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# THERMOECONOMIC ANALYSIS OF ALTERNATIVE FUELS ON ROTARY KILN PERFORMANCE OF OBAJANA CEMENT PLANT

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Abstract

A process model for the operation of rotary kiln in the cement production process was developed using Aspen Plus to study the effect of alternative fuels from used tyre, municipal waste (MSW) and sugarcane bagasse on clinker quality, emissions and thermal stability by introducing 5%, 10%, 15%, 20%, 25% and 30% of the alternative fuel mix with coal. The three fuels increased the Lime Saturated Factor (LSF) compared to 100% coal, but the observed values were within acceptable limits. Sugarcane bagasse had the best silica ratio (SR between 2.49458 to 2.49405), with Used Tyre and MSW having a low silica ratio below 1.6. However, the low SRs were complemented by their alumina ratios (ARs). Used Tyre and Sugarcane bagasse can maintain the kiln temperature (1640 $^0$C to 1690 $^0$C) up to the reference case. Tyre and MSW can reduce $CO_2$ emission, but sugarcane bagasse does the opposite with a capacity of up to 9.67 kg/tonne clinker increment in emission at 30% fuel mix. The three alternative fuels considered were found to increase $NO_x$ emissions. Used Tyre was the most preferred alternative fuel due to its ability to reduce $CO_2$ emission while ensuring thermal stability in exergy efficiency and kiln outlet temperature, coupled with its worldwide availability. However, caution must be employed to monitor its $SO_x$ emissions; hence it should not exceed 20% in the fuel mix to keep $SO_x$ emissions below 310 mg/Nm$^3$. The alternative fuels were more cost-effective (as higher configurations resulted in lesser costs, particularly in MSW with a cost-saving up to 613.92 $/hr in 30% fuel mix) but less efficient than coal in terms of exergy, with sugarcane bagasse as the potential best (difference of less than 3%). It can be inferred from the results obtained that the development of alternative fuel from blending sugarcane bagasse and coal for a rotary kiln is economical, reduces emissions and feasible.

**Keywords:** Cement, Kiln modelling, Energy performance, Alternative fuel, Emission.

## 1.0 Introduction

Cement production involves a mixture of limestone and clay; it requires a kiln temperature of 1500 degrees Celsius [11], [8]. Attaining this high temperature during cement production is possible by burning fossil fuel which is considered expensive [8]. Aside from the high price of fossil fuel, the environmental impact of burning fossil fuel also affects its wide acceptance for industrial application. For instance, study has shown that greenhouse gas and about 900kg of $CO_2$ are being released into the environment. This is attributed to the high amount of energy needed during the chemical reaction of the raw mix. This is why cement industry is held accountable for about 5–6% of anthropogenic $CO_2$ emissions. The emission causes about 4% of global warming [12], [6].

It is high time the world looked for sustainable alternatives to the daunting effects of finite fossil fuel. The resources of global fossil fuel, high prices and the damaging effect on our surroundings calls for the more reason to develop alternative fuel that can replace the existing energy for cement production process. This replacement is the fossil fuel. An alternative fuel source can replace fossil fuel in the cement production process. It provides trustworthy solution toward reducing fossil fuel usage and mitigation of pollutant emissions. It can be sourced from industries, agriculture, and municipals [4], [5], [10]. This is further necessitated by the high thermal requirement of the cement production process.

Despite the numerous thermal performance studies on the cement production process, there has been a lack of extensive studies on the thermoeconomic analysis of alternative fuel performance of the cement rotary kiln system, particularly on how the operational parameters of the rotary kiln affect its performance. Minimizing energy cost and environmental effect is the primary goal of cement and concrete production industry. Analytical decision tools are needed in providing vital pieces of information to recognize possible improvement in rational management of raw materials.

Dwindling resources coupled with environmentally unfriendly emissions has necessitated exploring alternative fuels used in the energy-demanding cement industry. Other sources of fuel offer the cement industries the chance to use minimal fossil-fuel derived from $CO_2$ emissions, reduce fuel costs and add to the conversion of waste streams at a time of increased pressure on landfilling of wastes. However, computer simulation provides the answer to what happens to a cement clinker production process after a switch of fuel.

Problems regarding clinker quality and emission have been related to the initiation of other fuel source in the cement manufacturing process, thus before the employment of the alternative fuel in this complex process, a detailed identification and assessment of all underlying factors must be exhaustively considered. Considering the associated economic risks with alternative fuel experimentation has limited research being conducted to test the cement plant. Alternatively, the process model has been regarded to proffer a realistic solution of testing series of alternatives fuels and forecasting corresponding clinker quality and pollutant emission changes.

Computational fluid dynamics (CFD) is a software package that is use to model majorly the kiln section of a cement production process [1], [3]. The use of Aspen Plus software is a completely different approach which focuses on the clinker chemistry, thermodynamics properties of materials and reaction stoichiometry, this has been reported [7],[16].

Azad Rahman et al; [2], Emad et al; [3] and Miller [9] came up with a model in form of a process of a precalciner kiln system. This was done using Aspen Plus software to bring about the effect of alternative fuels on energy performance and environmental pollutants generally. The other fuels used include; tyre, municipal solid waste (MSW), bone meal (MBM), plastic waste, sugarcane bagasse and meat. Using the cement plant as a reference, the developed energy and mass balance of the system was validated. The clinker's quality was also investigated by the group to determine its effect as an alternative fuel.

The outcome of the test has shown with the use of alternative fuels with a 20% mix in coal can be used to achieve a result that is about 4.4% reduction in $CO_2$ emissions and up to a 6.4% reduction in thermal energy required.

Research has also proved that other fuel source had a reduced influence on the quality of clinker with an exception of MSW. Generally, MBM can reduce energy requirement and $CO_2$ emissions; this makes it a better option than others.

From this reported work, it would be derived that economic and exergetic efficiency of alternative fuels was not investigated. Hence, this work would consider the thermo-economic analysis and exergetic efficiency of alternative fuels sources of Obajana cement rotary kiln.

The recent research developed a model for the Kiln of the cement manufacturing process, which was used to simulate the flue gas formation while using selected alternative fuels such as used tyre, Sugarcane baggasses and Municipal Solid Waste (MSW). Aspen Plus-based is the model developed. The model was verified using Obajana Cement Industry's plant data for coal used as the primary fuel in the burning zone. The validated model was run with the three selected alternative fuels, Tyre, MSW and Sugarcane bagasse, to study predictions of changes in emission, kiln environment, clinker quality and cost-effectiveness before the simulation results were used to optimize the usage of selected alternative fuels.
The result of this study will inform the use of locally sourced alternative fuels from wastes in the cement production industry. This kind of study in the cement production industry is unprecedented in Africa. It will add to the body of knowledge on the conversion of waste to wealth while fostering environmental friendliness of the cement production process.

## 2.0 Methodology

### 2.1 Extraction of data

Stream composition, temperatures, pressures and flows are all the needed operating data. The instrumentation diagram of the rotary kiln in the Obajana Cement Industry was collected from the plant operator.
The flow diagram was carefully studied to extract all the needed and available information, feed and product need for the simulation of the kiln using Aspen Plus was also collected.

### 2.2 Modelling

The cement manufacturing process is complex and it includes several endothermic and exothermic reactions. Heat transfer is not an exemption in this process. It is being transferred in the three phases (solid, liquid and vapor) of different materials.
Simulation Aspen Plus was used to develop the process model. Furthermore, it was built in accordance to the reference plant specification. This was achieved using about 6000-day clinker production capacity or tones.
Below are the assumptions made without changing the principles to simplify the model.

1) In two different reactors, the burning zone, the coal and other fuel combustion will occur.
2) The combustion of fuels and the calcination process lead to the production of $CO_2$.
3) Fuel combustion lead to the generation of $NO_x$ from the kiln.
4) In the clinker formation process, ash is involved. From the ash analysis of coal and alternative fuel.
5) To facilitate pyroprocesses, all the clinker formation reactions in the kiln took place in three separate reactors.
6) Throughout the entire model, air linkages were not considered.

Redlich Kwong Soave-Boston Mathias (RKS-BM) property method was selected for the suitability for coal and solid fuel combustion. All thermodynamic properties use the Redlich-Kwong-Soave (RKS) cubic equation of state with the Boston-Mathias (BM) alpha function for all its process.
Throughout the simulation, the MCINCPSD sub stream (MIXED, CISOLID and NC streams) with particle size distribution option was used. The feed to the kiln contained conventional part and all fuels were considered non-conventional.
HCOALGEN and DCOALICT attribute was used in the proposed model based on the elemental analysis of fuelsto calculate enthalpy and density respectively. This is for coal and selected alternative fuels.

Equilibrium and non-equilibrium equations can be used to generate a realistic output. Different reactor blocks were chosen for the process model.

Due to the introduction of alternative fuels all the output data regarding the composition of clinker and the stack gas provides vital information about any possible changes due to the introduction of alternative fuels in the system. Collected plant data was used to validate the model from clinker composition and pollutant emission perspective.

The exergoeconomic assessment were performed by the Specific exergy costing method (SPECO) to decide the potential enhancements in its efficiency and cost-viability.

**2.3 Model equations**

There is a need for the power in the rotary kiln to be balanced. Therefore, the average temperature of the walls was used in the mode.

The following equations for the gas, and solid walls, respectively [15] written.

$$Q = m_i Cp_i \Delta T_i \quad (1)$$

Where $m_i$($i$mass flow rate in kg/s), $Cp_i$($i$specific heat capacity in kJ/(kg·°C)), $\Delta T_i$($i$ temperature change according to°C), $Q$ (heat in kJ) is, and $m_i$replaced by equation two:

$$m_i = \rho_i v_i A_i \quad (2)$$

Where $\rho_i$($i$ density in kg·m$^3$), $v_i$($i$ speed in m/s), $A_i$($i$ surface area in m$^2$). Therefore, the temperature in the gas phase transport equations are:

$$A_g C_{pg} \rho_g v_g \frac{\partial T_g}{\partial z} = \beta_1 (T_w - T_g) + \beta_2 (T_w - T_g) + Q_{comb} \quad (3)$$

$$A_g C_{pg} \rho_g v_g = \rho_i v_i A_i$$

where $T_w$ (wall temperature by °C), $T$g(gas temperature in °C), $T$s(solid temperature in °C), $\beta_1$ (heat transfer coefficient between the wall and the gas in W/°C), $\beta_2$ (transfer coefficient between the solid and the gas temperaturein W/$^0$C), $Q_{comb}$(combustion heat in W), $v_g$(gas velocity in m/s), $\rho_g$(average gas density of 0.85 kg/m3),$\partial T_g/\partial z$ (gas temperature change over the elements in °C/m), $C_{pg}$(gas specific heat capacity of 1173.8 kJ/kg/°C)and $A_g$(of gas per m$^2$) and $v_g$obtained from the following equations:

$$v_g = \left(\frac{m_f + m_a}{A_g \rho_g}\right) \quad (4)$$

Where $m_f$ (fuel mass flow rate) and $m_a$ (air mass flow rate) is:

$$A_g = \frac{r_i^2}{2} (\rho - sin\rho) \quad (5)$$

Where $r_i$ (radius of the kiln according to m) and $p$ (surrounded by a solid angle 3π/2) and the solid phase are:

$$A_s C_{ps} \rho_s v_s \frac{\partial T_s}{\partial z} = \beta_2 (T_g - T_s) + \beta_3 (T_w - T_s) + A_s Q_c \quad (6)$$

Where $\beta_3$ (heat transfer coefficient between the wall and solid in terms of W/$^0$C), $Q_c$(heat of reaction in terms of W), $v_s$(solid velocity in m/s), $\rho_s$(solid density of 890 kg/m3), $\partial T_s/\partial z$ (solid temperature changes over the elements in °C/m), $Cp_s$(specific heat capacity of solid 1089.97 kJ/kg/°C) is, $As$ (solid surface in m$^2$) and $v_s$calculated from the following equations:

$$v_s = \frac{\dot{m}_s}{A_s \cdot \rho_s} \quad (7)$$

$$A_s = \frac{r_1^2}{2} (2\pi - p + \sin p) \quad (8)$$

**2.2 Process simulation and description**

The modeled Kiln in the simulation environment of Aspen Plus Software is as shown in Figure 1 below.

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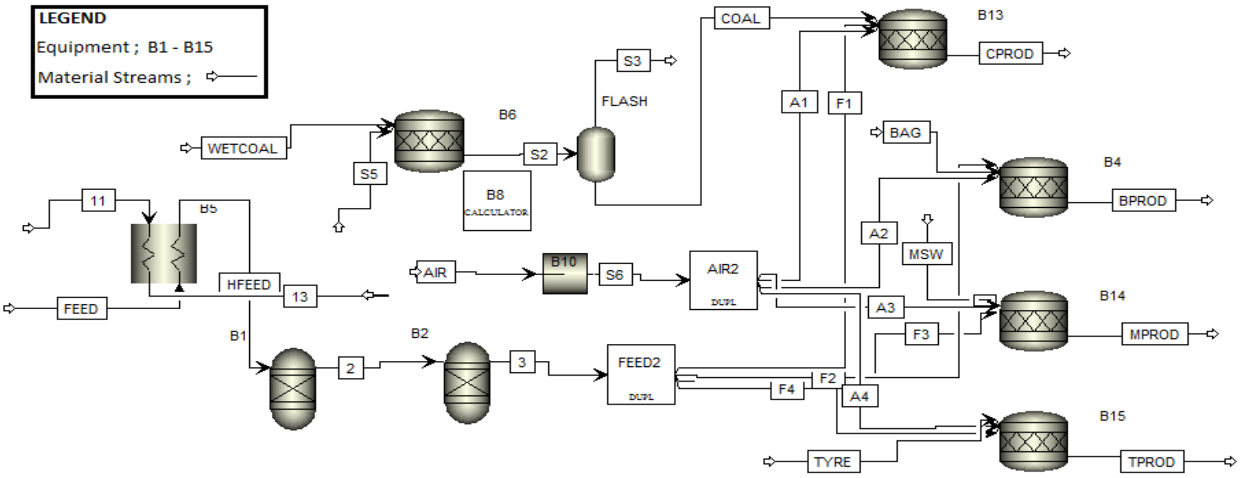


**Figure 1: Converged Model of Rotary Kiln System (Aspen Plus v8.0)**

A conventional stream containing feed to the kiln section was passed through a heat exchanger train B5 to raise the feed to a reaction temperature of 850 ºC. The hot product of the heat exchange (HFEED) was then passed into two sets of RGibbs reactors B1 and B2, operating at 1000 ºC and 1400 ºC, respectively, where reactions such as the formation of alite and belite took place. The product of the reactors (Stream 3) was passed into a Duplicator block FEED2, which was used to duplicate stream three into four streams (F1 – F4) that served as feed to four RSTOIC reactors (B4, B13, B14 and B15). Wet coal (WETCOAL), a nonconventional stream of raw coal, was treated with nitrogen gas (Stream S5) in an RSTOIC reactor B6. A calculator block (B8) was used to actuate the coal drying process, and the product (Stream S2) was passed into a separator (FLASH) where the nitrogen gas and water were flashed off from the top (Stream S3), and the treated coal (COAL) from the bottom was sent as fuel to block B13; one of the four RSTOIC reactors. Air (AIR) at 70 $^0$C and 1 bar were passed to a compressor block B10, and the outlet stream (S6) was sent to a Duplicator block AIR2, which was used to duplicate stream S6 into four streams (A1 – A4) that respectively supplied air for combustion reactions that took place in the RSTOIC reactors. Having served one of the RSTOIC reactors (B13) with fuel (COAL), air (A1) and clinker feed (F1), the system represented the existing process in the understudied plant. The product stream of the reaction was named “CPROD”. The three remaining RSTOIC reactors were served with alternative fuels. A non-conventional stream with the composition of bagasse fuel (BAG) was introduced to the reactor block B4, which had air (A2) and clinker feed (F2) also attached to it. The product stream of block B4 was named “BPROD”.

Similarly, streams with nonconventional components of MSW and TYRE were respectively served as fuels to RSTOIC reactor blocks B14 and B15. The reactor block B14 had air (A3) and clinker feed (F3) also attached to it, and the product stream was named “MPROD”. Reactor block BI5 also had a supply of clinker feed (F4) and air (A4) with its product stream called "TPROD".

### 3.0 Results and Discussion

This paper reports the Thermo-economic analysis of alternative fuel usage on rotary kiln performance of Obajana cement plant using Aspen plus simulation software. Therefore, the validation of simulated results needs to compare to plant data of coal measured in kg/kg clinker. Observed results from the simulation were compared with plant data and presented in Table 1. In 1 kg of clinker, the significant difference was 0.0097 in the composition of CaO (in oxide form) and 3.9783 (wt. %) in $C_3S$ composition. Also, a difference of 1.2501 was observed in the Lime Saturation Factor (LSF). These observations confirmed that the developed model in Aspen Plus is an accurate representation of the studied plant as variations are within limits that do not affect the clinker quality. The plant's emission data were not available; thus, that simulation was compared with acceptable limits and reported by a similar cement plant. Lesser emissions were observed in the simulation than the plant data, except in $SO_2$, where the emission was 4.542 gm/kg tonne higher. This value is still within the acceptable limits. The disparity could be attributed to the choice of the thermodynamic model.

Table 1: Validation of simulation results with plant data using 100% coal as a fuel source

| Variables | Plant Data | Simulation | Difference |
|---|---|---|---|
| Clinker (Oxide Form) | | | |
| CaO | 0.598 | 0.5883 | 0.0097 |
| $SiO_2$ | 0.19 | 0.1892 | 0.0008 |
| $Al_2O_3$ | 0.058 | 0.0503 | 0.0077 |
| $Fe_2O_3$ | 0.035 | 0.0328 | 0.0022 |
| MgO | 0.0045 | 0.006 | 0.0015 |
| Clinker (Compound Form) | | | |
| $C_3S$ | 62.435 | 66.4133 | 3.9783 |
| $C_2S$ | 14.7327 | 12.9318 | 1.8009 |
| $C_4A$ | 10.734 | 9.0484 | 1.6856 |
| $C_4AF$ | 12.098 | 11.6065 | 0.4915 |
| Clinker (Quality) | | | |
| Lime Saturation Factor | 72.5063 | 73.7564 | 1.2501 |
| Alumina Ratio | 1.6571 | 1.5335 | 0.1236 |
| Silica Ratio | 2.043 | 2.2768 | 0.2338 |
| Emissions | | | |
| $CO_2$(kg/tonne clinker) | 977 | 825.976 | 151.024 |
| $NO_x$(gm/tonne clinker) | 2200 | 2139.5 | 60.5 |
| $SO_2$(gm/tonne clinker) | 170 | 174.542 | 4.542 |

### 3.1 Alternative Fuels Performance

The introduction of a used tyre and MSW in the fuel mix increased the LSF compared to coal only (represented by 0 % with a value of 79.1077). This increase was optimum at 20 %

alternative fuel mix for both with 86.3407 and 86.3387 for used tyre and MSW respectively, as a further increase of the alternative fuel in the combination above this level brought about no noticeable change, due to saturation of the combustion reaction. In contrast, the introduction of bagasse alternative fuel resulted in a decrease in the LSF. This decrease was continuous until the highest mix of 30%, with a value of 78.1351. LSF indicates the amount of unacceptable free lime present in the clinker [14]; hence lesser values are more appreciable. This implies MSW had the best performance in this regard.
The introduction of 5% alternative fuels in the fuel mix resulted in a decrease in the value of AR from 1.2281 observed in 100% coal to a value of 1.1314 for bagasse and 1.1094 for both MSW and used tyre. The values for MSW and used tyre remained the same despite varying configurations remaining same up to a composition of 25% alternative fuel in the fuel mix but further reduced to 1.1092 and 1.1093 respectively for used tyre and MSW at 30% fuel mix. As for bagasse, a steady decrease in AR was observed with each increment of 5% Bagasse in the fuel mix, resulting in a value of 1.1349 with the introduction of 30% fuel mix. Though all the values observed in the various configuration of the alternative fuels fall within the acceptable limit of 1 to 4 for Portland cement [14], bagasse was considered to have the best performance in this regard since it was further from the baseline among the three alternative fuels. The introduction of 5% alternative fuels in the fuel mix resulted in a decrease in the value of SR from 2.5860 observed in 100% coal to a value of 2.4946 for bagasse and 1.4541 for both used tyres and MSW. However, higher configurations above 5% of the alternative fuels did not bring about a noticeable change in SR. Preferred SR ranges for Portland cement is between 2.0 to 3.0 [14] hence bagasse had the best performance in this regard. This finding is similar to a recent report that observed bagasse has a good SR compared to plastic and some other alternative fuel due to its relatively low $Al_2O_3$ content [2].

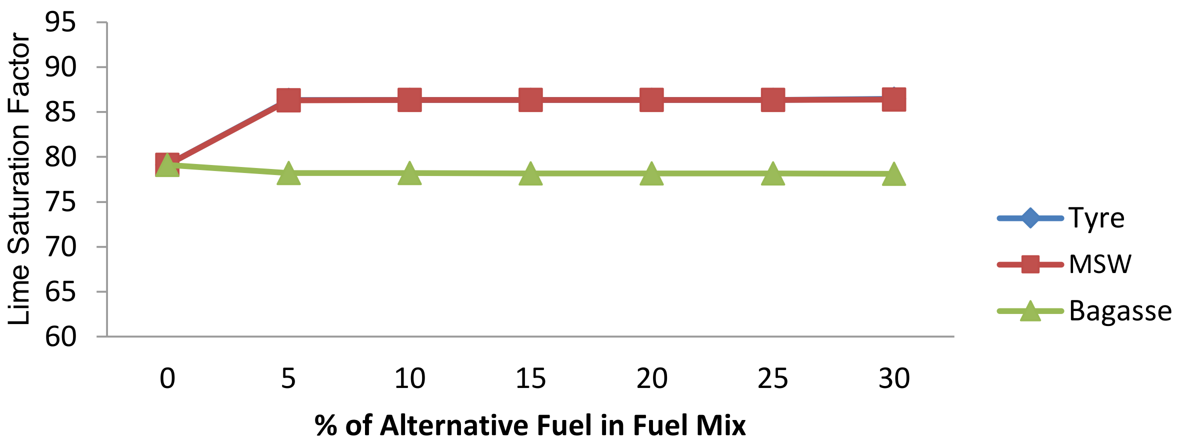


Figure 2: Lime Saturation Factor of Alternative Fuel in Fuel Mix

### 3.2 Environmental performance

An environmental assessment of the use of alternate fuel in the fuel mix was carried out to inform the ecological friendliness of the alternative fuels. The introduction of a used tyre and MSW in the fuel mix decreased $CO_2$ emission compared to coal only (represented by 0 % with a value of 825.98). This decrease was optimum for a used tyre at 20 % alternative fuel mix with a value of 817.434 kg/tonne clinker. The reduction in $CO_2$ emission with a higher configuration of MSW in the fuel mix was steady all through, and the opposite was observed with a steady increase in emission with higher configurations of bagasse. MSW had the best potential to reduce $CO_2$, and the used tyre came close. However, bagasse increased emission close to the acceptable limit of 900 kg/tonne clinker; hence it should not be used above 25% mix to ensure environmental friendliness.

One of the excellent options to lower $CO_2$ emission up to 4.7% is the use of MSW. This is achieved by replacing thermal energy needed of about 30%; a higher amount of fuel is required to keep the production amount near to the reference case because MSW has a lower energy requirement [2].

The introduction of a used tyre and MSW in the fuel mix decreased $CO_2$ emission compared to coal only (represented by 0 % with a value of 825.98). This decrease was optimum for a used tyre at 20 % alternative fuel mix with a value of 817.434 kg/tonne clinker. The decrease in $CO_2$ emission with a higher configuration of MSW in the fuel mix was steady all through. The opposite was observed with a steady increase in emission with higher configurations of bagasse. MSW had the best potential to reduce $CO_2$, and the used tyre came close. However, bagasse increased emission close to the acceptable limit of 900 kg/tonne clinker; hence it should not be used above 25% mix to ensure environmental friendliness.

MSW was found as the best option to reduce $CO_2$ emission up to 4.7% while substituting 30% of the thermal energy requirement. MSW has a lower energy content which implies that a higher amount of fuel is required to keep the production amount near the reference case [2].

Introduction of bagasse and used tyre in the fuel mix slightly increased $NO_x$ emissions from 890.001 mg/Nm$^3$observed in 100% coal to 891.704 mg/Nm$^3$and 891.406 mg/Nm$^3$respectively for bagasse and used tyre at 5% fuel mix. The slight increment in emission observed with higher configurations of the fuel mix was sustained till 30% at a value of 897.78 mg/Nm$^3$and 891.941 mg/Nm$^3$respectively for bagasse and used tyre. A more pronounced increase in $NO_x$ emissions from 890.001 to 941.712 mg/Nm$^3$at 5% fuel mix was observed in the case of MSW. This marginal increase was steady and resulted in the emission of 1032 mg/Nm$^3$and 1156.96 mg/Nm$^3$at 15% and 30% fuel mix, respectively. This high value (compared to reference 100% coal) is an indicator for carefulness in the use of MSW as an alternative fuel; hence, it should not be used above 25% mix. Though used tyres in fuel mix brought about a slight increase in $NO_x$ emission, it is relatively the best in these regards. MSW potentially reduces $CO_2$ emissions. An opposite scenario was observed in the case of $NO_x$ emission with a 29.5% increase in the stack gas, and all the selected alternative fuels were found to increase the $NO_x$ emission [2], [17].

$SO_x$ emission increased with the introduction of used tyres and MSW in the fuel mix. However, this increase is more pronounced in used tyres than MSW, proven by an increase from 281.102 mg/Nm$^3$observed in 100% coal to 279.306 mg/Nm$^3$and 291.322 mg/Nm$^3$respectively for MSW and used tyre at 5% fuel mix. The slight increase in emission observed in MSW was steady and resulted in the emission of 283.398 mg/Nm$^3$, 284.295 mg/Nm$^3$and 285.35 mg/Nm$^3$at 10%, 20% and 30% fuel mix, respectively. A similar but more marginal trend was observed in a used tyre, which resulted in $SO_x$ emission of 295.072 mg/Nm$^3$, 307.069 mg/Nm$^3$and 316.273 mg/Nm$^3$at 10%, 20% and 30% fuel mix, respectively. In a bid to ensure $SO_x$ emission below the marked 310 mg/Nm$^3$, it is recommended that the used tyre should not exceed 20% in the fuel mix. In contrast to observations in MSW and used tyres, the introduction of bagasse in the fuel mix brought about a notable decrease in $SO_x$ emission. This is evident in the observation of $SO_x$ emission of 273.142 mg/Nm$^3$, 261.754 mg/Nm$^3$ and 248.696 mg/Nm$^3$at 10%, 20% and 30% bagasse fuel mix. Evidently, bagasse showed the best potential for $SO_x$ emission. $SO_2$ emission remained almost constant for the case of MSW. Due to the sulfur content of the tyre MSW produced about 11% more $SO_2$ than the reference case [2].

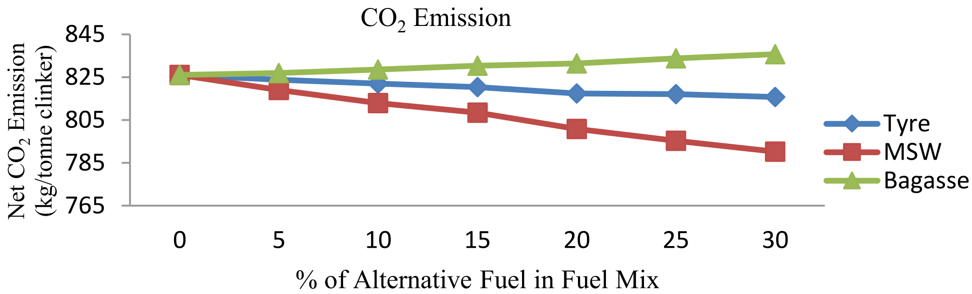


Figure 3: Net $CO_2$ Emission of Alternative Fuel in Fuel Mix

### 3.3 Thermal stability

Though sugarcane bagasse showed some potential for keeping the kiln outlet temperature at an acceptable value of 1687 ºC at 5% fuel mix, the used tyre was able to maintain the reference temperature of 1689 ºC at 5% fuel mix while MSW notably dropped the kiln outlet temperature to 1669 ºC. Though there was a marginal decline in the temperature with higher configurations, the used tyre maintained the reference temperature even at the highest configuration (30 % fuel mix) considered at 1688.5 ºC. Sugarcane bagasse had a drop of 2 ºC with each increment of 5% in the fuel mix which resulted in acceptable temperatures of 1685 ºC, 1681 ºC and 1677 ºC at 10%, 20% and 30% fuel mix, respectively. The notable drop in the kiln outlet temperature of MSW was steady through the configurations, resulting in 1639 ºC, 1589 ºC and 1549 ºC at 10%, 20% and 30% fuel mix, respectively. Used tyre performed best in this regard and sugarcane bagasse came close, MSW, however, did not show good temperature profile, hence should not be introduced in the fuel mix beyond 15% with an outlet temperature of 1609 ºC to ensure the kiln outlet temperature does not go below 1600 ºC in order not to change the clinker chemistry.

According to the result obtained from the simulation, kiln temperature was markedly low for the case of MSW, change the clinker chemistry apart from bagasse. All other three alternative fuels can maintain the kiln temperature up to the reference case [2].

### 3.4. Exergy efficiency

Exergy efficiencies decreased with the introduction of alternative fuels, resulting in an efficiency of 75.5% for bagasse and 72.7% for both used tyres and MSW at 5% fuel mix, compared to 82.5% efficiency observed in 100% coal. Higher configurations of alternative fuels brought a marginal reduction in efficiency in the three alternative fuels, resulting in efficiencies of 75.3%, 72.5% and 72.4%, respectively, for sugarcane bagasse, used tyre and MSW at 10% fuel mix. At 30% fuel mix, efficiencies of 74.3%, 71.8% and 71.6% were respectively observed for bagasse, used tyre and MSW. Sugarcane bagasse was the most efficient of the three alternative fuels considered. However, the other two had a good performance as well. Table 2 shows the results of exergy efficiency at different configuration

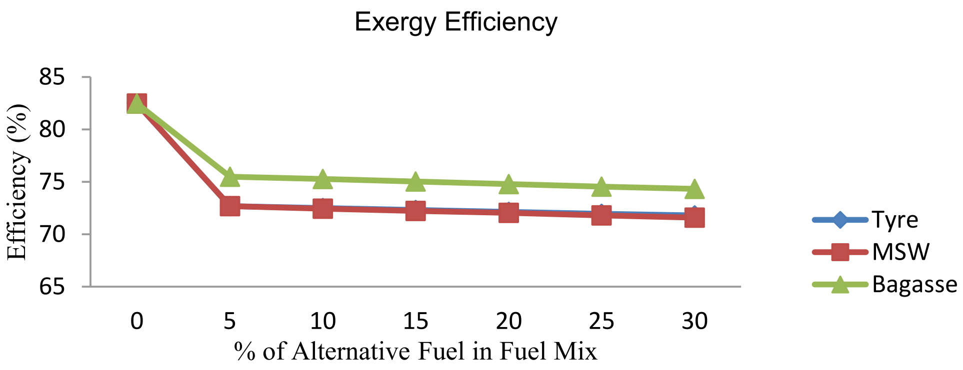


Figure 4: Efficiency (%) of Alternative Fuel in Fuel Mix

### 3.5 Energy Costing

Energy costing regarding alternative fuels usage in cement plants will enable us to minimise cost and maximise profit by cutting down the cost of conventional fuels usage. This research shows that the cost of fuels decreased with alternative fuels, resulting in $1411.40 for sugarcane bagasse and approximately $13952 for both used tyres and MSW at 5% fuel mix, compared to $14350.02 observed in 100% coal. Higher configurations of alternative fuels brought a marginal reduction in cost in the three alternative fuels. However, the three alternative fuels were cost-effective (with MSW having the potential to save 613.92 $/hr in 30% fuel mix). Table 2 shows the results of fuel cost at different configurations.

**Table 2: Cost Analysis of Coal and Alternative Fuel at different Configurations**

| Component | Exergy (KJ/h) | Exergy (KW/h) | Costing ($/h) | Efficiency (%) |
|---|---|---|---|---|
| 0 % Fuel Mix | | | | |
| Coal | 430500751.10 | 119583.54 | 14350.02 | 82.46 |
| 5 % Fuel Mix | | | | |
| Bagasse | 423582101.60 | 117661.69 | 14119.40 | 75.49 |
| MSW | 418434063.40 | 116231.68 | 13947.80 | 72.68 |
| Used Tyre | 418547583.20 | 116263.22 | 13951.59 | 72.70 |
| 25 % Fuel Mix | | | | |
| Bagasse | 418291522.50 | 116192.09 | 13943.05 | 74.55 |
| MSW | 413332289.50 | 114814.52 | 13777.74 | 71.79 |
| Used Tyre | 414338829.60 | 115094.12 | 13811.29 | 71.97 |
| 30 % Fuel Mix | | | | |
| Bagasse | 416965171.20 | 115823.66 | 13898.84 | 74.32 |
| MSW | 412083088.40 | 114467.52 | 13736.10 | 71.57 |
| Used Tyre | 413308574.50 | 114807.94 | 13776.95 | 71.79 |

## 4.0 Conclusions

In the cement manufacturing, a process model was used for the operation of rotary kiln. Aspen Plus was used in the study of energy performance, and the effect of other fuels on clinker quality, emissions, thermal stability and cost effectiveness. Used tyre, municipal solid Waste (MSW) and sugarcane bagasse were the three alternative fuels used.

The model confidence was established with the aid of Obajana plant data, literature data, and acceptable limit. The model was validated with reference cement plant data, and the validated model was run for the selected alternative fuels. In the reference condition, it was noticed that selected alternative fuels had a minimum influence on clinker quality except for MSW. MSW was particularly capable of reducing $CO_2$ emissions while sugarcane bagasse increased it. Though the three alternative fuels were found to be cost-effective (with MSW having the potential to save 613.92 $/hr in 30% fuel mix), used tyre was found to be the best option due to its ability to reduce $CO_2$ emission while ensuring thermal stability both in terms of exergy efficiency and kiln outlet temperature, coupled with its worldwide availability.

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