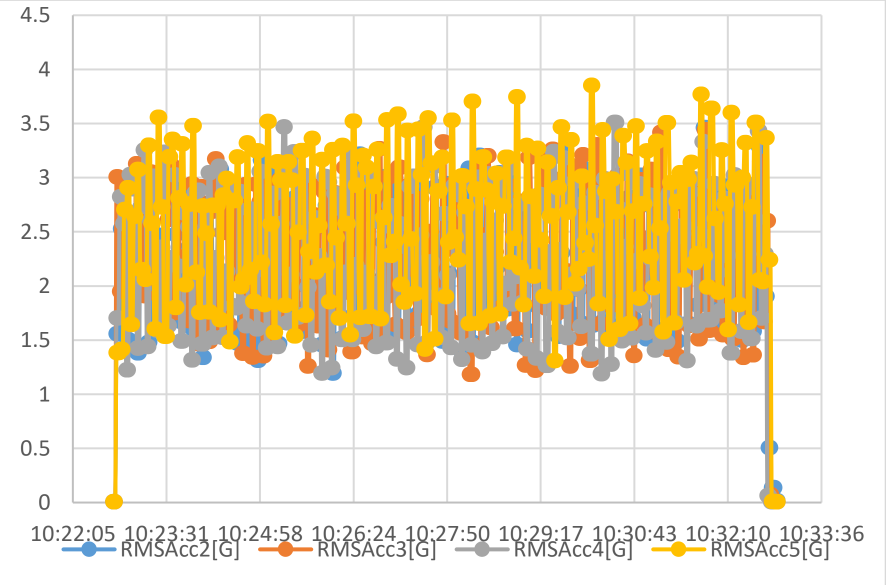

Fig.6.82 Measured values for RMSA at clinker A crushing

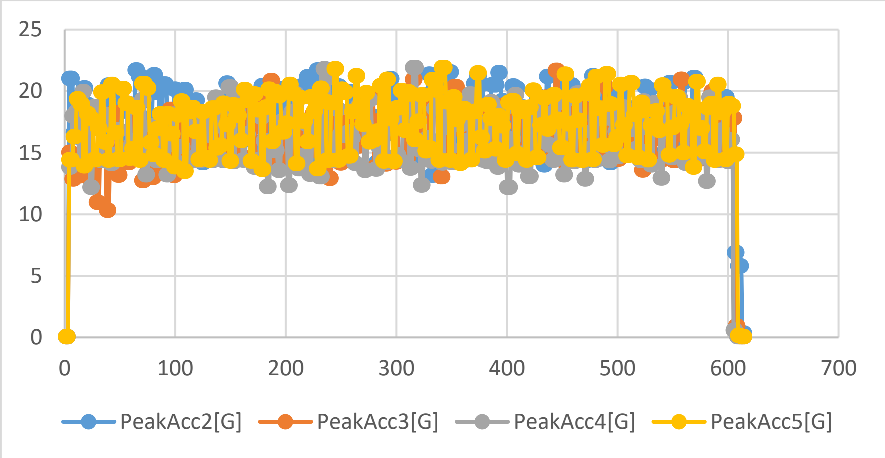

Fig.6.83 Measurement values for Peak at clinker A crushing

After carrying out the vibration measurements for the samples for crushing of the clinker type A and type F and registering the obtained data, as well as plotting the graphs, it is found that the difference in the vibrational acceleration over time of the RMSAcc and PeakAcc values is almost equal, namely: the maximum RMSAcc value (mm/s) for type A clinker is 3.852 < 4.928 (mm/s) over type F clinker. The same can be said for the peak value PeakAcc (mm/s) where the value for type A clinker is of 21.049 < 22.12 (mm/s) for F-type clinker. The conclusion is that F-type clinker is harder than A-type clinker, producing more vibration in the laboratory mill.

6.6. Influence of clinker crushing process parameters on small size clinker categories

6.6.1. The relationship between the degree of grinding and the amount of particles smaller than 1 micron

Table 6.57 Resulting cement values by granulometric classes

Nr. Crt	Granulo metric classes	Cumulative passes [%]														
		Sample code														
		85	86	87	88	89	95	96	97	98	113	114	115	116	117	118
1	<1 µm	4.9	1.2	1.2	0.4	0.4	4.6	0.4	0.4	0.4	0.4	4.9	0	0	0.4	0.4

The moisture content of the cement particles has an important role in the measurement result. The more wet they are, the harder they pass through the sieve, adhere to their surface and negatively affect the degree of grinding. From the attached table it can be seen that the samples with codes 85 and 114 respectively have the highest passage through the sieve < 1 µm of 4, 9%, sample 95 – 4.6%, the rest of the samples almost not passing through the sieve.

6.6.2. The relationship between the degree of grinding and the amount of particles smaller than 5 microns

Table 6.58 Resulting cement values by granulometric classes

Nr. Crt	Granulo metric classes	Cumulative passes [%]														
		Sample code														
		85	86	87	88	89	95	96	97	98	113	114	115	116	117	118
1	<5 µm	10.7	8.1	5.1	2.0	2.5	9.6	5.4	4.0	3.2	2.7	7.8	5.4	3.3	3.4	3.2

From the attached table it can be seen that the smallest passage of particles through the sieve < 5 µm was in sample 88 of 2% and the highest in sample 85 of 10.7%. We can conclude that with small amount of clinker (5 kg) and large balls Ø70+Ø65 the amount of material remaining uncrushed is high and starts to decrease as the size of the grinding balls (Ø70+Ø65+Ø45) mm increases.

6.6.3. The relationship between the degree of grinding and the amount of particles smaller than 10 microns

Table 6.59 Resulting cement values by granulometric classes

Granulometric classes	Cumulative passes [%]														
	Sample code														
	85	86	87	88	89	95	96	97	98	113	114	115	116	117	118
<10 µm	20.6	12.7	8.2	3.6	5.5	16.6	12.9	7.5	6.1	5.3	14.7	10.0	6.9	6.4	5.5

From the attached table, it can be seen that the smallest passage of particles through the sieve < 10 µm was for sample 88 of 3.6% and the highest for sample 85 of 20.6%. The same conclusion can be drawn for particles smaller than 10 microns.

6.7. Experimental determinations of the clinker crushing process in cement plants

6.7.1. Aspects regarding the determination of the characteristics of cement components during its production (experiments in plants)

During the measurements, information was collected from a cement plant in Romania regarding the characteristics of the clinker components in order to draw a parallel with the measurements made in the CEPROCIM laboratory regarding grinding in the ball mill and to determine the correlation coefficient with industrial mills. The range of cement produced was CEM II/A-LL 42.5R, having as component clinker, limestone, gypsum and dust from the kiln filter (CKD). During grinding, ADM additives, dosage 1.74 l/min, were used in order to improve the grinding process and SYNCHRO 206 additive, dosage 0.6 l/min, to reduce Cr^{6+}.

Table 6.62 The values obtained regarding the grinding efficiency

Parameter	M.U.	Value	Remarks
Production (dry)	t/h	74.2	low production
Cement grinding fineness	cm^2/g	3174	fineness corresponding to the type of manufactured cement
Fineness electrofilter dust	cm^2/g	3598	the possibility of increasing the air speed through the mill
Electricity consumption			relatively good consumptions
workshop	kwh/t	41.6	
mill	kwh/t	32.6	
Recirculation coefficient	-	1.51	low value
Airspeed above the load	m/s	0.78	speed outside the usual range (1-1.5 m/s)
Diameter max/min balls CI	mm	80/60	appropriate structure in both rooms
CII	mm	50/18	
Degree of filling CI	%	29.27	degree of filling calculated from H measured with material in the mill
CII	%	27.08	
Average weight of the ball CI	kg	1.40	relatively low weights
CII	g	48.44	
Grinding chart $R_{2,5\,mm}$ to the wall	%	1.99	good value (in the conditions of a mill insufficiently loaded with material)
Idle speed	% from critical speed	76.4	appropriate speed

Table 6.65 The values obtained for the degree of filling and the specific consumption

Parameter	M.U.	Value
Room I		
Degree of filling	%	26.70
Average weight of the ball	kg	1.32
Average diameter of the ball	mm	68.68
Specific electricity consumption	kWh/t	9.60
Room Il		
Degree of filling	%	29.34
Average weight of the ball	g	51.34
Average diameter of the ball	mm	23.25
Specific electricity consumption	kWh/t	23.40
Totally mill		
Specific electricity consumption	kWh/t	32.90

We observe that the degree of filling in chamber I located at the lower limit of the range recommended by the specialized literature is 27-33% and the degree of filling in the second chamber included in the range recommended by the specialized literature is 25-32%.

The grain size of the clinker in the cement mill for the CEM II/A-LL 42.5R cement assortment is presented in Table 6.66.

Table 6.66 The values obtained by optical granulometry at the cement mill (experiment 1), [22]

Sieve mesh, mm	40	30	25	15	10	7	5	3	1	0
Residue, %	1.25	1.60	2.10	9.30	13.45	17.60	8.60	21.95	10.70	13.45
Cumulative residue,%	1.25	2.85	4.95	14.25	27.70	45.30	53.90	75.85	86.55	100.00
Cumulative pass, %	98.75	97.15	95.05	85.75	72.30	54.70	46.10	24.15	13.45	0.00

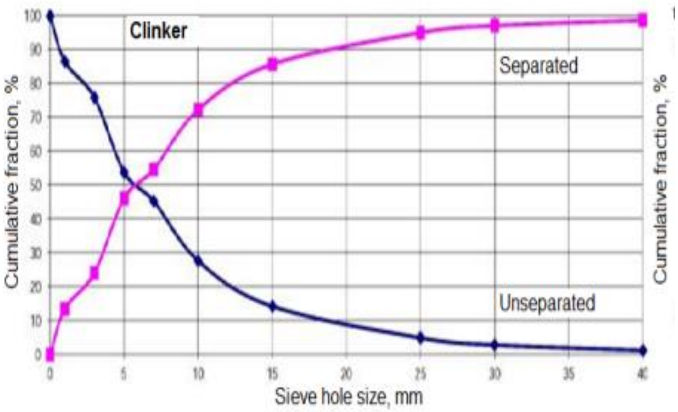

Fig.6.89 Granulometry of the clinker (cement assortment: CEM II/A-LL 42,5R)

Table 6.67 The values obtained by optical granulometry at the cement mill (experiment 2), [22]

Sieve mesh, mm	40	30	25	15	10	7	5	3	1	0
Residue, %	1.90	2.14	2.77	9.21	12.54	15.73	8.12	20.36	11.94	15.29
Cumulative residue , %	1.90	4.05	6.82	16.02	28.56	44.30	52.41	72.77	84.71	100.00
Cumulative pass, %	98.10	95.95	93.18	83.98	71.44	55.70	47.59	27.23	15.29	0.00

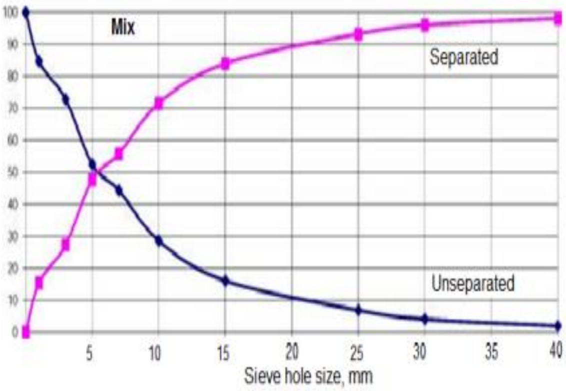

Fig.6.90 Granulometry of the clinker (cement assortment:CEM II/A-LL 42,5R), [22]

On the material samples taken from inside the mill, residues were determined on sieves with mesh sides of 5mm, 2.5mm, 1mm, 200pm, 90µm, 64µm and 32µm and specific Blaine surfaces (chamber II). The obtained results were used to draw the grinding diagram - fig.6.91

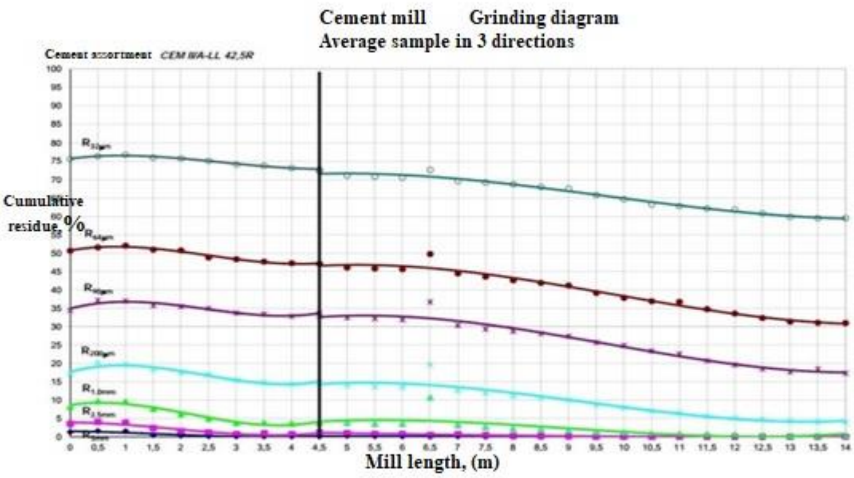

Fig.6.91 Three-way grinding diagram at cement plant

The grinding diagram highlights the following aspects:

Room I

-very well prepared material in room I - R25mm=0.81/1.24% at the partition wall. Recommendation: R2.5mm < 5%;

- active grinding on approx. 65 ÷ 70% of the length of the chamber.

Room Il

-$R_{90\mu m}$ at the mill exit - 17.36%. Recommended value $R_{90\mu m}$ approx. 25%;

- active grinding along the entire length of the chamber.

6.7.2. Determinations regrading the grinding degree in the mill of cement plant

An experiment regarding the chemical and laser granulometric analyzes of the grinding material (cement type CEM I 42.5 R) shows the data presented in Table 6.69:

Table 6.69 Results on granulometry classes of crushed cement in plant

Nr. Crt	Granulometric classes	Cumulative passed [%]														
		Sample code														
		314	315	316	317	318	319	320	321	322	323	324	325	326	327	328
1	<1	5.7	6.1	5.7	6.9	7.3	6.9	2.0	1.6	2.8	7.3	6.9	7.3	6.9	7.4	6.9
2	<1.5	7.3	7.3	7.3	7.3	8.2	7.8	3.7	2.9	3.7	8.2	8.7	8.6	8.2	8.6	8.2
3	<2	10.2	10.3	10.2	10.2	11.5	10.6	4.5	4.1	4.9	11.1	11.1	11.5	11.5	11.1	11.1
4	<3	15.2	15.6	15.6	17.2	18.5	17.9	6.1	6.5	7.4	18.1	17.7	18.9	18.1	18.9	18.4
5	<4	19.7	21.0	20.4	22.5	23.8	22.8	7.5	7.8	9.4	24.2	23.1	23.9	23.5	23.8	25.3
6	<6	25.5	28.8	29.5	30.2	30.3	30.1	9.9	10.6	11.9	30.7	30.5	30.8	32.6	32.1	34.7
7	<8	30.8	35.4	35.2	35.9	35.2	36.7	11.6	11.9	13.6	36.1	35.8	35.4	37.0	36.9	41.2
8	<12	39.5	44.9	44.2	44.5	43.9	46.4	13.2	13.1	15.6	45.0	43.3	44.0	45.6	48.1	50.7
9	<16	46.0	51.9	51.2	51.4	51.6	55.0	14.0	14.0	17.7	51.6	51.8	51.8	55.1	56.6	56.4
10	<24	60.0	65.1	64.2	69.0	69.3	68.9	16.0	16.0	20.1	69.6	68.3	69.5	70.3	70.2	69.5
11	<32	69.5	75.4	74.1	78.8	79.1	78.6	23.0	22.6	24.6	80.3	79.9	80.2	80.2	80.0	79.7
12	<48	81.4	91.9	90.8	90.6	90.6	90.5	37.5	38.1	41.1	92.2	92.3	92.5	92.9	91.1	93.6
13	<64	92.9	96.4	95.7	95.1	95.1	95.4	55.2	54.9	55.1	95.8	96.3	96.2	96.2	96.0	96.9
14	<96	97.5	98.5	97.8	97.6	98.0	97.4	77.9	73.4	77.2	97.9	98.4	98.3	98.3	98.1	97.7
15	<128	98.7	98.9	98.2	98.0	98.4	97.8	87.0	86.5	86.3	98.3	98.8	98.7	98.7	98.5	98.1
16	<192	98.7	98.9	98.2	98.0	98.4	97.8	90.7	90.2	90.4	98.3	98.8	98.7	98.7	98.5	98.1
Rezidue*																
17	>192 µm	1.3	1.1	1.8	2.0	1.6	2.2	9.3	9.8	9.6	1.7	1.2	1.3	1.3	1.5	1.9
Statistical parameters																
18	$D_{50[\mu m]}$	18.0	14.8	15.3	15.1	15.1	13.5	58.8	58.8	57.6	14.9	15.0	15.0	13.7	12.8	11.7

The samples for analysis were collected from the conveyor belts (fine cement right-left) that lead to the cement silos of the cement plant - fig.6.92 a , fig.6.92 b , respectively from the conveyor belt from the mill separator (grit cement) which re-enters the mill for grinding - fig. 6.92 c.

Fig.6.92 c) Conveyor belt for grit cement

Fig.6.92 a) Right conveyor belt for fine cement

Fig.6.92 b) Left **c**onveyor belt for fine cement

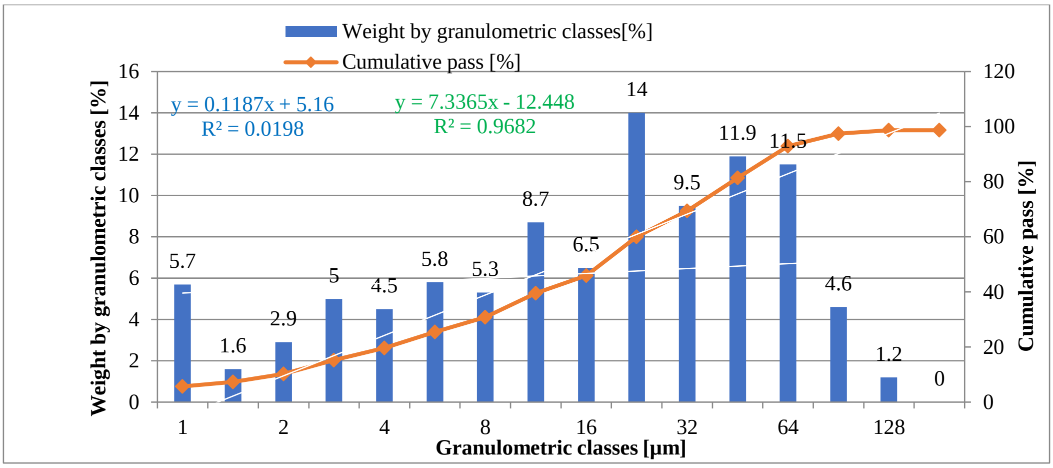

Fig.6.93 Weight by granulometric classes - sample 314

It can be seen that the highest cumulative pass T(%) is on the granulometric class sieve < 24μm of 60% according to Table 6.69 and a weight of 14% according to fig.6.93.

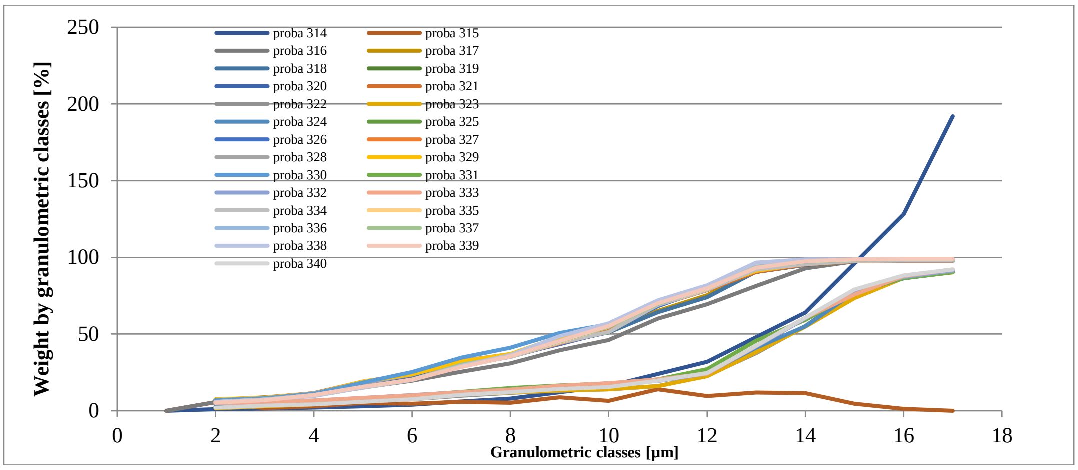

Fig.6.94 Graphical representation of weight by granulometric classes of all samples from the cement plant

According to the graphic representation, it can be seen that all the analyzed samples have a percentage of over 90% cumulative pass T (%) on the granulometric class sieve < 192μm.

6.7.3. Determinations regarding concentrations of particles in suspension due to clinker grinding

The paper deals with the method of determining dust emissions (dust concentration in gases in dry conditions - mg/Nm^3) at the chimney of the ball cement mill - mill outlet and separator outlet.

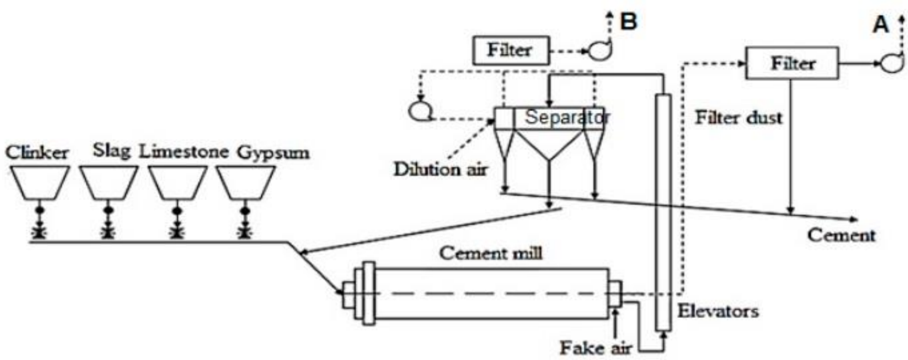

Fig.6.95 Cement grinding flow chart, [16, 20, 22, 164]

The measurements were carried out at a cement plant in Romania at the following points: Cement Mill - Mill Outlet; Cement Mill - Separator Outlet and it was aimed to determine the average monthly concentration (mg/Nm^3) from the 2 points in relation to the maximum limit of the Integrated Environmental Authorization - AIM of the cement plant. The measurements were carried out under reference conditions for atmospheric emissions: 273 °K, p= 101.3 KPa, dry gas, 10%O_2.
The concentration of dust in the gases from the installation is determined by relating the mass of dust obtained to the volume of gas extracted from the pipeline (Table 6.71).

$$C_{dry}=\frac{Dust\ mass}{Vdry}=\frac{Final\ mass-Initial\ mass}{Vdry}\ \text{mg/Nm}^3 \quad (6.24)$$

Table 6.71 Average values of monthly concentrations at the cement mill, [16,17]

Nr.Crt	Period	Emission source/ Code	Issue point/ Code	Nox issued	Average monthly concentration achieved mg/Nm^3	The maximum limit of the authorization mg/Nm^3
1	March	Cement mill 1 / S4	Bag filter FS 76 / E4	Total powders	**1.87**	**30**
		Separator MC1 / S5	Bag filter FS 7-21/ E5		**4.13**	
2	April	Cement mill 1 / S4	Bag filter FS 76 / E4		**1.59**	
		Separator MC1 / S5	Bag filter FS 7-21/ E5		**2.81**	
3	May	Cement mill 1 / S4	Bag filter FS 76 / E4		**2.29**	
		Separator MC1 / S5	Bag filter FS 7-21/ E5		**3.08**	
4	June	Cement mill 1 / S4	Bag filter FS 76 / E4		**2.39**	
		Separator MC1 / S5	Bag filter FS 7-21/ E5		**3.02**	
5	July	Cement mill 1 / S4	Bag filter FS 76 / E4		**3.73**	
		Separator MC1 / S5	Bag filter FS 7-21/ E5		**2.83**	
6	August	Cement mill 1 / S4	Bag filter FS 76 / E4		**4.60**	
		Separator MC1 / S5	Bag filter FS 7-21/ E5		**3.58**	
7	September	Cement mill 1 / S4	Bag filter FS 76 / E4		**3.63**	
		Separator MC1 / S5	Bag filter 7-21/ E5		**3.27**	
8	October	Cement mill 1 / S4	Bag filter FS 76 / E4		**5.06**	
		Separator MC1 / S5	Bag filter FS 7-21/ E5		**4.36**	
9	November	Cement mill 1 / S4	Bag filter FS 76 / E4		**4.54**	
		Separator MC1 / S5	Bag filter 7-21/ E5		**3.80**	
10	December	Cement mill 1 / S4	Bag filter FS 76 /E4		**3.79**	
		Separator MC1 / S5	Bag filter 7-21/ E5		**3.24**	

Next, the distribution of the concentrations obtained during the entire measurement period at the two measurement points was represented: cement mill no. 1 - mill outlet and separator outlet.

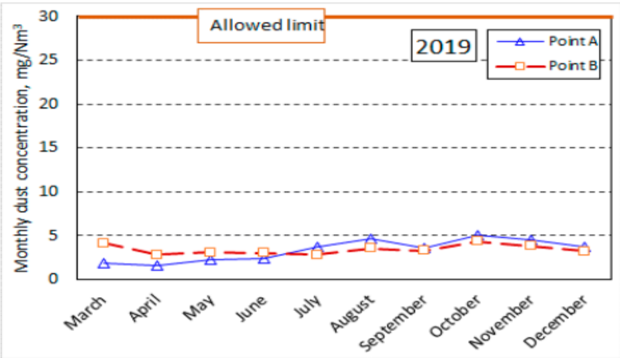

Fig.6.96 a) Distribution of dust emissions at Cement Mill No. 1 of the monitored cement plant, [16]

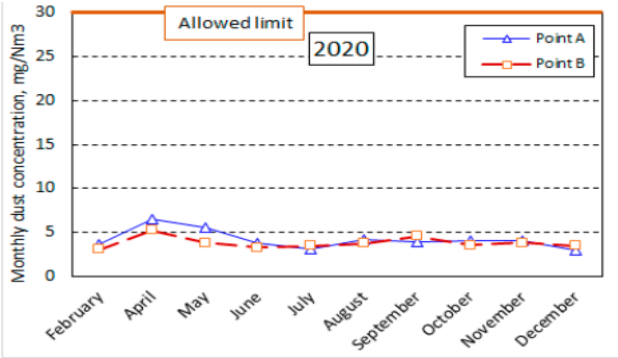

Fig.6.96 b) The distribution of dust emissions at the Cement Mill Separator No. 1 from the monitored cement plant, [16]

6.8. Conclusions regarding experimental research

During the doctoral internship, several experimental researches were carried out, resulting in the following conclusions:

a) For experiment no. 1 - clinker and slag grinding using the laboratory ball mill according to the CEPROCIM method

For the clinker samples analyzed, it was observed that the energy consumption, over the same time interval, was about 10% higher for the clinker from factory A, compared to the clinker from factory F, possibly due to the raw materials used (limestone).It was also found that the variation of energy consumption is relatively linear with time of grinding, the average value of the specific energy consumption being about 1.11 kWh/kg·min at factory A, 1.01 kWh/kg·min at factory F and 1.09 kWh/kg·min for blast furnace slag. Tests performed on grinding clinker with balls of different diameters led to the observation that the larger the diameter of the balls and the smaller the mass of the ground material, the higher the specific energy consumption for both analyzed types of clinker. Likewise for blast furnace slag.

Also during the period when the grinding of clinker and granulated furnace slag was carried out, the vibrations of the mill were also determined. The vibration determinations were carried out according to the work methodology (5 vibration measurements were carried out on the scheduled days for grinding) in order to obtain the acceleration of the laboratory mill. The conclusion is that type F clinker is harder than type A, producing more vibration in the laboratory mill (maximum value RMSAcc (mm/s) type A clinker is 3.852 < 4.928 (mm/s) type clinker F).

b) For experiment no. 2 - clinker grinding using the laboratory mill with balls of different sizes according to different amounts of material

An interesting finding is that the specific energy consumption becomes smaller with the longer the grinding time and the larger the amount of clinker introduced into the mill (fig. 6.37, a, b).

With regard to SSB, this is also the lower the greater the amount of material in the mill (fig.6.37 c), instead the residue on the 90 µm sieve increases with the increase in the amount of material introduced into the mill, at the same grinding time (fig. 6.37).

These findings refer to the grinding of clinker with a mixture of Ø70 + Ø65 mm balls, but the same findings were also observed when grinding clinker with a single type of ball (Ø60 mm) –

fig.6.38, as well as when grinding clinker with a mixture of balls of diameters Ø70 + Ø65 + Ø45 mm (fig.6.39).

c) For experiment no. 3 – clinker grinding using the laboratory ball mill and Zeisel device in order to determine the grindability

If we compare the results obtained in the laboratory on Zeisel apparatus for determining the grindability, we find a small influence (see table 6.52) of crushing and pressing at 100 MPa according to grindability evidenced by the consumption of electricity.

The results obtained on Zeisel laboratory device confirm the statements in the specialized literature that a pressure of up to 100 MPa exerted on the material is not sufficient to obtain results that justify the use of roller mills or crushers, a fact also demonstrated in the case of determining the aptitude to grinding on CEPROCIM laboratory mill (with balls).

d) For experiment no. 4 - clinker grinding using industrial cement mill in order to determine the degree of grinding in the mill of the cement plant

It can be said that an appropriate clinker granulometry has been obtained, recommended range – R25mm < 5%, and large aggregate sizes and compositional variability are factors that can negatively influence the specific grinding consumption and cement quality (according to table 6.45). The degree of filling in chamber I located at the lower limit of the range recommended by the specialized literature is 27-33% and the degree of filling in the second chamber included in the range recommended by the specialized literature is 25-32%.

The average annual concentration reached (mg/Nm^3) at the time of measurements for dust emissions into the atmosphere was approximately ~10% of the maximum limit of the operating license (of 30 mg/Nm^3), i.e. 3.35 mg/Nm^3, at the point of emission FS64 of the bag filter, model FS64 of the cement ball mill and 3.41 mg/Nm^3 of the bag filter, type FS7-21 of the cement mill separator.

e) For experiment no. 5 - clinker grinding using PULVERISETTE 19 laboratory micro-mill and the quantitative analysis of the solid particle size by dry sieving with Analysette 3 Spartan sieve classifier

From fig. 6.74 and table 6.47 it can be seen that the clinker was crushed very finely, a fact resulting from the cumulative T(%) pass of 99.8%, a pass of 80.5% through the 0.2 mm sieve and a percentage of residue of 19.3% on the same sieve of Analysette 3 Spartan sieve classifier. The most residue remained on the sieves of 6.3 in proportion of 84.9 and on the sieve 5 in proportion of 80.6 and on the sieve 3.15 in proportion of 70.1. Through these obtained values it can be said that the clinker used for grinding is of good quality from a mechanical - chemical point of view in order to obtain, in addition to the grinding additives used, a type of cement corresponding to current standards.

CHAPTER 7. FINAL CONCLUSIONS. PERSONAL CONTRIBUTIONS. RECOMMENDATIONS AND RESEARCH PERSPECTIVES

7.1. Final conclusions regarding theoretical and experimental research

1. The grinding of materials in ball mills is reflected in the entire cost of the product. Closed circuit mills double the specific energy consumption, but this is where the work process and separator settings come into play. Even though conventional ball mills have been used in grinding processes for more than a century, they are still being made to improve their grinding efficiency and performance.

2. The sensor technology of the cement grinding process in ball mills contributes to the automation of installations, in order to monitor and reduce energy consumption per production unit. Variations in grind factor (clinker hardness factor) in the process are a key element in determining product quality and productivity of cement manufacturing plants.
3. The technological modernizations carried out in cement factories in Romania in recent years have contributed to the reduction of electricity consumption per unit/tonne of products, the reduction of dust emissions.
4. Following the research on the grinding speed of materials in the cement industry, it was possible to follow the change in the granulometric curve of the material as a function of time, the proposed model reflecting the real phenomena that take place during the grinding process.
5. The relationship between the grindability index and the specific energy consumption of the tube mill which demonstrated that the non-dimensional Hardgrove index allows both the comparison of materials, from the point of view of grindability, with certain reference materials, and the evaluation of a similar energy index with Bond's.
6. Existing mathematical models of the grinding process are developed based on mass balance or energy balance equations that describe the particle size reduction of the ground material as a function of the grinding time or as a function of the specific energy consumed.
7. Among the parameters that affect the process and grinding capacity of mills in the cement industry, we can mention: mill size, ball loading rate, shape, temperature and humidity of raw materials entering the mill, circulating load in the system, ambient air conditions, speed of rotation of the mill.
8. For an optimal design and management of facilities, along with the material balance, it is also necessary to establish the energy, quality and informational balance, and the use of matrix calculation can be of real use as it is easier to apply.

7.2. Personal and original contributions of the paper

1. According to the laboratory analyzes following the grinding of clinker samples A and F, it is remarked that the mineralogical composition according to Bogue's calculation C_2S clinker A > C_2S clinker F (11.48% > 6.8%) which results that clinker A requires additional consumption of energy during grinding because it has a higher content of C_2S. (calcium silicate), a fact also shown by the energy consumption (Clinker A 111.05 kwh/t > Clinker F 101.25 kwh/t).
2. The results of the Laser granulometric analysis determinations for Clincher A, and Clincher F, showed that both clinkers at the 115μm granulometric class the cumulative pass (% material volume) is 100% integral.
3. After modeling the conclusion is that for a lower kinetic energy of the balls when they hit the surface it is better to use more balls and more material to crush.
4. From the simulation it was remarked that the speed gives information about the charge movement, because at the beginning of the grinding it seems that all the particles are uniformly distributed inside the charge, and if the speed of the mill increases, the particles concentrate near the wall and are launched higher from shoulder the load.
5. Determination of the specific surface area (SSB) of the crushed material using the Blaine permeameter method. The Blaine procedure is applicable to all cements defined in the EN 196-6: 2018 standard.

6. The results obtained for determining the ability to grind in CEPROCIM S.A. laboratory mill. and with the laboratory apparatus Zeisel confirms the statements in the specialized literature that at low pressures the influence of the pressure is not noticeable, there being a minimum of 50 MPa at which it must be achieved. From the analysis of the data presented, it follows that the use of prestressing materials by pressing becomes profitable at pressures over 200 Mpa.
7. The results obtained on Zeisel laboratory device confirm the statements in the specialized literature that a pressure of up to 100 MPa exerted on the material is not sufficient to obtain results that justify the use of roller mills or crushers, a fact also demonstrated in the case of determining the grindability on CEPROCIM S.A. type laboratory mill.
8. The sample subjected to laser granulometric analysis was represented by the material passed through the 1000 µm sieve. The value of the residue on the 1000 µm sieve was R1000 = 0.0%. Following the results obtained, the graph of the cumulative pass of material (%vol) was plotted according to the granulometric class (µm) from 0.10 µm to 1000 µm.
9. Following the experiments we can draw the conclusion that with a small amount of clinker (5 kg) and large balls Ø70+Ø65 the amount of remaining material is large and starts to decrease as the size of the grinding balls increases (Ø70+Ø65+Ø45) mm.
10. Optical microscopy determinations showed that the quantitative analysis considered the distinct phases of the clinker, optically identifiable, including both the main phases (alite, belite, tricalcium aluminate and calcium ferrite aluminate) and minor phases (slaked lime, crystallized magnesium oxide).
11. Regarding the experimental determinations regarding the grinding process and the characteristics of the material when grinding clinker in cement factories, it was observed that the grinding fineness corresponds to the type of cement manufactured.
12. For determinations regarding the separation efficiency, according to the efficiency parameters of the WEDAG separator of the cement mill, calculated on the basis of the residues on the sieve with a mesh side of 90µm, the following was found: good separation of fines, poor separation of grit, relatively good separation efficiency and a low recirculation coefficient.
13. It is necessary to correlate the results of theoretical and experimental research with those found from modeling - simulation of the working process of ball mills, in order to obtain high clinker grinding yields with low energy consumption and low resulting powder emissions. According to theoretical research, the required number of balls of different diameters in a mill should be proportional to the number of granules that can be ground with different diameters. The DEM approach was applied in a sampled way to investigate the ball milling process, including the trajectory, velocity and distribution of powder particles and balls inside the mill and correlation with industrial ones.
14. During the measurements of total dust (emissions) from stationary emission sources, carried out at a cement factory in Romania, at the measurement points: cement mill - mill exit and separator exit, the aim was to determine the average monthly concentration (mg/Nm^3) to the 2 points mentioned in relation to the maximum limit in the integrated environmental authorization - AIM of the cement factory. The values provided in the AIM (below 30 mg/Nm^3) were confirmed by the distribution of the concentrations obtained throughout the measurement period at the two measurement points (the measured values did not exceed 5 mg/Nm^3).

7.3. Recommendations and research perspectives

For future research activities it is recommended:

1. Continuing the research of the working process of tubular two-chamber ball mills, in factories, by performing process and energy audits, as well as laboratory research using other types of materials (specific to the cement industry) in order to establish the influence of different structural parameters and functional of the industrial mill on their process parameters (energy consumption, ground material quality).

2. Continuation and expansion of research on the behavior of crushed material (clinker, gypsum, slag, limestone, etc.) during the grinding process through specific laboratory analyses.

3. Creating working models of the clinker grinding process by modeling and simulating the working process of a ball mill, biconical or truncated body.

SELECTIVE BIBLIOGRAPHY

[16] ***Ciobanu C***., *Istrate I.A., Tudor P., Voicu Gh*., *Dust Emission Monitoring in Cement Plant Mills: A Case Study in Romania,* Int.J.Environ. Res. Public Health (IJERPH) 2021, MDPI, *18*(17), 9096, ISSN 1661-7827 https://doi.org/10.3390/ijerph18179096.

[17] *Ciobanu C., Istrate I.A., Tudor P., Voicu Gh., IJERPH | Free Full-Text | Dust Emission Monitoring in Cement Plant Mills: A Case Study in Romania* | HTML (mdpi.com).

[18] ***Ciobanu C***., *Tudor P., Constantin G.A., Musuroi G., Determination of granulometrical composition of the clinker by grinding in a ball mill to determine the specific consumption of additional energy*, 9 th International Conference on Thermal Equipment, Renewable Energy and Rural Development, E3S Web of Conferences, 180, 04007 (2020), https://doi.org/10.1051/e3sconf/202018004007.

[19] ***Ciobanu C***., *Voicu Gh., Istrate I.A., Voicu P., Munteanu M.G*., *Variation of energy consumption and Specific Surface Blaine resulting from simulation of clinker grinding in a cement mill* , International Symposium ISB-INMA TEH , Agricultural and Mechanical Engineering, Bucharest 6-8 October 2022, ISB-INMA TEH' International Symposium.

[20] ***Ciobanu C***., *Voicu Gh., Istrate I.A., Tudor P., Aspects Regarding Polluting Emissions to the Stack of Clincher Ovens in Romanian Cement Factories | Scientific.Net*

[21] ***Ciobanu C***., *Voicu Gh., Istrate I.A., Tudor P., Grinding ability of unprocessed and processed clinker from cement industry* , U.P.B. Scientific Bulletin (Submission ID: 12745), 2022, ISSN 1454-2358.

[22] *Ciobanu C., Voicu Gh.,Toma M.L., Tudor P, Aspects on the working process of the cement mills and dimensional characteristics of the raw material*, 7 th International Conference on Thermal Equipment, Renewable Energy and Rural Development. Conference Proceedings is indexed (BDI) in EBSCO Publishing Databases and INDEX COPERNICUS INTERNATIONAL , pp 205-210, Proceedings-TE-RE-RD-2018-CD-ROM.pdf (pub.ro)

[53] *Ipate G.,* ***Ciobanu C.***, *Voicu Gh., Ilie F., Manaila F., Cardei P., Gageanu I., Cujbescu D., Adaptive Neuro-Fuzzy Model for the control system of the clinker grinding process in ball mills in cement factories,* International Symposium ISB-INMA TEH , Agricultural and Mechanical Engineering, Bucharest 6-8 October 2022, ISB-INMA TEH' International Symposium.

[70] *Neville A.M*., Proprietăţile betonului, Edit. Tehnică Bucureşti, 2003

[71] *Opriș S.*, Manualul Inginerului din industria cimentului-volumul I,Editura tehnica 1994.

[96] *Voicu Gh.,* ***Ciobanu C.***, *Istrate I. A., Tudor P., Aspects regarding dust emissions at cement factories in Romania and methods to reduce them,* International Symposium ISB-INMA TEH , Agricultural and Mechanical Engineering, Bucharest 30 October 2020, ISB-INMA TEH' International Symposium.

[97] *Voicu Gh.,* ***Ciobanu C.***, *Toma M.L., Tudor P., Aspects regarding the grinding efficiecy of a cement mill from Romania,* (ISBN 978-619-7408-47-8, ISSN 1314-2704), 18th International Multidisciplinary Scientific

Geo Conference SGEM 2018, 02-08 July, 2018, pp 89-96, Albena, Bulgaria, DOI:10.5593/sgem2018/5.2/S20.012012.
[99] *Wei Du, Lixiu Ma, Hongkui Li, Peng Huang, Zhenzhen Li,* System dynamics model of output of ball mill (sciendo.com).
[107] ***, https://cirom.ro/obiective-de-mediu/
[108] ***, ISO 14001 - Sistemul de Management de Mediu - Romanian Certification SystemsRS Cert - Certificari ISO Romania
[109] ***, www.tuv-austria.ro/certificari/certificare-iso-9001-sisteme-managementul-calitatii/
[110] ***, www.tuv-austria.ro/certificari/certificare-iso-45001-ohsas-18001-sanatate-securitate-munca/
[111] *** SA 8000 - certificare - responsabilitate socială | SGS România (sgsgroup.ro)
[112] *** ROMPRFIEN034-20160212121510 (anpm.ro)
[113] *** DECIZIA ETAPEI DE INCADRARE „Amplasare instalatie reducere noxe bazata pe apa amoniacala SC CRH CIMENT (ROMANIA) SA - Drafturi acte reglementare - ANPM
[114] *** http://cementnet.ro/resurse/csr-si-ciment

List of Papers in the Field of Doctoral Thesis
Drd. Ing. Cristian-Bogdan CIOBANU

2016

1. **Cristian Ciobanu**, Gheorghe Voicu, Magdalena-Laura Toma, Silviu Marcu, *Dioxins / Furans (PCDDs/PCDFs) Control in Cement Industry in Romania*, Journal of Engineering studies and research **2016**, pp 18-23, Bacău, Volume 22, No.3, Revistă categoria B+, https://doi.org/10.29081/jesr.v22i3.99.

2017

2. **C. Ciobanu**, Gh.Voicu, M.L. Toma., *Continuous monitoring equipment calibration of the dust and gaseous compounds emission from a cement plant,* (ISBN 978-619-7408-09-6, ISSN 1314-2704), 17th International Multidisciplinary Scientific Geo Conference SGEM 2017, 29 june-05 july, 2017, pp 225-232, Albena, Bulgaria, DOI:10.5593/sgem2017/52/S20.030

2018

3. **C. Ciobanu**, Gh.Voicu, M.L. Toma , Paula Tudor, *Emissions Monitoring of Heavy Metals and their compounds resulted from combustion processes in clincker kilns in Romania,* Journal of Engineering studies and research, pp 17-23, Bacău ,Volume 24 (2018) No.1, Revistă categoriaB+, https://doi.org/10.29081/jesr.v24i1.63

4. **C. Ciobanu,** Gh Voicu, M.L. Toma, P. Tudor, *Aspects on the working process of the cement mills and dimensional characteristics of the raw material*, 7 th International Conference on Thermal Equipment, Renewable Energy and Rural Development. Conference Proceedings is indexed (BDI) in EBSCO Publishing Databases and INDEX COPERNICUS INTERNATIONAL , pp 205-210, Proceedings-TE-RE-RD-2018-CD-ROM.pdf (pub.ro)

5. Voicu Gh., **C. Ciobanu**, M.L. Toma, P. Tudor., *Aspects regarding the grinding efficiecy of a cement mill from Romania,* (ISBN 978-619-7408-47-8, ISSN 1314-2704), 18th International Multidisciplinary Scientific Geo Conference SGEM 2018, 02-08 July, 2018, pp 89-96, Albena, Bulgaria, DOI:10.5593/sgem2018/5.2/S20.012012

2020

6. Voicu Gh., **C.Ciobanu** , Irina Aura Istrate , P. Tudor, *Emissions control of hydrochloric and fluorhydric acid in cement factories from Romania,*Int.J.Environ. Res. Public Health (IJERPH) **2020**, MDPI, *17*(3), 1019, ISSN 1661-7827 https://doi.org/10.3390/ijerph17031019(*articol ISI, WOS:000517783300344, IF 4, 614, Q1*).

7. **C. Ciobanu,** P. Tudor, G.A.Constantin, G.Musuroi, *Determination of granulometrical composition of the clinker by grinding in a ball mill to determine the specific consumption of additional energy*, 9 th International Conference on Thermal Equipment, Renewable Energy and Rural Development, E3S Web of Conferences, 180, 04007 (2020), https://doi.org/10.1051/e3sconf/202018004007

8. Voicu Gh., **C. Ciobanu,** I. A. Istrate, P. Tudor, *Aspects regarding dust emissions at cement factories in Romania and methods to reduce them,* International Symposium ISB-INMA TEH, Agricultural and Mechanical Engineering,

Bucharest 30 October 2020, pp 138-145, ISSN-L 2344 – 4118, ISSN 2537 – 3773, index Copernicus, ISB-INMA TEH'International Symposium, Hunedoara, Vol.19, Iss. 2, May2021:23-30, https://www.proquest.com/docview /2568721025

2021

9. C.Ciobanu , Voicu Gh., I. A. Istrate , P. Tudor, *Aspects Regarding Polluting Emissions to the Stack of Clincher Ovens in Romanian Cement Factories,* Scientific.Net, Trans Tech Publications Ltd, Switzerland **2021**, ISSN 2234-99IX, Vol 42, pp 159-166, https://doi.org/10.4028/www.scientific.net/AEF.42.159

10. C.Ciobanu, I. A. Istrate , P. Tudor, Gh. Voicu, *Dust Emission Monitoring in Cement Plant Mills: A Case Study in Romania,* International Journal Environmental Research Public Health (IJERPH) **2021**, MDPI, *18*(17), 9096, ISSN 1661-7827 https://doi.org/10.3390/ijerph18179096, (*idexat ISI, WOS:000694081200001, IF(2020)=3.39,Q1*).

11. C. Ciobanu, Gh. Voicu, I. A. Istrate, P. Tudor, *Pollution reduction through waste co- processing in Romanian cement plants,* International Symposium ISB-INMA TEH, Agricultural and Mechanical Engineering, Bucharest 29 October 2021 online, pp 370-377, ISSN-L 2344 – 4118, ISSN 2537 – 3773, index Copernicus, Hunedoara, Vol. 20, Iss. 2, May 2022: 161-166, https://www.proquest.com/ openview/ a7e93c1953df9eeee5d862b8dc60978e/1?pq-origsite=gscholar&cbl=616472.

2022

12. C.Ciobanu, P. Tudor, I. A. Istrate, Voicu Gh., *Assessment of Environmental Pollution in Cement Plant Areas in Romania by Co-Processing Waste in Clinker Kilns,* Energies **2022**, *15*(7), 2656, ISSN: 1996-1073; https://doi.org/10.3390/en15072656, (*articol ISI, WOS:000781541400001, IF. 3,252*).

13. C.Ciobanu , Voicu Gh., I. A. Istrate , P. Tudor, *Grinding ability of unprocessed and processed clinker from cement industry* , U.P.B. Scientific Bulletin, seria D, vol.85, nr.1/**2023**, ISSN 1223-7027

14. George Ipate, **C. Ciobanu**, Gh. Voicu, Filip Ilie, Florentina Manaila, Petru Cardei, Iuliana Gageanu, Dan Cujbescu, *Adaptive Neuro-Fuzzy Model for the control system of the clinker grinding process in ball mills in cement factories,* International Symposium ISB-INMA TEH, Agricultural and Mechanical Engineering, Bucharest 6-8 October 2022, vol. 68, no 3/2022, https://api.inmateh.eu/public/uploads/68-57-N788-George-IPATEa812124f-d528-4774-84ad-b7b84bd5025b.pdf.

15. C. Ciobanu, Gh. Voicu, I. A. Istrate, P.Voicu, M.G. Munteanu, *Variation of energy consumption and Specific Surface Blaine resulting from simulation of clinker grinding in a cement mill,* International Symposium ISB-INMA TEH, Agricultural and Mechanical Engineering, Bucharest 6-8 October 2022, pp 378-387, ISSN-L 2344 – 4118, ISSN 2537 – 3773, index Copernicus, ISB-INMA TEH' International Symposium