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Partial Substitution of Coal with Palm Kernel in Cement Kilns: Effects on Cement Production and Quality

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Abstract. The production of Portland cement is a complex process involving several chemical reactions and different materials, complex systems, and high temperatures (up to 1500 °C). Traditional fossil fuels such as coal, petroleum coke and natural gas have been used as primary source of energy for the process, though still abundant, their supply is slowly being depleted, and costs associated with obtaining these fuels are increasing with time. Therefore, alternative fuels such as biomass waste (palm kernel, rice, and coffee husks etc.) or processed waste materials (refuse derived fuel, waste tires, waste plastics, used oil etc.) and other types of waste have gained much interest recently in cement industries as they present a potential substitution option. In order to achieve the aim of this study, chemical and physical properties of both coal and palm kernel (PK) have been determined and compared. Results show that the PK has an average calorific value ranging from 18-20 MJ/kg which is significantly acceptable and means that the waste can directly be used as fuel in the cement kiln for clinker production. Coal thermal substitution rate was progressively increased depending on the process conditions with the reference case for each kiln run (2% in August 2021, 3% in September 2021 and 5% in January 2022). Impacts on the product quality and process, benefits in terms of emissions and production cost were evaluated and discussed. Technical challenges encountered during the coal and palm kernel milling process and combustion process have been identified and possible solutions have been recommended. This paper discussed on the utilization of palm kernel as an alternative fuel for partial replacement of coal in cement production process. Overall, the result demonstrates that palm kernel has high energy potential for the generation of energy in the cement production process.

Key words: Cement production, fossil fuel, alternative fuel, palm kernel, thermal substitution rate, physico-chemical analysis.

1. Introduction

The cement industry contributes largely to the development and modernization of cities and infrastructure worldwide. However, cement production is an energy and carbon-intensive process due to large quantities of fossil fuels used; high temperatures are required to heat the raw materials to a level that brings about the necessary chemical reactions to make clinker (Madlool et al., 2011). Fossil fuels such as coal, petcock, and heavy fuel have been used as the primary energy source in cement industry, with coal being the predominant fuel burned in cement kilns (Nalobile et al., 2020). The sustainability and environmental impact associated with the use of fossil fuels has consequently drawn attention to developing alternatives and clean fuel sources in cement manufacturing industries, as it is the case in the Pretoria Portland Cement (PPC) factories all over Africa (Zieri & Ismail, 2018).

Around 40-60% of the production cost is incurred due to thermal energy required for the pyroprocessing whereby coal is the major contributor to the high production cost (Nalobile et al., 2020). The use of alternative fuels (AFs) can significantly reduce the production cost in the manufacturing of cement due to its availability and lower price, and they can also contribute to the reduction of emissions and waste disposal requirements (Uson et al., 2013). Therefore, the utilization of AFs such as palm kernel, rice husks, coffee husks, waste tires, plastics, refused derived fuel and many others in cement making process has been identified as one of the sustainable ways to remediate to these challenges (Thomas & Jennings, 2006). However, little research has been made on the use of palm kernels as an AF in cement production plants.

Few studies have examined the usage of AFs in kilns and their effect on clinker and cement quality; it was reported that approximately 90% of coal substitution with AFs can be achieved in kilns. In 2015, a cement plant in Lengfurt, Germany was able to achieve 90 % of coal substitution with AFs (Schaller & Kaufmann, 2016). It was confirmed that CO2 emissions and production cost have been continually reduced (Hashem et al., 2019). In order to reduce the energy cost while enhancing the value of waste as alternative sources of energy in the manufacture of cement without compromising its quality or quantity as well as to reduce environmental impacts related to CO_2 emissions.

Alternative fuels are clean and affordable sources of energy, which are constantly being renewed; they are mostly made up of industrial, agricultural and municipal solid waste. Cement kilns are well suited for waste combustion because of their high temperature processes; therefore, waste such as palm kernels can be used as a potential coal substitute in the cement kiln and strategies are being put in place for maximizing the consumption of these wastes. Several factors such as the availability of the waste, the calorific content, burnability, moisture content, volatile contents and ash content need to be considered for the selection of palm kernel as a coal substitute in cement kilns (DeBeer et al., 2017).

The aim of the present work is to assess technically and economically the feasibility of partial substitution of coal by palm kernel as an alternative fuel to satisfy the heat energy requirement of clinker production. This was done via studying proximate and ultimate analysis of the fuel as well as elemental compositions of the fuel; their impacts on the clinker production process and quality along with their environmental impact's comparison to traditional fossil fuels.

2. Materials and Methodology

2.1. Study area

All experiments were carried out in a well-equipped laboratory within the PPC Barnet (PPCB) plant facility. PPCB is the latest factories of the PPC Group (South Africa) with 1.2 million tons of cement capacity per annum and a design capacity of 3000 tons of clinker per day (PPC International, 2017). The plant is located in the western part of the Democratic Republic of Congo. The close proximity of the plant to traditional palm oil producers will play an important role in the continuous availability of palm kernel and sustainability

2.2. Research approach

In order to achieve the aim and the objectives of this study, a schematic diagram as shown in Figure 1, summarizes the research approach used to answer the research questions.

Throughout this study, chemical, physical, and elemental analyses were performed on all process inputs (RM1, RM2, RM3, RM4, RM5, and RM6), including fuels (coal and palm kernel) and as well as on the process outputs (clinker, kiln dust, cement). Sample collections were performed during normal production operations of kiln runs. Each kiln run covers a period of 30 days; experiments were conducted based on the kiln campaigns period.

The experimental approach conducted in this research does not involve animal experimentation or human participants.

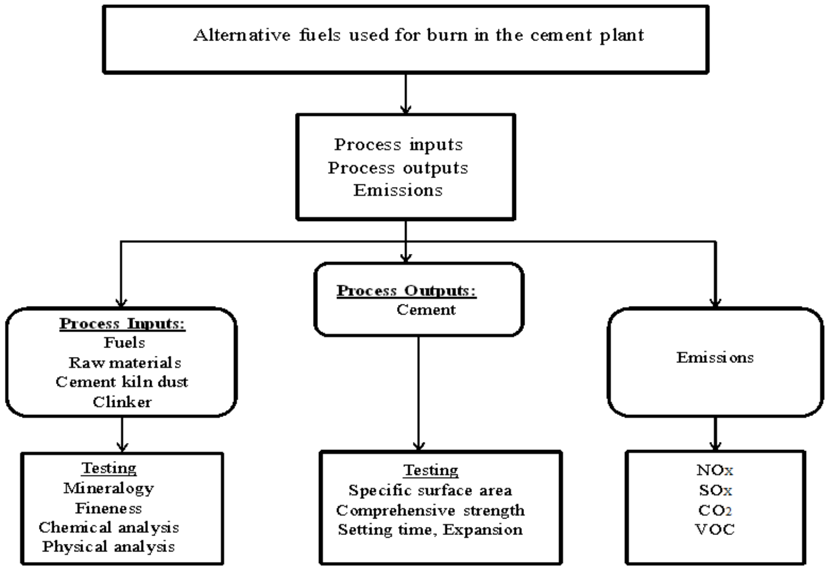

Fig. 1. Research approach summary.

2.3. Main equipment used

All trials and analysis were conducted within the PPC Barnet plant facility. Chemical and physical analyses as well as sample analysis were carried out in a well-equipped laboratory (Table 1) with apparatuses calibrated according to specified standards and maintained in accordance with manufacturer recommendations.

Table 1. Specific equipment used for the current study.

Equipment	Description
Parr oxygen bomb calorimeter	Equipment used to determine the calorific content of the fuel in terms of degree Celsius. The bomb calorimeter was tightly closed and filled with O_2 to 25 atm.
Sulphur analyser	Used to determine the Sulphur content of both coal and palm kernel
Weighing balance	Used to determine the weight of the sample
Digital Blaine air apparatus	Apparatus used to determine the specific surface area of cement
Oven	Instrument used to dry-off moisture in fuels and raw materials
Furnace	Equipment used to heat up (<1500^{o}C) materials
Vicat Apparatus	Used to determine the setting time of cement
Curing bath	Tank filled with water used to place the mortar depending on number of days
Sampling points	Sample points are used to collect sample all process inputs and outputs
Compression testing machine	Used to determine the strength of the cement mortar prism
Cement mortar mixer	Used to mix the cement paste used for mortar prism
Le Chatelier's machine	Apparatus used to determine the cement expansion/soundness
X-Ray Fluorescence (XRF)	Used to determine the elemental composition of input &output materials
Scanning electron microscope (SEM)	Used to produce detailed images of clinker by scanning its surface
Geo-scan	Used to determine the elemental composition of limestone as it passes through the analyser on a conveyor belt
Equipment	Description

2.4. Sampling and collection

Samples of all materials were collected during normal production operations considered from 6 a.m. to 6 a.m. as the plant runs for 24 hours. It should be noted that fewer samples of clinker and fuel mixture may have been collected due to some unexpected situations during the burns such as power interruption, equipment stoppage due a technical issue or material accumulation caused by rain. Raw materials were sampled once during each burn upon receipt at the factory, the remaining materials were sampled at a regular frequency per shift. Only daily composites averages are presented in this study.

3. Results and discussion

This study focuses on the use of palm kernel as a secondary fuel in the cement manufacturing process; the thermal substitution was done at three (3) different proportions over a period of three (3) kiln campaigns. Plant operating conditions were kept constant besides some unavoidable changes such as coating ring formation (mass of clinker or dust particles that adheres to the wall of the kiln), blockages from material accumulation, process disturbance, and rain related to the study and that were necessary for the cement facility to maintain its normal operations. Values in Table 2. present a summary of plant operating conditions targets as set by the cement plant during kiln runs.

Table 2: Summary of plant control parameters for clinker production

Parameters	Coal	Coal and Palm kernel mix		
Kiln run period	May-21	Aug-21	Sep-21	Jan-22
Kiln feed ton per hour (tph)	220	220	220	220
Raw Mill ton per hour (tph)	270	270	270	270
Clinker production ton per day (tpd)	3120	3120	3120	3120
Coal mill ton per hour (tph)	24	24	24	24
Coal calorific value (CV)	26	26	26	26
Thermal substitution rate target (TSR %)	0%	2%	3%	5%
Specific heat consumption (MJ/ton clinker)	3.42	3.42	3.42	3.42

3.1. Physical and chemical characteristics of fuel

It is important to know the physical and chemical properties as well as the elemental analysis of the waste fuel as means of understanding its potential as an alternative fuel in cement kiln. Fuels samples, both coal and palm kernel were taken at the stockpile upon delivery on-site and tested for proximate and ultimate analysis. The fine fuel mixture made of coal and Palm kernel was then tested with the use of an automated sample. At this stage, proximate, ultimate, and combustion analyses as well as each fuel's standard parameters were determined in addition to the fineness of the fuel mix (Table 3).

Table 3. Comparison of raw coal and palm kernel properties.

	Parameters	Raw Coal				Raw palm kernel			
		May-21	Aug-21	Sep-21	Jan-22	May-21	Aug-21	Sep-21	Jan-22
Proximate Analysis	Caloric content	26.64	26.68	26.87	26.18	19.55	20.12	21.06	20.42
	Ash content	15.34	19.73	17.33	15.99	4.22	5.43	4.33	3.75
	Free Moisture	9.1	9.5	8.5	5.5	23.55	24	25.5	10.89
	Inherent Moisture	1.46	1.44	1.54	1.28	7.22	8.75	7.50	6.37
	Volatile Matter	24.47	19.75	15.87	15.87	46	47.53	48.31	67.38
	Sulfur Content	0.45	0.43	0.54	0.32	0.22	0.14	0.20	0.14
Ultimate Analysis	Carbon	65	65.28	64.88	65.48	44.55	40.39	46.38	42.91
	Nitrogen	1.68	1.65	1.55	1.68	0.65	2.01	0.92	0.45
	Sulfur	0.65	0.67	0.65	0.68	0.13	0.12	0.1	0.1
	Oxygen	14.7	14.27	14.07	14.66	39.41	48.01	46.42	47.55
	Hydrogen	4.55	4.39	4.22	4.41	5.36	5.2	5.49	5.27

The amount of energy that the palm kernel waste samples contain is necessary in understanding the potential of the waste feedstock as a source of fuel. The bomb calorimeter was the instrument used to determine the coal and palm kernel energy content in terms of the calorific value (MJ/kg). From Table 3, It is seen that the calorific values of palm kernel obtained from this study ranged from 19 to 21 MJ/kg with an average of 20 MJ/kg. This result shows that palm kernel is a potential coal substitute and can combust effectively.

In an analysis of the results obtained, it can be deduced that palm kernel is characterized by high moisture contents compared to coal. This is due to the fact that palm oil extraction sites are normally located closed to rivers which favor humidity. The moisture content is an important factor in the combustion of fuels since it directly affects the heating values. Freed and inherent moisture contents of samples were calculated, while the total moisture content is determined by adding free and inherent moisture content. Palm kernel used in January 2022 had less moisture content because the stockpile was spread and exposed on the sun before being crushed. Results obtained have shown high volatile matter contents in the palm kernel compared to coal; Palm kernel samples tested in August 2021 gave an average volatility of 46%, 47.53% in September 2021 and 67.38% in January 2022 compared to coal which gave an average volatility of 22.83% in August 2021, 23.67% in September 2021 and 27.47% in January 2022. The high volatile matter in the PK has slightly influenced the length of the kiln flame during January 2022 kiln run since palm kernel consumption was increased progressively.

Table 4. Mixed fuel (coal and palm kernel) properties.

	Coal and Palm kernel mix			
Proximate Analysis	Thermal substitution rate	2%	3%	5%
	Properties	Aug-21	Sep-21	Jan-22
	Caloric content (MJ/ton)	25.92	26.44	26.11
	Ash content (%)	14.79	14.82	15.11
	Inherent Moisture (%)	2.05	1.88	3.11
	Volatile Matter (%)	27.47	25.77	24.86
	Sulfur Content (%)	0.44	0.39	0.48
	Res.(90μ)	12.98	10.60	13.04
Ultimate Analysis	Carbon (%)	49.90	52.98	48.22
	Hydrogen (%)	7.07	8.23	7.33
	Nitrogen (%)	1.52	3.35	1.02
	Oxygen (%)	41.95	35.65	43.23
	Sulfur (%)	0.20	0.29	0.22

From the results shown in Table 4, it can be noticed that no major change was observed in terms of calorific content due to low proportions of palm kernel in the fuel mix. The moisture content of the fuel is an important parameter as it affects the ease with which coal can be handled and burnt and also has an important impact on the cost. The high moisture content of the Palm Kernel results from the way it is stored after the oil has been extracted. The high moisture content of Palm Kernel has led to coal mill inlet and diaphragm blockages but also directly affected the coal mill output and created process operation disturbances. In terms of environment, Palm kernel generally attracts mosquitos around the factory and can be responsible for some diseases like malaria; this can lead to health and safety issues for employees at the plant. Therefore, the storage of palm kernel at the plant must be properly managed.

The volatile matter analysis of the fuel mixture possesses relatively high percentage compared to fine coal; the high volatile matter content indicates easy ignition of the fuel, although it has a significant effect on the combustion mechanisms and consequently on the design and operation of the combustion systems for this fuel. Ash content of the fuel mix are also low and are within the acceptable range. This is advantageous during the burning process as it helps eliminate or reduce particulate pollution. Sulfur content of the coal and palm kernel mix appeared to remain fairly lower compared to the sulfur content of pure coal but remains within the range (< 0.8%). This reduces issues related to SO_2 emissions during the combustion process of the fuel (Wilson, et al., 2010).

3.2. Chemical compositions of clinker

Clinker is the output of the pyro-processing and it is also considered as the input in the cement milling process. Approximately 8 clinker samples were taken per day, composite specimens were considered in this study. The composite clinker specimens were tested to determine the Bogue compounds of clinker produced for each kiln run as tabulated in Table 5 (Sedaghat, et al., 2015). From the data presented in Table 5, it can be seen that the Bogue composition of clinker made from the thermal substitution of coal and palm kernel waste is quite similar to the Bogue composition of clinker made from coal as the main fuel. From August burn, the Bogue compounds all fall in the range with a negligible difference compared to the May kiln run. The highest content of belite and aluminate were obtained in September kiln run; 18.45% and 9.03% respectively. Ferrite level was slightly higher in May 2021 trial burn where 100% of coal was used as fuel compared to the trials burns where coal was substituted partially. This might be caused by the difference in the raw material or fuel compositions.

Table 5. Bogue compositions.

Kiln run period	May-21	Aug-21	Sep-21	Jan-22
Target TSR %	0	2%	3%	5%
Actual TSR %	0	2.73%	3.28%	6.56%
Parameter's average (wt. %)				
Alite (C_3S)	61.33	61.23	57.66	58.36
Belite (C_2S)	15.01	15.23	18.45	17.19
Aluminate (C_3A)	8.07	8.82	9.03	8.19
Ferrite (C_4AF)	10.15	8.91	8.83	8.99
Liquid Phase	25.59	24.97	25.42	24.06

The liquid phase is critical in the pyro-processing as it directly affects the early strength development, setting time and workability of cement; results obtained have shown acceptable liquid phases ranging from 24 wt.% to 26 wt.% for all clinker produced with mixed fuel at different ratios, all figures are within acceptable target range.

The degree of difference between Bogue compounds results obtained with pure coal and palm kernel proportions means was fairly small.

3.2.1. Scanning electron microscopy (SEM)

Scanning electron microscopy or SEM was used to produce detailed images of clinker made from coal and palm kernel mix by scanning its surface to create a high-resolution image. Figure 2 shows individual minerals in the clinker nodules produced from 5% TSR using the scanning electron microscope (SEM), which was acquired at 5000x magnification, with a resolution of 5μm/pix.

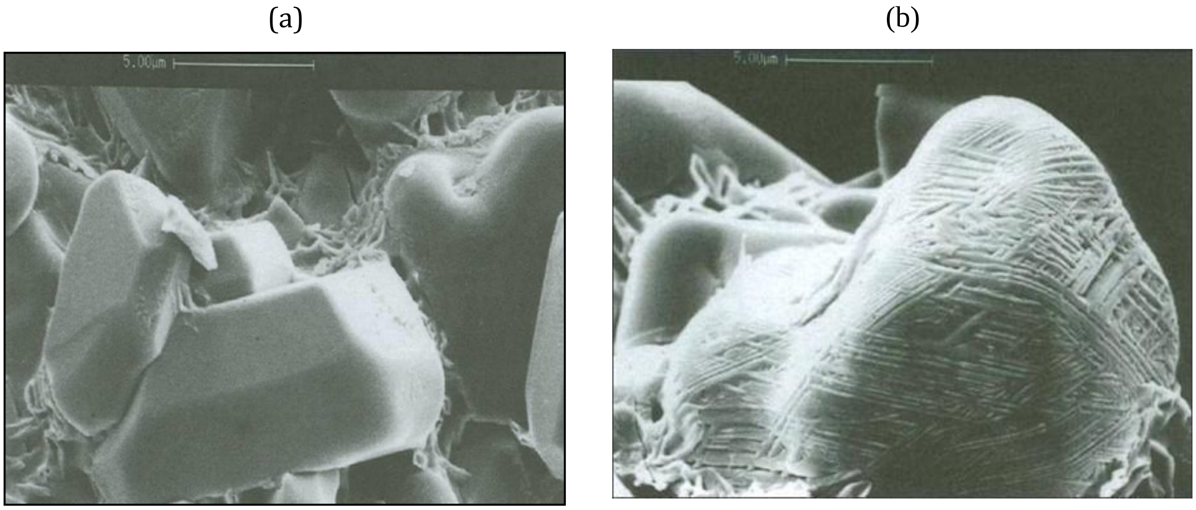

Fig. 2. (a) Alite crystals and (b) belite crystals of clinker made from fuel mix (5%TSR).

Figure 2 illustrates random alite (a) and belite (b) crystals made from 5% coal substitution by palm kernel on SEM images; both minerals can be clearly distinguished from its colours, alite being light grey and belite is dark grey; Alite crystals are generally lengthened and hexagonal in shape. Results obtained shows alite minerals with a size ranging from 20μm to 60 μm. on the other hand, belite clusters are rounded in shape and 10 μm to 30 μm in size.

Figure 3 shows SEM images of both aluminate and ferrite of clinker nodules produced from 5% thermal substitution rate:

The clinker samples collected during each kiln run period were tested to determine the chemical compositions of clinker. The burning behavior of palm kernel differs slightly from the behavior of coal in terms of clinker quality due to material densities, higher particle sizes and logistics (transport of waste fuel to site).

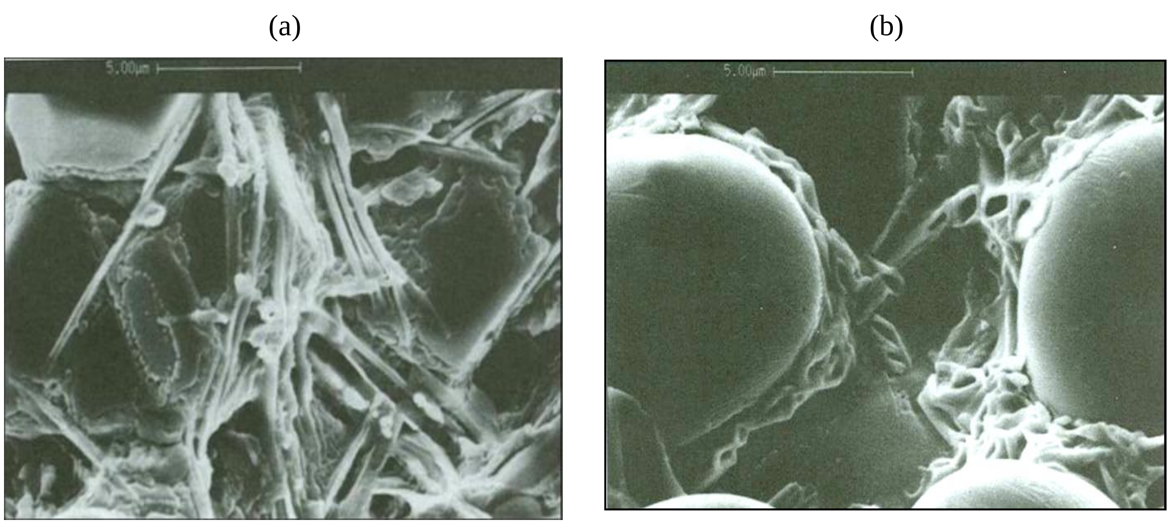

Fig. 3. (a) Clinker aluminate crystals (5%TSR) and (b) Clinker ferrite crystals (5%TSR as target).

3.3. Physico-chemical properties of cement

Portland cement is considered as the final product of the manufacturing process. All the cement produced during the trial burns by the cement plant was done according to ASTM C150 specifications for Type II cement (Wilson, et al., 2010). Impacts of the thermal substitution rates on the cement quality were evaluated and results obtained by the cement plant are tabulated in Table 6.

Table 6. Summary of physical properties of Portland Cement (Surecem) for all burns.

Cement grinds properties					
Kiln run period	Aim	May-21	Aug-21	Sep-21	Jan-22
Thermal substitution rate (TSR %)	5%	0%	2%	3%	5%
Properties					
Blaine specific surface area, (m^2/kg)	3800	3824	3895	3732	4323
Compressive strength, (MPa)					
2 Days (2D)	14	15.6	16.3	16.7	18.9
28 Days (28D)	36	36.9	43.2	31.3	43.3
Initial Setting time, min	>40	172	128	257	126
Final Setting time, min	<390	134	188	345	195
Autoclave expansion, mm	<10	0.5	0	0	0.5
SO_3, (%)	1.8	1.81	1.73	1.8	1.82

Based on results obtained from the cement grinds expressed in Table 6, the majority of results from properties fall within the requirements set by the ASTM specifications. The fineness of cement is expressed as the total surface area in square meters of all the cement particles in one kilogram of cement; this was measured using the Blaine air-permeability apparatus (ASTM C-204). The Blaine SSA of the cement produced at different burns were within the acceptable requirement range except for September kiln run where 3% of TSR was achieved with a Blaine SSA of 3732 m^2/kg. This drop in the Blaine SSA might have been resulted from the raw materials fluctuations, clinker compositions and disturbance caused by process conditions.

All expansion results are within the targets (<10 mm); No cracking of hardened cement paste was observed during the test and there was no major change in volume (expansion) of the cement paste produced from the clinker made from the mixed fuel (coal and palm kernel). Expansion is normally influenced by the temperature and humidity. The significance of cement expansion (soundness) within the construction sector is crucial as it can lead to structural instability, which can result in problems such as cracking and diminished longevity and durability of concrete structure over time. The effect of thermal substitution of fuels on the cement strength and expansion is considered to be minimal.

The overall average of initial and final setting time results obtained in the four kilns runs were all with the acceptable range. It can be concluded that the partial substitution of coal by palm kernel had a minimal impact on the setting time results.

The compressive strength of all cement mortar specimens was conducted on 40 mm x 40 mm x 160 mm cubes according to ASTM C-109 by using a compressive testing machine of a 300 kN capacity at the ages of 2 and 28 days. Figure 4 and 5 show the early and late cement strengths obtained with different palm kernel substitution rates.

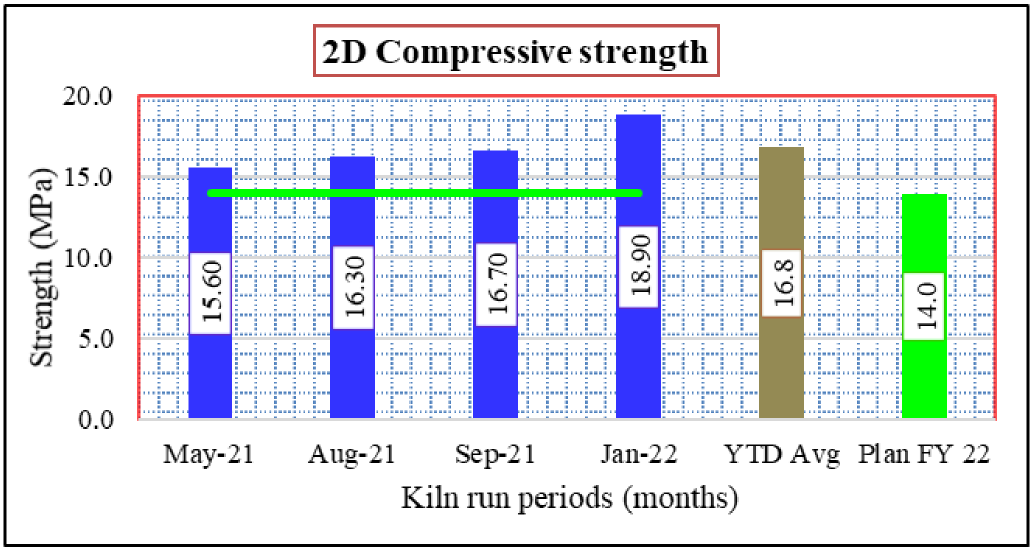

Fig. 4. Early compressive strength based on kiln run period

The cement plant results of all mortar cube strength results at early ages met the requirements. The mortar cube strength results that exceeded the aim for 2-day strengths (18.9 MPa vs 14 MPa as planned target) was achieved at the highest thermal substitution rate of coal by palm kernel in January kiln run. On the other hand, the mortar cubes strength at late ages (Figure 5) fell significantly above the aim (36 MPa) except the mortar cube strength made in the September (31.3 MPa) trial burn which was slightly below the allowable compressive strength requirements, this might be caused by the reduced alite C_3S in the clinker.

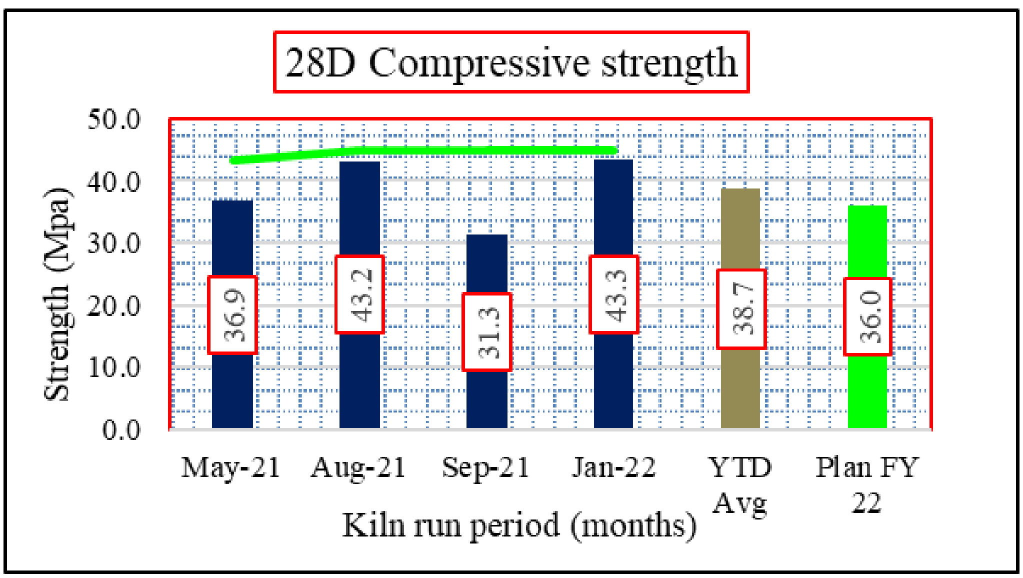

Fig. 5. Final compressive strength based on kiln run period

Both early and final strengths were mainly affected by the calcium silicate hydrate formation from the hydration of alite (C_3S) and belite (C_2S). The use of palm kernel as a substitute to coal in the kiln did not affect the strength of cement as the reactivity of both alite and belite crystals as the clinker was brought to burning temperature quickly. The length and temperature of the flame in the kiln was maintained during the burn at different thermal substitution.

From the results illustrated in Table 6, all SO_3 contents were falling within the targets. It is clear that gypsum plays an important role not only as cement set regulator but also affects the strength rate development of cement paste by either accelerating or decelerating the hydration of the alite phase. It is important to note that the effect of SO_3 on some mechanical properties of cement paste do not only depends on the C_3A phase, but as well on the available alkali equivalent within the clinker.

3.4. Impact of palm kernel utilization on the clinker production process

The utilization of alternative fuels such as palm kernel offers not only economic benefits by reducing the cost of cement production but also preserve fossil fuel resources and reduce the volume of palm oil waste that are generally disposed, consequently a decrease in the global greenhouse effect. The substitution of fossil fuel by different alternative fuels varies from one region to another as the availability of the AFs is dependent on the seasonality. The cement industry needs to ensure sustainable and environmentally friendly use of energy sources while increasing profit margins and without affecting the quality of cement produced (Akkapeddi, 2008). Some important parameters such as calorific value, moisture content, ash content, and volatile matter have to be carefully considered in order to optimize the consumption of palm kernel in the cement making process. Effects related to process operation, clinker and cement quality, emissions and as well as cost impacts are discussed below.

3.4.1. Impact on the process operation

A number of challenges were encountered in terms of handling and storage in the plant as these palm kernels are delivered in bags, therefore extra labour is required for offloading, cutting and emptying. Storage of high volumes of palm kernel is a problem as the bulk density of palm kernel is very low and occupies a large space for storage and gets contaminated with foreign materials such as metal scraps and nylon bags, and is exposed to moisture during rainy seasons and thus creating a problem of flowability during feeding and co-firing in the system. Long term storage of palm kernel might create instant fire as shown in Figure 6, The source of the fire remains unknown. Therefore, much attention needs to be paid to avoid the spread of the fire along the storage area.

Fig. 6. Raw palm kernel stockpile.

Some measures were taken to ensure safe storage of palm kernel such as the use of tarpaulins to cover the palm kernel stockpile so that it does not get contaminated and get protected from rain.The crushed coal and PK mixture were dosed and co-ground together in the coal mill after being dosed with the ratio of 10:2, the fuel mixture was then fed into the calciner for calcination process and main burner. A number of technical challenges were encountered during coal mill operation, such as blockages of diaphragms, high differential pressure, decrease in outlet temperature, decrease in mill filling level, and increase in CO content.

Figure 7 illustrates blockages found inside the coal mill diaphragms during co-grinding of coal with palm kernel.

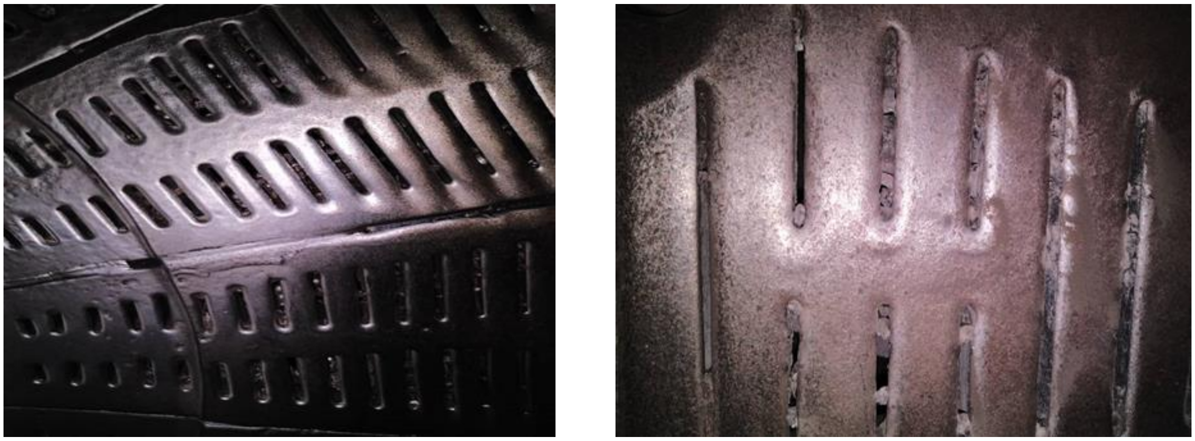

Fig. 7. Coal mill diaphragm blockages.

Important parameters such as mill inlet and outlet pressure, mill outlet temperature, mill differential pressure, mill filling level, separator bearing temperature and CO level need to be controlled and monitored properly during the grinding process. The behaviour of coal mill during co-grinding of coal and palm kernel in September 2021 kiln run was unstable and several fluctuations were encountered during the operation. The coal mill feed had to be reduced to avoid the mill to get full; the feed was reduced down to 10 tph. The mill differential pressure (dp) was increasing up to 4000 Pa; the mill outlet temperature was kept on the higher side to avoid chokes and blockages.

3.4.2. Impact on clinker and cement quality

The quality of clinker and cement was not affected as long as essential parameters of the fuel were met. Some criteria's such as the fuel ash content must be controlled as the ash becomes part of the clinker, therefore can affect its composition. The ash content of palm kernel obtained was less than 20%, which means that it does not affect in any case the quality of clinker and does not disturb the process. The fuel ash chemistry is directly linked to the fuel feeding consistency and clinker quality, any sudden interruption of the palm kernel feeding during the burning process could negatively affect the clinker chemistry since in most cases there will not be enough time to adjust the raw meal composition accordingly. Hence, it is crucial to keep a sustainable and continuous feeding of palm kernel for a stable clinker chemistry.

The effect of minor components can either be beneficial or harmful. The presence of minor or trace elements is beneficial in a way that they can improve the process through accelerating clinkering reactions, or lowering the temperature at which such reactions occur, or increasing reactivity of the product. Harmful effects include decreasing the alite content of the clinker, increasing risk of ring build-ups, decreasing the durability of the final product, or the introduction of poisonous elements or contaminants.

3.4.3. Effect of palm kernel usage on emissions

It is necessary to consider the level of nitrogen, sulphur and chlorine content in the substitute fuel for clinker production since these components are responsible of oxides which can be harmful and can disturb the production process. Emissions were continuously monitored by the cement plant to evaluate the impact of palm kernel. Table 7 illustrates emissions results during the thermal substitution of coal by palm kernel at different substitution rates.

Table 7. Emissions results based on kiln runs.

Kiln run period	NO_x mg/Nm^3	SO_x mg/Nm^3	CO_2 kg/ton of clink	Dust kg/ton of clink
May-21	545.34	134.85	849	0.01
Aug-21	722.79	90.93	834	0.01
Sep-21	720.53	74.84	868	0.02
Jan-22	710.09	86.90	843	0.01

Most gases results fall within the standards range which is 600 mg/Nm^3 for NO_x, 400 mg/Nm^3 for SO_x, and 825- 890 kg/ton of clinker for CO_2 emissions (Sanjuan, et al., 2020). Although most NO_x emissions were higher than the target, the values obtained are still within national limits (500-1000 mg/Nm^3). High NO_x emissions might have been caused by high heat load at front or back end of the kiln during pyro-processing. Due to the low contents of sulfur, SO_2 emission problems would not be expected during palm kernel combustion. CO_2 emission has significantly reduced with the increase in thermal substitution rate. This study has demonstrated that the utilization of palm kernel waste as a substitute of coal has a high potential as a source of environmental-friendly energy that reduces pollution and provides a waste management option.

3.4.4. Cost impacts analysis

The high price of coal has a direct impact on the production cost; as a result, cement industry tends to switch their interest to a cheaper and eco-friendly source of energy to reduce their cost of production and reduce the business risk of coal import (Shafiee & Topal, 2010).

Table 8. Cost impacts results of palm kernel utilization.

Alternative fuel cost impact implications						
	UOM	May-21	Aug-21	Sep-21	Jan-22	Total/Average
Clinker production target	Tons	70,000	70,000	50,000	70,000	330,000
SHC budget	MJ/kg clinker	3.42	3.42	3.42	3.42	3.42
Total fuel requirement	Tons	9,85	9,61	6,82	9,71	45,81
Coal requirement	Tons	9,85	9,42	6,617	9,23	44,43
Coal CV	MJ/kg	26	26.64	26.82	26.36	26.45
Coal moisture	%	7%	7%	7%	7%	7%
Palm kernel requirement	Tons	0	273	280	677	2193
Palm kernel CV	MJ/kg	19	20.42	21.06	20.12	19
Palm kernel moisture	%	0%	8.75%	7.50%	6.37%	15.00%
Actual TSR	%	0%	2.47%	3.28%	6.56%	3.08%
Cost of coal	$/ton	185	185	185	365	176
Cost of palm kernel	$/ton	65	65	65	75	75
Cost savings	$	-	17,843	19,651	126,563	77,431
Cost savings	$/ton	0.00	0.25	0.39	1.81	0.23

Coal prices are relatively unstable due to multiple challenges related to logistics such as purchasing price, freight and inland transport, loading and unloading, and import duties.

Cost impact analysis of the utilization of palm kernel was calculated based on several parameters such as clinker production, specific heat consumption, fuel requirement, coal and PK calorific content, moisture content of both coal and PK, cost per ton of coal and PK. Table 8 illustrates savings achieved through PK utilization in the cement kilns.

According to the results obtained, cost savings in terms of USD were $17,843, $19,651 and $126,563 for actual thermal substitution rates of 2.47%, 3.28% and 6.56% respectively. In terms of $/ton, cost savings of 0.25 $/ton was achieved in August 2021, 0.39$/ton and 1.81$/ton achieved in September 2021 and January 2022 respectively. The higher the substitution rate, the higher the cost saving. The landed cost of coal went from 185 $/ton in September to 365 $/ton in January 2022, the rapid increase of cost of coal is due to local import duties and has a direct increase the production cost of cement. The following economic benefits are expected to be gained over the long term at the cement plant when switching fossil fuels (coal) to alternative biomass fuels (like palm kernel):

- Annual savings average of approximately $309,724 USD to the company considering 4 kiln campaigns per year;
- Business opportunity would be created for different local individuals and communities involved in the palm oil production activities as well as in the waste collection preparation;
- For a country like DR Congo where global energy market is volatile, using biomass alternative fuels from local sources do play a great role in energy security and will impact the local cost of cement;
- The optimization of waste utilization (up to 60% thermal substitution) will contribute to issues related to waste management in communities on a long-term basis;
- Job opportunity would be created as large plantations of palm tree and other biomass would be considered.

4. Conclusion

In this work, palm kernel was used as an alternative fuel to partially replace coal in the production of clinker. The focus of the study was to assess technically and economically the feasibility of partial substitution of coal by palm kernel as an alternative fuel to satisfy the energy requirement of clinker production. Coal was co-fired with palm kernel at different ratios (2%, 3% and 5%) in order to lessen the demand for traditional fuels. The cement plant successfully implemented palm kernel utilization to produce a consistent product quality while reducing the cost of production and environmental impacts of the cement plant; The utilization of palm kernel waste has proven to be a viable replacement option for the traditional coal in the cement kiln in terms of compatibility with the facility's production process. The replacement rates can be increased step by step while observing the effect on clinker quality and operational disturbances that could lower the kiln output. Some plant adjustments and modifications are required such as a storage facility made of a covered shed, weighing system with solid flow meter to control the flow of AFs, and a hammer mill needs to be designed to facilitate the milling of any type of alternative fuels and also optimize its consumption.

5. Conflicts of interest

The authors declare no conflicts of interest regarding the publication of this paper.

6. Acknowledgments

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