Uses of Alternative Fuels as Best Practices to Reduce CO_2 Emissions from the South African Cement Industry

Labana Beltran
Post Graduate School of Engineering Management
University of Johannesburg
Auckland Park, 2092, South Africa
beltranjll@gmail.com

Telukdarie Arnesh
Post Graduate School of Engineering Management
University of Johannesburg
Auckland Park, 2092, South Africa
arnesht@uj.ac.za

Abstract

This research paper presents a study conducted on the use of alternative fuels in the South African cement industry as part of a remedy strategy against CO_2 emission. Ordinary Portland Cement affects the environment negatively by emitting between 0.9 to 1 tons of dioxide of carbon per ton of cement produced and makes the cement industry the second largest pollutant in the world. It should be noted that the CO_2 emission from cement production is well understood and documented; this knowledge directs government entities and international organizations to recommend initiatives such as the Carbon Tax Bill and the Cement Sustainability Initiative (CSI). Among all the best practices, the use of alternative fuels in the cement Kiln is regarded as one of the most significant reduction method. To obtain the optimum combination of three fuel materials such as coal, used tyres and waste oil, a mathematical model is developed for minimizing the CO_2 emissions. The waste oil emits 44.55% less of CO_2 compared to used tyres, the latter has the most efficient thermal energy conversion at 20% relative to used oil. Furthermore, the study determined that 16.76% of CO_2 emissions is reduced by burning the alternative fuels in Kilns.

Keywords
Energy, Cement, Alternative fuels, Sustainability.

1. Introduction

Cement is a necessity for economic development and essential for infrastructure and building construction (Benhelal, et al., 2013 and Uwasu, et al., 2014) this necessity is produced in millions of tonnes to satisfy the world demand. Due to the growing demand from China, India and the demographic trend in Africa to use the infrastructure developments as an instrument to fight poverty, the world demand in cement keeps growing faster and (Hasanbeigi, et al., 2012) estimated that the demand and production may reach a total volume between 3680 to 4380 million tonnes in 2050. Benhelal, et al., (2013) noted that for each tonne of cement produced the cement plant emits around 0.9 tonne of dioxide of CO_2; this emission maybe greater, up to 1 tonne of CO_2 depending on the consumption of electricity by all the electrical equipment in the cement plant such as motors, fans, etc. Therefore, the reduction of carbon dioxide emissions from the cement manufacturing process is an environmental issue to be addressed.

Gartner, (2004) specified that CO_2 emissions are derived from two main sources, within raw materials CO_2 referred as ($RMCO_2$) and those from the combustion of fossil fuel referred as “fuel-derived” CO_2 ($FDCO_2$). However, (Usón, et al., 2013 and Benhelal, et al., 2013) categorized the sources of CO_2 in the cement plant into three types; the decomposition of limestone, the combustion of fossil fuel and electricity consumption. To quantify the electricity consumption in the cement plant, (Sathaye, 2005) inferred that the current best practice in the consumption of electrical energy is around 75 to 80 kWh per tonne of clinker; (Gartner, 2011) evaluated that 100 kWh of electricity consumption emits up to 100 kg of CO_2 per tonne of cement by considering coal as the main fuel to produce electricity. In the South African cement industry context, the decarbonisation of raw materials and the combustion of fuel materials have the same values compared to other regions of the world. Typical electrical consumption of South African cement plants are estimated to be 110 kWh/ tonne of cement (Otterman, 2011 and Ohanyere, 2012) and the current emission from Eskom (the local electricity supplier) corresponds to 1 kWh of electricity to 1.03kg of CO_2 emission. The CO_2 emissions related to electrical consumption and other sources are presented in Figure 1.

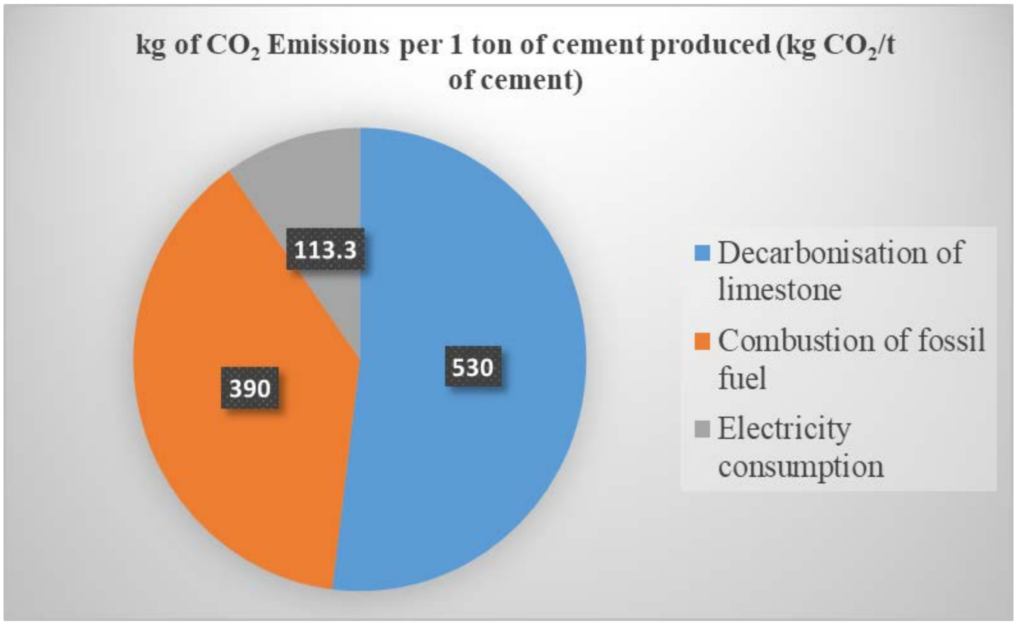


Figure 1. Source of CO_2 emission in the South Africa cement manufacturing process

In terms of percentage, the decarbonisation of limestone represents 51.29 percent of the total emission while combustion of fossil fuel is 37.74 percent and the electricity consumption is 10.97 percent. The CO_2 emissions from the three sources mentioned above occur at different moments of the cement production process which are detailed below and presented in Figure 2:

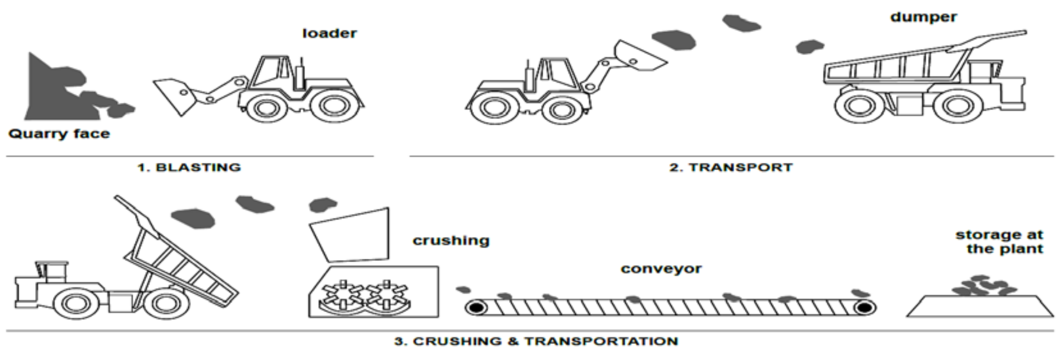
- The raw material preparation.
- The Portland cement clinker production also known as the pyro-processing.
- The clinker grinding and cement production.

A summary of cement production and current initiatives related to cement level of emissions is discussed.

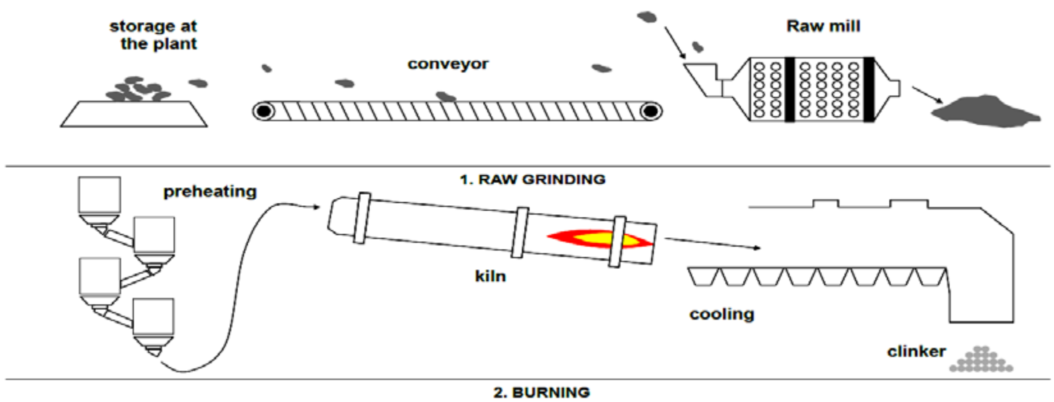
Summary of cement production

At the raw material preparation, the CO_2 recorded is originated from the transport of raw materials from the quarry to the crushing mechanism and from the electrical devices located at the crushing and conveyor mechanism. The electrical energy consumption at this stage is in the order of 19.50 kWh/t or 26 percent of the total electricity consumption and 1.94 percent of the total CO_2 emissions (Usón, et al., 2013 and Madlool, et al., 2011). The pyro-processing is the core of the cement manufacturing process, where 90 percent of the total thermal energy required for the cement production is utilized and the processing unit consists of the preheater, calciner, kiln and the coolers. This stage has the highest level of CO_2 emission with more than 89.03 percent occurring here due to the decarbonisation of limestone and combustion of fuel material. An extra 2.69 percent of CO_2 emission should be accounted for the electrical consumption (Usón, et al., 2013 and Madlool, et al., 2011). Therefore, the total CO_2 emission at this stage is 91.72 percent.

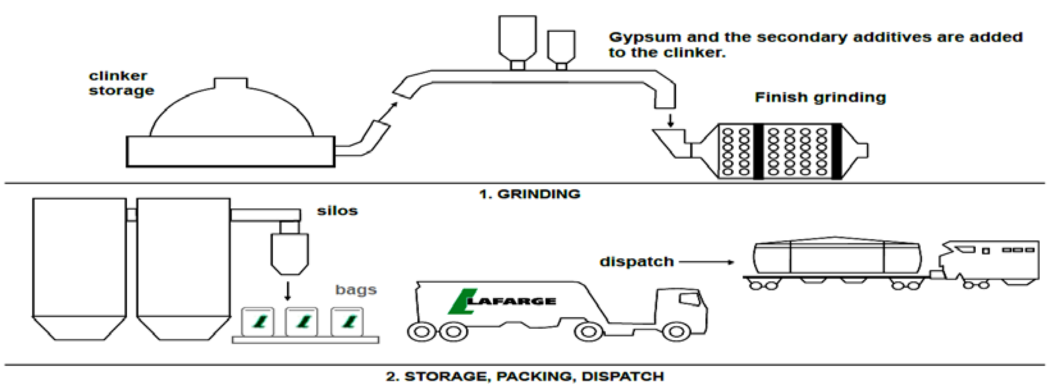
At the final stage of grinding and cement production, the remaining 6.34 percent of the total CO_2 emission is emitted. This emission is due to the electrical consumption of equipment for grinding and packing of cement product. According to a publication from InEnergy report related to emissions accounted here are regarded as scope 1 of Greenhouse Gas (GHG) emissions and exclude any emissions related to transport of raw materials from the quarry to the cement plant and the dispatch of cement from the plant to the customer or to the storage rooms. An illustration of the cement production process is presented in Figure 2.



a) Raw material preparation process



b) Clinker production process



c) Grinding and cement production

Figure 2. Cement manufacturing process

Current Initiatives

Based on this level of emissions, several initiatives are proposed and adopted by different organisations. One of the initiatives is the Cement Sustainability Initiative (CSI) developed by the World Business Council on Sustainable Development (WBCSD) to help industry leaders to understand and manage the impacts of their products and processes (Uwasu, et al., 2014) on the environment. The CSI aims to contribute significantly to the sustainability of the cement industry by addressing the challenges such as climate protection, air emissions, fuels and raw materials use, and local impacts on land and communities (WBCSD, 2007) encountered by CSI members. However, this initiative suffers from lack of participation from all cement producers with members representing around 30 percent of global cement producers (WBCSD, 2014). In South Africa, the government introduced the carbon tax policy to promote good governance and effective implementation of the national climate change response strategy in accordance to the Kyoto Protocol. It should be noted that the CSI and the national climate change response strategy have the same outcomes such as:

- The reduction of the impact of greenhouse gas on the climate change.
- Emphasizing environmental protection by implementing best practice of production of ordinary Portland cement.
- The long-term sustainable development of the cement industry.

Many investigations conducted on the manufacturing process and production of cement identified best practices in the industry as the adequate response to reduce greenhouse gas emissions.

2. Best practices in cement industry

Benhelal, et al., (2013) and Schneider, et al., (2011) identified three main strategic approaches toward carbon mitigation such as: energy efficiency in clinker production, alternative fuels and alternative raw materials. The most energy efficient kiln technology is the dry rotary kiln with preheater and pre-calciner as presented in Table 1. Benhelal, et al., (2013) noticed that shifting from wet process to dry process saves up to 50 percent of required energy and reduces 20 percent of CO_2 emissions. It should be noted that in South Africa, all cement kilns use the dry process (Muigai, et al., 2013). In addition to further improvements on energy efficiency efforts, discussions have been going on for some time on using the waste heat from the flue gas (preheater) and hot air (cooler systems) in waste heat recovery systems Benhelal, et al., (2013) and Schneider, et al., (2011). To generate electricity from these two steams with the advantage of reducing the dependency of cement plant equipment on the national grid. This new method of production may be regarded as green production of electricity and more environmental friendly with possibility in South Africa to reduce the CO_2 emissions to close 10 percent as detailed above. Table 1 ranges in the thermal energy consumption and quantifications of the $FDCO_2$ released per tonne of clinker depending on the type of kiln technology.

Table 1. Ranges in the thermal energy consumption and CO_2 released (Usón, et al., 2013 and Damtoft, et al., 2008)

Kiln technologies	**MJ/t of clinker**	**kg fuel-derived CO_2/kg of clinker**
Dry rotary kiln with preheater and pre-calciner	3000-4000	0.31-0.38
Dry long rotary Kiln	Up to 5000	0.4-0.6
Wet rotary Kiln	5000-7500	About 0.6

In the perspective of using alternative raw materials, several investigations were conducted and the possibility of substitution of Portland clinker with suitable materials that react with calcium hydroxide are commonly named Supplementary Cementitious Materials (SCMs): Fly Ash (FA), Granulated Blast Furnace Slags (GBFS), Silica Fume (SF) and natural pozzolans (Schneider, et al., 2011; Habert, et al., 2010; Damtoft, et al., 2008). It should be noted that FA, GBFS and SF are industrial by-products from other industries such as coal fire plant and steel plant. Kajaste & Hurme, (2016) recognized the substitution of clinker with alternative raw materials as an efficient way to improve GHG management in the cement industry; increasing the global use of alternative raw materials to the level of 34.2 percent in cement production would save 312 Mt CO_2 with the 2013 level of annual cement production. Concerning the use of alternative fuel material in the cement kiln, (Gartner, 2004) observed that the cement industry had its first revolution on alternative fuel material in mid-1970 due to the OPEC oil embargo, which led western countries to intensify research and development of new process technologies for the cement industry. However, (Habert, et al., 2010) found that the new process technologies had an energy efficiency of 10 percent during 1973 to 1983 and a decrease in the improvement rate from 1983 to 2003; the reduced improvement rate coupled with the necessity for the reduction of the cost of production and lower CO_2 emission paved the way for new research area of carbon-neutral fuels as new combustible.

Usón, et al., (2013) classified the alternative fuels into three groups: gas (e.g. natural gas, biogas), liquid (e.g. used oils and solvents) and solid (used tyres, waste wood, plastic, animal meat, municipal waste, Sludges). Schneider, et al., (2011) argued that the substitution of fossil fuels with alternative fuels may have an influence on the clinker properties; however, they noticed the possibility of manufacturing high performance Portland cement clinker by the implementation of adequate comprehensive production control for the significant substitution rates of alternative fuels. Furthermore, (Cembureau, 2017) estimated that by 2050 the thermal energy consumed in the kiln will be potentially from the combustion of 40 percent of traditional fuels (30% and 10% for coal and petcoke, respectively) and 60 percent of alternative fuels (about 40% could be biomass), which could lead to a reduction of 27 percent of $FDCO_2$ emissions. In this research paper, two alternative fuel materials are used, tyres and waste oil; both alternative materials are burnt simultaneously with coal to meet the required energy level. To quantify the weight of each fuel material needed for the reduction of CO2 emissions, a mathematical model is used.

3. Mathematical model

The mathematical model is developed for the optimisation of CO_2 from the manufacturing process of cement. It should be noted that this mathematical model only deals with the combustion of fuel materials in the kilns to produce clinker. The mathematical model consists of an objective function to find the best mixture in proportion of the three fuel materials (coal, used tyres and waste oil) for the reduction of CO_2 emissions from the combustion of fuel materials in the kiln. The objective function is resolved by using the linear programming Lingo software and the final solution to the mathematical model represents the weight of the constituents, namely: coal, used tyres and waste oil. The first objective function can be written as:

$$Z\left({}^{Rand}/_{year}\right) = \sum_{i=1}^{n}\sum_{j=1}^{m} a_i X_{ij} + \sum_{i=1}^{n}\sum_{j=1}^{m} c_i X_{ij} \quad \text{.......................... eqn. (1)}$$

Where:

Z : annualized cost of fuel materials used in the production of cement (R/ year)

a_i : cost of purchasing fuel material i (with i = 1, 2, 3, n). For this study the value of n is limited to 3 fuel materials: coal, used tyres and waste oil.

c_i : cost of CO_2 emitted from the combustion of fuel material i (with i = 1, 2, 3, n).

X_{ij} : the quantity of fuel materials i to be burn in unit j (where j = 1, 2, 3, …, m).

The first term in the objective function is related to the cost of purchasing the fuel material while the second term represents the cost of CO_2 emitted from combustion of fuel materials in kiln units. The constraints of cement production applicable to the objective function are presented below:

Demand constraint

The production P of cement should be greater than or equal to the demand of cement. Therefore, the demand D used in this study is equal to:

$$\sum_{j=1}^{m} P = D \quad \text{.. eqn. (2)}$$

Energy satisfaction

This constraint is linked to the type of process of the cement production. As established, all South African cement plants are using dry kiln process and the energy satisfaction are:

$$\sum_{i=1}^{n}\sum_{j=1}^{m} e_i X_{ij} \geq 3000xD \quad \text{... eqn. (3)}$$

$$\sum_{i=1}^{n}\sum_{j=1}^{m} e_i X_{ij} \leq 4000xD \quad \text{.. eqn. (4)}$$

Where:

e_i: is the energy obtained from the combustion of fuel material i and presented in Table 2.

Table 2. Average value of e_i for different fuel material (Laboy-Nieves, 2014 and Steyn & Minnitt, 2010)

	Coal	Used tyres	Waste oil
Energy e_i in GJ/t	26	31.4	20

Fuel proportion

To avoid the changes of clinker properties, six limits in the proportions of fuel materials are considered. For proportions of fuel materials:

$$\frac{\sum_{j=1}^{m} x_{1i}}{\sum_{i=1}^{n}\sum_{j=1}^{m} x_{ij}} = z \quad \text{………… eqn. (5)}$$

Where:

z = Representing the value of proportion and presented in Table 3

Table 3. z-value for proportions of fuel materials

Item	Lower Quantity	Higher Quantity	Optimum value
Coal	0.75	1	≥ 0.75
Used tyres	0	0.20	≤ 0.20
Waste oil	0	0.05	≤ 0.05

Capacity constraint

Each unit of production has its own limit in the volume of cement to be manufactured. In perspective of good management approach in the production of cement and protection of unit of production, an assumption of only 80 percent of full capacity in energy equivalent may only be utilised. Therefore, the total capacity from the unit is:

$$\sum_{i=1}^{n}\sum_{j=1}^{m} e_i X_{ij} = 0.8x4000xCAP_j \quad \text{………… eqn. (6)}$$

By solving the objective function with Lingo program for the lower and the higher limits of proportions of each fuel material, X_{ij} will provide the minimum and the maximum weights of fuel materials needed in the optimization of the CO_2 emissions.

4. Case study

An existing cement producer with the following data is studied and the main purpose of this study is to reduce the CO_2 emissions while minimizing the cost of fuel materials by a fixed target.

Cement Demand D = 3 752 000 kg of cement; Total capacity of the producer: 4 055 000 kg of cement.

By solving the linear equation with Lingo software programme, the results are presented in Table 4 and in Figure 3.

Table 4. Weight of fuel material obtained from different proportions.

Proportion of materials	Weight (in tonnes) of fuel material.		
	Coal	Used tyres	Waste oil
Lower proportion	51444.2	-	-
Higher proposition	72153.9	13855.2	3042.5
Optimised proportion	55219.2	13855.3	-

From Table 4, it may be observed that there is not contribution of used tyres and waste oil at the lower proportion. The energy obtained for lower proportion is under produced and the cement Kiln is no used efficiently. At the higher proportion, all three fuel materials are contributing to the higher percentage of each fuel material; the total energy obtained is 125 percent which is higher than the capacity of the cement Kiln. The optimised proportion is balanced between the coal and used tyres, the weight of waste oil is nil and may not be taken into consideration. The total weight of mix fuel material (coal and used tyres combined) is 4.3 percent less heavy compared to the higher proportion of coal alone. Values in Table 4 are plotted in Figure 3 and interpreted as follows:

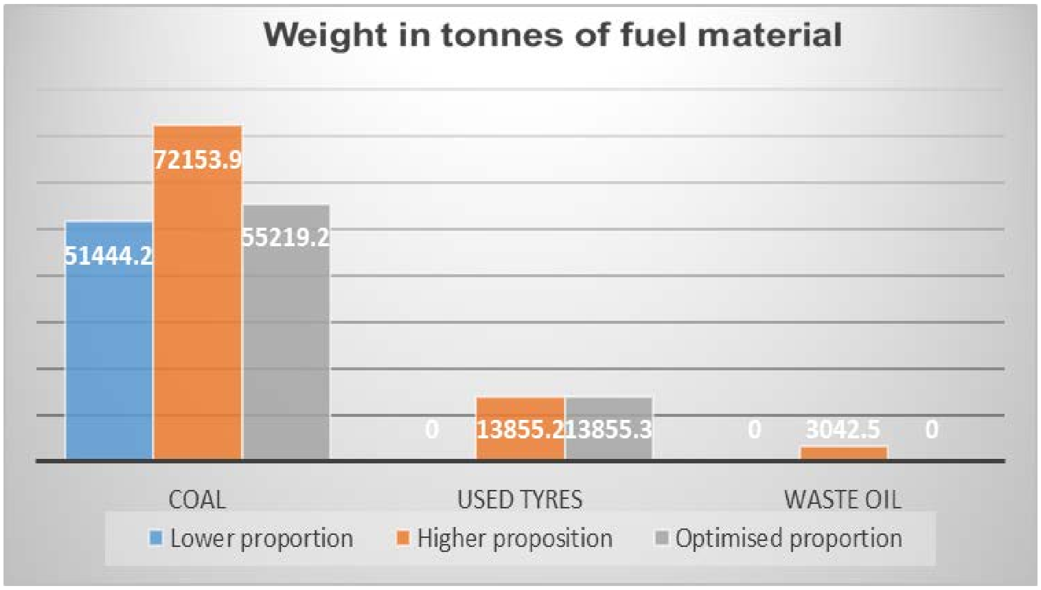
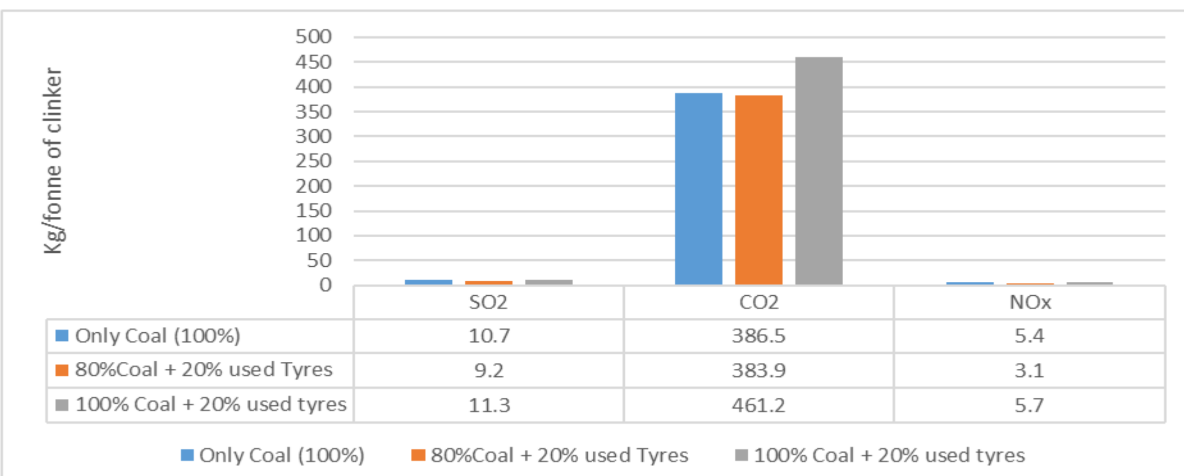


Figure 3. Comparison between different proportions of energy requirements

5. Discussion

It is observed that waste oil may not be used in combination with the other fuels materials, namely coal and used tyres as the energy contribution is nil. Therefore, the contribution of energy is distributed between coal and used tyres for 55419.248 and 13855.294 tonnes, respectively. The difference between the higher limit of proportion of used tyres to the optimum proportion for used tyres is in order of 8.011x10-4 percent higher which is negligible and it may be considered that used tyres are burned together with coal in proportion of 20 to 80 percent. Another observation from Figure 3 is that used tyres provide the most efficient energy at 20 percent compared to waste oil whist the CO_2 emissions from wasted oil and used tyres are 14.8×10^2 kg and 26.69×10^2 kg, respectively; with waste oil emitting 44.55 percent less of CO_2. The CO_2 and other greenhouses gases (GHG) emitted from the production of cement is presented in Figure 4. The results presented show that production of cement with 100 percent coal emits more CO_2 and other GHGs such as SO_2 and NO_x than using coal in combination with alternative fuels such as used tyres.



	SO2	CO2	NOx
Only Coal (100%)	10.7	386.5	5.4
80%Coal + 20% used Tyres	9.2	383.9	3.1
100% Coal + 20% used tyres	11.3	461.2	5.7

Figure 4: Comparison of three different types of fuel material mixes.

This CO_2 reduction of 16.76 percent in emission between a) 80% coal + 20% used tyres burned together in the cement kiln and b) 100% coal + 20% used tyres burned separately in different kiln may not be enough to help the local cement producers to meet their targeted quota required by the South African government. However, this will encourage the producers to assess more options in the reduction.

Conclusion

This study focused on the use of alternative fuels namely: used tyres and waste oil in combination with coal in the cement kiln for reduction of CO_2 emission. For this purpose, a mathematical model is developed to solve an objective function for weight of fuel materials to be used simultaneously. Results obtained from the Lingo software program for the objective function show that waste oil, used tyres and coal may be used to 0%, 20% and 80%, respectively. Further studies should be conducted on the development of a mathematical model which considers alternative raw materials and energy efficiency in electrical consumption.

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Biographies

Arnesh Telukdarie holds a Doctorate in Chemical Engineering from the Durban University of Technology, South Africa. Prof. Telukdarie is currently a Senior Lecturer in the School of Engineering Management at the University of Johannesburg and a Professional Consulting Engineer. Prof. Telukdarie has over 20 years of industrial experience, research interest includes Manufacturing and Corporate Systems.

Labana Beltran holds a master degree in Engineering Management from the University of Johannesburg, South Africa.