Energy-Exergy Analysis and Carbon Emission of Nigerian Cement Manufacturing Industry.

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Abstract

Two of the largest cement manufacturing plants in Nigeria, named Plants A and B, were studied and the data collected for the 10-year period 1995 – 2005 from them enabled an analysis of their energy consumption, energy cost per tonne, efficiency of energy use from exergy analysis, and carbon dioxide emission rates. The two plants account for over 70% of total local cement production in Nigeria. Both plants utilize thermal and electrical energy. With both plants having thermal to electrical energy utilization ratio of 90:10 compared to the 70:30 recommended best global practice. The Input-Output Analysis methodology was used to evaluate the embodied energy intensity which was found to increase over the period in both plants, with Plant A having the highest increase from 7.1 to 9.4 GJ/tonne. The embodied energy intensity for both plants was 50% higher than the recommended best global practice of between 2.9 and 3.2 GJ/tonne. The energy cost per tonne for both plants increased by about 1000% over the period despite a 33% reduction in total energy consumption. Efficiency of energy use evaluated from an exergy analysis in Plant A increased from 50% to 59% while in Plant B the increase was from 33% to 45% over the period, compared to the recommended global best practice of 50%. Carbon dioxide emission in both plants declined over the period, for Plant A from 765903 Tg to 548310 Tg (40%) and for Plant B from 604255 Tg to 543658 Tg (16%) over the period.

Keywords: Cement plants, Energy, Exergy, CO_2 Emission.

1.INTRODUCTION

Cement production is highly energy intensive and globally accounts for two – thirds of total energy use in the production of non – metallic minerals [1]. The global cement industry is also considered a key source of CO_2 in the world accounting for 9 – 10% of total global emission [2]. It is due to the aforementioned facts that the industry has been the subject of significant number of energy studies.

In this study, analysis of energy consumption, energy cost per tonne, efficiency of energy use from exergy analysis, and carbon dioxide emission rates were performed for the Nigerian cement industry. Data for the work was collected for the period 1995 – 2005 from two major cement manufacturing plants which accounts for over 80% of cement production in Nigeria.

The structure of the paper is organized as follows. The first section includes the introduction. The description of the cement production process of the Nigerian cement industry is given in section 2. Section 3 makes a theoretical analysis of the methods used for the determination of the embodied energy Intensity, efficiency of energy use, total pollution rate, CO_2 emission and the energy cost of production. Section 4 is a presentation and analysis of the energy and production data obtained from the two plants. The section also discussed and analyzed the cement production trend, energy utilization patterns, efficiency of energy use, CO_2 emission, pollution rate and energy cost of production for the two plants. The section concludes by making a comparative analysis of the two plants with best international practices. Section 5 concludes.

2. Description of Cement Production Process

The principal steps in the manufacturing of cement are raw material preparation, clinker production and finish grinding.

2.1 Raw material preparation

This process includes the raw material extraction, limestone crushing, raw material storage and pre – homogenization and raw milling. The raw material for cement production including limestone, shale and clay are usually obtained by large – scale open – cast mining or quarrying operations. The limestone dislodged from its natural deposit by blasting from a coarsely fragmented rock pile, which is reduced by crushing to a fine powder usually between 80 and 20mm in particle size.

The crushed limestone is stockpiled to reduce day – to-day variation in the chemical characteristics of the raw material and also to provide buffer stock to maintain continuous raw milling. At the raw mill, the raw material is ground to powder fine enough (up to 15% residue captured on a 90mm sieve) to burn in the kiln. Also additives such as sandstone, clay and shale are added to adjust the chemical composition of the raw mix and improve its sintering capacity. These materials are then ground to a fine powder in the proportion needed for the cement. These can be ground as a dry mixture or combined with water to form slurry. The addition of water at this stage has important implication for the production process and for the energy demands during production. Production is often categorized as dry process or wet process; additionally, if equipment is added to remove some water from the slurry after grinding, the process is then either semi – wet or semi – dry.

2.1.2 Clinker Production

The Mixture of raw materials enters the clinker production (or pyroprocessing) stage. During this stage, the mixture moves through a system of cyclones called a preheater, undergoing gradual heat treatment at temperature up to 900°C; thereafter rotary kilns are used to roast the materials at over 1400°C. This process drives off all moisture, dissociates carbon dioxide from calcium carbonate, and transforms the raw materials into new compounds. The output from this process, called clinker, must be cooled rapidly to prevent further chemical changes. Clinker production is the most energy – intensive step, accounting for about 80% of the energy use in cement production.

2.1.3 Finish Grinding

Clinker is the basic ingredient of cement, and it largely determines the quality of the end product. Cement is produced by grinding the cooled clinker with gypsum. The grinding usual takes place in a tubular mill, partly filled with steel balls. The major cement produced in Nigeria is the Portland cement. The cement produced is stored in silos, which are medium term storage facility.

3.0 Theoretical framework

3.1 Estimation of the Embodied Energy of Cement Production.

This study utilized the energy intensity model of the Input **– Output Energy Analysis (IOEA)** to estimate the **Embodied Energy Intensity** of the Cement Manufacturing Industry in Nigeria. The equation for the energy intensity model is expressed as:

$$\varepsilon = D^T (I - A)^{-1} \qquad (1)$$

Where ε is embodied energy, D^T is the direct energy intensity vector; A is the technology matrix and I the identity matrix. The Direct Energy Intensity vector D^T is derived from the expression:

$$D^T = \frac{TEUS}{TQPS} \qquad (2)$$

Where TEUS is the total energy used in the sector and TQPS is the total Quantity Produced in the sector.

The Technological matrix (A) is a 4 x 4 matrix and is a ratio of the input to a sector divided by the output of the sector transferred to another sector and it is expressed as follows:

$$A_{ij} = \frac{X_{ij}}{X_j} \qquad (3)$$

Where X_{ij} is the input variable and X_j is the output.

Based on equation (1) two Input – Output (I – O) tables are constructed to show the transactions of the economic producing sector of the cement industry. The two I – O tables are the Input – output table for the production or mass transfer and the input table for the energy transactions. These two tables are used for the estimation of the embodied energy.

3.2 Estimation of efficiency of energy use and pollution rate

Exergy is defined as the maximum useful work that could be obtained from the system at a given state in a specified environment [4]. An exegetic analysis of a system helps to identify primary sources of loss and provides a more accurate picture of the performance relative to the theoretical idea. Exergy analysis has been used in the study for the estimation of the efficiency of energy use and pollution rate for the cement manufacturing industry in Nigeria.

The first step in an exergy analysis is to determine the exergy balance of a process or a system. This is depicted in figure 1. The exergy balance is depicted in the following equation.

$$B_{input} = B_{product} + B_{losses} + B_{waste} \qquad (4)$$

The exergy losses are mainly due to irreversibilities while the exergy of waste includes the exergy of solid and liquid waste, and air emissions. The useful exergy is the exergy of the products. This can be calculated from the exergy balance as,

$$B_{product} = B_{input} - B_{losses} - B_{waste} \qquad (5)$$

The Process efficiency or efficiency of energy use is defined as the percentage of the useful exergy to the total input exergy:

$$\varnothing_p = \frac{B_{product}}{B_{input}} \qquad (6)$$

Where $\varnothing_p$ is the exergetic efficiency.

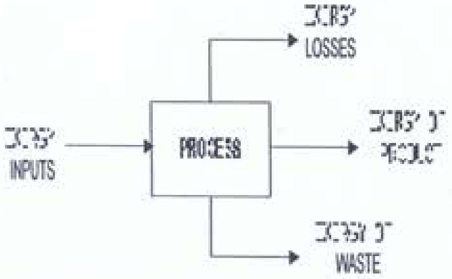

Figure 1. Exergy Balance of a Process

The efficiency of energy use obtained with the determination of the exergetic efficiency ($Ø_p$) is complemented with calculation of the Total Pollution Rate (R_{pol}) . This index was initially proposed by Makarytchev [3] for a cogeneration plant, in order to define an index of environmental hazard that characterizes the exergy destruction caused by the deactivation of process waste. In this study the total pollution rate is defined as follows:

$$R_{pol} = \frac{B_{waste}}{B_{product}} \quad (7)$$

If the total pollution rate $R_{pol} >> 1$ it implies that the process under consideration produces emissions and wastes which produce a great impact on the environment. If $R_{pol} = 0$, then the process is said to be reversible and does not cause impact on the environment. If $0 < R_{pol} < 1$ it implies that the impact of the process on the environment is a function of the technological limitation of the energy conversion process.

3.3 Estimation of Carbon (IV) Oxide (CO_2) emissions

In cement production, CO_2 is emitted from two major sources. The first source is from the combustion of carbon – based fuels burned during the calcinations and other stages of the cement production process; this type of emissions is called combustion – based CO_2 emissions. The second source is from the by – product of the chemical conversion process used in the production of clinker, a component of cement, in which limestone ($CaCO_3$) is converted to lime (CaO); this type of emissions is called process – based CO_2 emissions. The total CO_2 emission is derived by adding up the combustion and process based emissions from the Cement Industry.
The Revised 1996 IPCC (Intergovernmental Panel on Climate control) of the United Nations Framework Convention on Climate Change (UNFCCC) Guidelines for National Greenhouse Gas Inventories (IPCC Guidelines) provides a general approach for the estimation of CO_2 emissions both for the combustion and process – based emissions from the Cement industry. This IPCC guideline was used in this study to estimate the CO_2 emission from the selected cement manufacturing plant in Nigeria.

3.3.1 Estimation of combustion – based CO_2 for the cement industry.

The calculation of CO_2 emission from fuel combustion is discussed under the Tiers 1 method (Reference Approach) of the IPCC guidelines [4] and it involves the following steps:
Step 1: Estimate the fuel consumption in original units
Step 2: Convert to a common energy unit
Step 3: Multiply by emission factors to compute the carbon content.
Step 4: Calculating carbon stored.
Step 5: Correcting for carbon unoxidized.
Step 6: Converting to CO_2 emissions

3.3.2 Estimation of process – based CO_2 emission from cement production.

Carbon – dioxide (CO_2) is released during the production of clinker. Specifically, CO_2 is released as a by –product during calcinations of $CaCO_3$ which occurs in the upper, cooler end of the kiln, or a precalciner, at temperatures of 600 – 900^{0}C, and results in the conversion of carbonates to oxides. The simplified stoichiometric relationship is as follows:

$$CaCO_3 + Heat \rightarrow CaO + CO_2 \quad (8)$$

CO_2 is also emitted during the calcinations of Cement Kiln Dust (CKD) in the kiln. CKD is a by – product of the kiln process and a portion of the CKD is placed back in the kiln and incorporated into the clinker. The remaining portion is lost – placed in a landfill or used for other purposes. The lost CKD represents additional CO_2 emissions not accounted for in the clinker emission estimate.
There are two recommended approaches to quantifying the CO_2 emissions during cement production and CKD: the clinker based methodology and the cement based methodology. However the IPCC guidelines strongly recommend using clinker data and the clinker – based methodology rather than the cement data to estimate CO_2 emissions because CO_2 is emitted during clinker production not cement production. Thus study utilized the clinker – based methodology for estimating the process – based CO_2 emitted in cement production. Equation 9 presents an overview of the clinker – based approach.

$$CO_2\ Emission = (P_{clinker} * EF_{clinker}) + (CKD_D * EF_{CKD}) \quad (9)$$

Where $P_{clinker}$ is the mass of clinker produced, $EF_{clinker}$ is the clinker emission factor, CKD_D is mass of cement kiln dust discarded and EF_{CKD} is the cement kiln dust emission factor.The clinker emission factor is the product of the fraction of lime in the clinker multiplied by the ratio of the mass of CO_2 released per unit of lime. This gives:

$$EF_{clinker} = \text{fraction CaO} * 0.785 \quad (10)$$

The multiplication factor (0.785) is the molecular weight ratio of CO_2 to CaO in the raw material mineral calcite ($CaCO_3$), from which most or all of the CaO in clinker is derived.

The IPCC guidelines recommend two possible methods for calculating the emission factor. The Tier 1 method uses the IPCC default value for the fraction of lime in clinker, which is 64.6%. This results in an emission factor of 0.507 tons of CO_2/ ton of clinker, as shown below:

$$EF_{clinker} = 0.646 * 0.785 = 0.507 \quad (11)$$

The Tier 2 method is to calculate the average lime concentration in clinker by collecting data on clinker production and lime fraction by type. Based on this method Chia et al (1986)[5] determined the CaO fraction of Portland cement in Nigeria to be about 62% by weight. This results in an emission factor of 0.487 tons of CO_2/ton of clinker, as shown below:

$$EF_{clinker} = 0.62 * 0.785 = 0.487 \quad (12)$$

The emission factor derived in equation (12) is used in this study. The recommended method to estimate the additional CO_2 emissions from the lost CKD is to multiply an emission factor by the amount of lost CKD. it is recommended that since the CO_2 from the lost CKD is generally equivalent to about 2 – 6% of the total CO_2 emitted from clinker production, that a percentage between 2 – 6% is selected and multiplied by the estimate of CO_2 emissions from clinker production to get an estimate of CO_2 emitted from the lost, calcined CKD. For this study 2% was selected and multiplied to the estimated CO_2 emission from clinker production to give the estimated CO_2 emission from discarded CKD. Thus for this study equation 9 has been modified to give the process – based CO_2 emission from the cement plant as;

$$CO_2\ \text{Emission} = 1.2 * (P_{clinker} * EF_{clinker}) \quad (13)$$

3.4 Estimation of energy cost of production

The Energy Cost of Production (EC/p) for the cement manufacturing plants under consideration has been estimated using an energy accounting methodology. It is a ratio that indicates the total cost of energy in the production of one unit of cement and is expressed mathematically as:

$$EC/p = \frac{TECT * EI}{TEC} \quad (14)$$

Where EC/p (Naira/tonne) is energy cost per unit production, TECT is total energy cost, EI is the embodied energy intensity and TEC is the total energy consumed.

4.0 Results and discussion

The two selected cement plants for the study were labeled as Plant A and Plant B. Plant A is a wet process plant with total installed capacity of 1,000,000 metric tonnes, while plant B is a dry process plant with total installed capacity of 700,000 metric tonnes. The two cement plants considered in the study reflect the two major cement production process type available globally, thus the comparison of the production process of the two plants will help to determine the degree to which the cement industry in Nigeria had taken advantage of improved global cement production technology. Table 1 is the summary of result of the yearly production and energy input – output analysis; while Table 2 is the summary of the exergy analysis and energy cost of production for the two plants respectively.

4.1 Production and Input – output analysis results

For the period under review both plants witnessed a decline in their production. The total energy consumed by Plant A declined by 25%, while that of Plant B declined by 22% between 2000 – 2002 and increased by 23% between 2003 – 2005. Thermal energy consumption for both plants constituted between 90 – 94% of total energy consumption, while electricity consumption made up the remaining 6 – 10%. The study also observed a very wide fluctuation in the estimated value of embodied energy intensity for both plants. For the period under consideration, the embodied energy for Plant A ranged between 7.07GJ/t – 9.37GJ/t, while that for plant B was in the range 4.96GJ/t – 6.27GJ/t.

Comparing best technology specific energy use with the energy consumption in Nigeria's cement plant, the energy consumption pattern for both plants contrasts the primary energy requirements for Portland cement production in industrialized countries were energy consumption consists of 70% thermal and 30% electricity [6]. With regards to embodied energy intensity the best technology practices recommend for a 4 – 5 stage pre – heater dry kiln an energy intensity of 3.06GJ/tonne of clinker, and for the wet process it is recommended that energy intensity use be 5.3 – 7.1 GJ/t [7]. This shows that for both plants an energy saving of over 50% is possible if various energy saving practices and programs are put in place.

4.2 Exergy analysis and CO_2 emission.

The study showed that Plant A recorded a total exergy of product of between 54 – 60% of total exergy input and efficiency of energy use or exergy efficiency in the range 54 – 60%, this is considered optimum when compared with best global practices which recommends an optimum level of 50% [8]. For Plant B, the total exergy of product constituted 33 – 45% of total exergy input, while the efficiency of energy use was in the range 33 – 45%, which is considered below the recommended optimum best practices of 50%.

The study also showed that the total pollution rate at Plant A for the study period was in the range 0.68 – 0.85, while that for Plant B was in the range 2.04 – 1.22. This implies that the impact of the production process in Plant A, were the pollution rate is below 1.00, on the environment is a function of the technological limitations of the energy conversion process at the plant. For Plant B, with pollution rate of over 1.00, it implies that the impact of the cement production process on the environment was very high; nonetheless going by the trend in reduction of pollution, it would seem that the cement plant was making effort at reducing the pollution rate.

The study also observed that for Plant A, the process – based emissions constituted between 52 – 56% of the total reported CO_2 emissions for the study period, while the combustion – based emissions constituted only 44 – 49% of total emissions. For Plant B process – based emission constituted 55 – 61% of total emissions, while the combustion – based emission constituted only 38 – 44% of total emission. In terms of total emissions, Plant A reported a gradual decline in the period 2000 – 2005, while Plant B reported increase in emissions. The reduction in emissions from Plant A was due mainly to reduction of energy consumption by 33% and fall in utilization capacity by 27% during the period. For Plant B the increase in emissions was due to increase in utilization capacity and thermal energy consumption.

Table 1 Summary of yearly production and energy input – output analysis

YEARS	PLANTS	INDICATORS				
		TOTAL PRODUCTION (Metric Tonnes)	TOTAL ENERGY CONSUMED (GJ)	THERMAL ENERGY CONSUMED (GJ)	ELECTRICITY CONSUMED (Mwh)	EMBODIED ENERGY (GJ)
1995	A	950332	6588716.53	6230091.42	98856	7.74
	B	NA	NA	NA	NA	NA
1996	A	857326	5905181.8	5580966.54	89399	7.82
	B	NA	NA	NA	NA	NA
1997	A	925755	6627237.02	6256890.7	102186	7.38
	B	NA	NA	NA	NA	NA
1998	A	917694	6465282.67	6096441.49	101750	7.11
	B	NA	NA	NA	NA	NA
1999	A	955247	6731198.82	6352837.51	104367	7.11
	B	NA	NA	NA	NA	NA
2000	A	960892	6965743.92	6601303.66	103807	7.56
	B	801916	3538792.19	3250632.67	109664	5.06
2001	A	876849	6160262.07	5829497.85	91158	7.88
	B	750894	3362185.9	3049517.51	94504	4.96
2002	A	876064	6459432.41	6138217.98	88447	8.82
	B	719870	3544664.49	3268830.16	92470	5.19
2003	A	710842	6179585.12	5893550.09	78754	9.37
	B	700461	3282761.06	3014831.05	99315	5.14
2004	A	742273	5609313.6	5322501.5	78843	9.04
	B	699448	3700291.1	3399402.78	99501	5.52
2005	A	692655	4638516.92	4390085.75	85494	7.07
	B	705317	3600775.79	3331795.52	104087	6.27

4.3 Energy Cost of Production

A the energy cost increased from ₦411.8 million to ₦ 4.549 billion, while that of Plant B increased from ₦231.7 million to ₦ 2.239 billion. This very sharp increases was due to the change in petroleum prices during the period by over 500%. From the analysis of the energy cost of production from the two plants, it is clearly seen that it is much cheaper to produce with a dry process than with a wet process. The energy cost of production in Plant B dry process plant was consistently lower than that of the Plant A wet process plant. The study also showed that increases in the

Both cement plants reported for the study period over 1000% increase in energy cost of production. For Plant prices of petroleum product has adversely affected the operations of both cement plants as this has resulted in exponential increases in the total energy cost of production per tonnes. Comparing the figures obtained for energy cost of production with best practices around the world, and the cost of cement in the international market (₦ 4,350 - ₦ 5,600 per tonne) [9] it is obvious that it is expensive producing cement in Nigeria

Table 2 Summary of exergy analysis, CO_2 emission and energy cost of production

YEARS	PLANTS	INDICATORS					
		TOTAL EXERGY INPUT (GJ)	TOTAL EXERGY OF PRODUCT (GJ)	EFFICIENCY OF ENERGY USE (%)	TOTAL POLLUTION RATE	TOTAL CO_2 Emission (Tg CO_2)	TOTAL ENERGY COST (N million)
1995	A	677455.17	3923482.56	58	0.73	765903.39	411.8
	B	NA	NA	NA	NA	NA	NA
1996	A	5953138.17	3318559.85	56	0.78	687732.52	393.5
	B	NA	NA	NA	NA	NA	NA
1997	A	6683815.77	3616491.58	54	0.85	799058.9	437.4
	B	NA	NA	NA	NA	NA	NA
1998	A	6616679.85	3579014.33	54	0.85	786908.04	800.3
	B	NA	NA	NA	NA	NA	NA
1999	A	6740164.88	3718849.2	55	0.81	797054.86	887.3
	B	NA	NA	NA	NA	NA	NA
2000	A	7116829.84	4181836.45	59	0.7	791225.06	957.02
	B	3682724.13	1219876.44	33	2.04	604255.27	231.68
2001	A	6275441.66	3507399.22	56	0.79	728585.37	4,439.9
	B	3575810.52	1214095.38	34	1.95	574104.86	2,309.2
2002	A	6722465.29	3958408.97	59	0.7	739157.27	4,548.6
	B	3754948.06	1331809.84	35	1.82	596894	2,063.6
2003	A	6225503.4	3711066.39	60	0.68	685629.84	4,293.7
	B	3495477.02	1258870.01	36	1.8	550829.39	2,021.4
2004	A	5898545.77	3411547.39	58	0.73	655734.73	4,159.4
	B	3974483.9	1550143.64	39	1.56	604465.58	2,239.4
2005	A	4729483.44	2633979.77	56	0.8	548310.89	3,552.4
	B	705317	1714835.03	45	1.22	543658.31	2,154.5

5.0 Conclusions

The study showed that the energy utilization reported for the two selected plants in Nigeria is high when compared with best practices and that contrary to expectations the dry process plant was found to be less energy efficient than the wet process plant, even though both plants reported reduction in CO_2 emission and pollution rate. The study also showed that it is expensive to produce cement in Nigeria due to high and astronomical increases In petroleum products over the period under review.

6.0 References

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