Environmental Benefits of Using Spent Pot Lining (SPL) in Cement Production

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Abstract

Spent pot lining (SPL) is a toxic waste material produced during the pot replacement process in the aluminium industry. Recently, SPL has been diverted from landfills to cement manufacturers as a raw material replacement. This paper presents a comprehensive environmental assessment of a case study in the United Arab Emirates (UAE), where SPL from Emirates Global Aluminium (EGA) was used as a feedstock at a cement plant in Ras Al Khaimah, UAE. Three areas of environmental concern were studied: fuel savings and CO_2 reductions, changes in NO_x emissions, and raw material repurposing and toxic substance destruction. Using 0.6 % SPL in feedstock was estimated to reduce coal consumption by 3.5 %, CO_2 emissions by 0.65 %, and NO_x emissions by 3.8 %. These changes are primarily attributed to the fluoride content in SPL creating fluoride fluxing effects that reduce the high temperature requirements of the cement kiln. Lower kiln temperatures lead to lower coal consumption and thermal NO_x generation. Toxic materials such as cyanides and fluorides were destroyed or fixed during the cement production process to below detection limits. However, SPL addition to cement production is limited by maximum alkali content standards of cement products. The use of SPL in cement production is shown to yield significant environmental benefits in terms of reducing emissions and coal consumption and destroying toxic substances. This initiative bolsters the concept of a circular economy in which different industries collaborate to improve environmental sustainability.

1. Introduction

Aluminium smelting is often viewed as significantly detrimental to the environment [1]. The primary reason for this perspective is the large amount of electricity that is required by the electrolytic process to produce aluminium metal and the oxidation of the carbon anode, both of which would release substantial amount of carbon dioxide (CO_2) if the electricity is generated through fossil fuel combustion. In addition, the process also produces significant quantities of toxic spent pot lining (SPL) materials as a by-product [1]. Consequently, the motivation for this study was to understand the viability of repurposing SPL waste material while deriving environmental and sustainability benefits.

In aluminium production, the cathode and refractory lining of the pot is exhausted after it has spent 4 – 5 years producing aluminium in the pot line. The pot is then taken out of service and the lining material removed becomes spent pot lining. The SPL contains toxic materials such as cyanides and fluorides. As one of the primary aluminium producers in the world, Emirates Global

Aluminium (EGA) produces approximately 33 000 tonnes of SPL per year. Since 2009, EGA has been diverting SPL from landfills to cement manufacturers as a raw material replacement. The main reason for the diversion is to reduce the ecological footprint of aluminium production. For the cement plant accepting SPL, traditional feedstock flow can be decreased because a substantial amount of metal oxides in SPL are the same as those in standard cement raw materials [2 – 5].

There are three major stages in cement production: 1) physical processing, 2) clinker production, and 3) cement grinding. In the physical processing step, limestone and supplementary feedstock such as sand, shale, iron ore, SPL, and others are extracted and milled. The feedstock materials are combined in specific proportions to produce a mixture with tightly controlled compositions called raw meal. The raw meal enters the clinker production process and undergoes successive application of heat in various stages to produce clinker nodules: pre-heater cyclones, the calciner, and the rotary kiln. Clinker quality is primarily determined by the free lime (CaO) content, which is a main determinant of the resulting concrete strength. In addition, clinker quality is determined by other parameters such as total alkali and density. In the last step, clinker nodules are ground with gypsum to produce cement [6].

SPL can play several roles in the cement manufacturing process. In a cement plant, coal is the traditional fuel used in the kiln and calciner, and the carbon in SPL can act as an alternative fuel source. Silicon, aluminium, iron, calcium, and magnesium oxides in SPL act to replace traditional cement raw materials and are incorporated into the final clinker product. [2] Fluorides in the SPL can act as fluxing agents which may lower the required reaction temperature and produce catalytic and mineralization effects [7 – 8]. The lowered reaction temperature can reduce the amount of thermal nitrogen oxides (NO_x) produced and the amount of fuel coal required. Since the combustion of coal releases significant quantities of CO_2 and NO_x, a reduction in coal usage can lower the emissions of both CO_2 and NO_x. Cyanide-containing compounds from the SPL can potentially serve as a scrubber for NO_x, leading to lower NO_x emissions [9].

The primary environmental benefit of using SPL in cement production is the transformation of "unwanted" waste SPL into valuable feedstock for industries such as cement manufacturing, iron and steel production, and brick manufacturing, promoting cross-industrial cooperation and a circular economy. Secondly, there may be reductions in the environmental footprint with respect to CO_2 and NO_x and due to the repurposing of SPL materials. This study seeks to assess the environmental effects of SPL utilization in cement production through estimating reductions in NO_x emissions, fuel consumption and carbon emissions, and waste and/or toxic materials.

2. Methods

To assess the environmental benefits of SPL utilization in cement manufacturing, a cement plant located in Ras Al Khaimah, UAE was used as a case study. This cement production facility produces around 8000 – 8500 tonnes of clinker ($t_{clinker}$) per day (347 $t_{clinker}$/h), with an annual capacity of around 2.8 million $t_{clinker}$, and has been using 0.6 % SPL as part of its raw meal for the past few years. Both laboratory experiments and computational modeling were used to estimate the effects of SPL addition.

Burnability tests were performed at the analytical laboratory in this cement plant to quantify the effects of SPL on clinker quality, cement manufacturing process conditions, and toxic materials destruction. This test is typically carried out at cement plants before introducing any new Alternative Raw Material (ARM) to understand the impact of ARM on clinker quantity. The burnability tests were performed by forming nodules from the raw meal and drying them in an oven at 105 °C. Subsequently, the dried nodules were fired in a muffler furnace at a constant temperature for 30 min. The parameters varied were the quantity of SPL addition (0, 0.5, 0.75, 1.0, 1.5, 2 %), and the muffler furnace firing temperature (1250, 1300, 1350, 1400, 1450 °C). In preparing the different raw meal mixtures, other raw materials including limestone, shale, sand, and copper slag content were adjusted based on established mass-balance algorithms, so as to achieve targets for three parameters. These parameters were the lime saturation factor (LSF), silica modulus (SM), and alumina modulus (AM). LSF is the ratio between the actual quantity of lime to the theoretical quantity of lime required by the other main oxides in the raw meal, SM is the weight ratio of silica to the summation of alumina and ferric oxide in the raw meal, and AM is the weight ratio of alumina to ferric oxide in the raw meal [10]. When the LSF is greater than 100, there will always be some free CaO remaining in the clinker product. The cement facility's targets for LSF, SM, and AM were 101, 2.3, and 1.5 respectively. No repetition experiments were performed. The experimental outputs were the percent free CaO and the clinker chemical composition as well as the change in mass during the furnace firing [11]. In addition, to confirm the destruction and fixation of toxic materials at cement manufacturing temperatures, the fluoride and cyanide content of burnability test clinker samples was analyzed.

Material balance was performed over the cement production stages, and all fuel and energy consumption and carbon and NO_x emissions were calculated based on this process facility, taking process parameters and calorific values from the plant’s measurements. Furthermore, to estimate how SPL addition will affect NO_x emissions and cyanide conversion, MATLAB and Aspen Plus were used to solve a transport-kinetics model and examine thermodynamics limits and kinetics rates respectively. All of the material balance and modeling results were combined to determine the effect of SPL addition on reducing fuel consumption and emissions in cement production.

3. Results and Discussion

3.1 Burnability and Fluoride Flux Effects

The burnability test was conducted at the cement plant as per the standard operating practice at five different temperatures and seven SPL levels in the raw meal [11]. The results are shown in Figure 1.

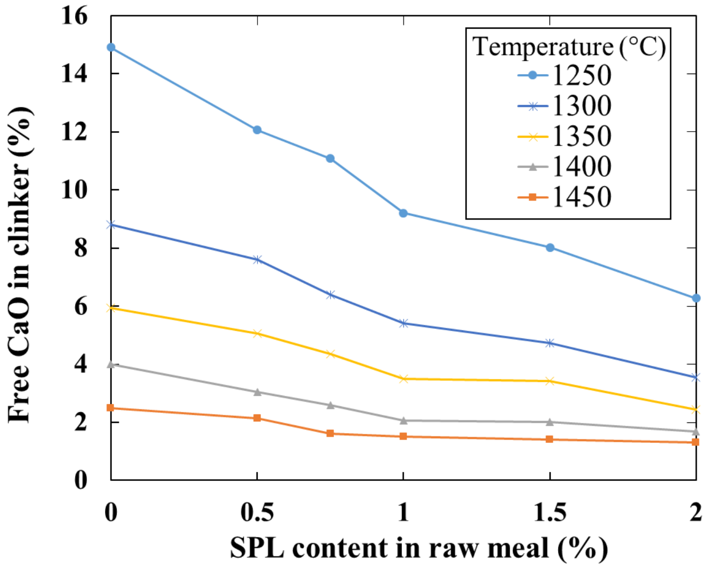


Figure 1. Burnability test: Free CaO in clinker for different raw meal SPL % at various firing temperatures.

An inverse correlation was observed between the firing temperature and the level of free lime (CaO) in the clinker. As the temperature increases from 1250 to 1450 °C, the free CaO content decreases at all SPL levels in raw meal. Furthermore, as the SPL concentration in the raw meal is increased from 0 to 2 %, the free CaO in the clinker decreases substantially through fluoride flux effects induced by the fluoride content in SPL [7 – 8]. This decrease in free CaO with increasing SPL is much more pronounced at lower temperatures than at higher temperatures.

A surface plot of the results is shown in Figure 2. The experiment conducted at 1450 °C, with 0 % SPL resulting in 2.5 % free CaO in the clinker, was taken as the control case for adequate clinker quality. This is slightly different from free CaO observed during actual production (1 – 2 %). The difference arises from the limitations of burnability apparatus to fully replicate the actual process. Therefore, a free CaO % of 2.5 is taken as the threshold to analyze the results of burnability test. To produce cement with adequate strength would require free CaO in the clinker to be below this threshold, which is depicted by a translucent plane in Figure 2. This can be achieved either with high kiln temperatures or the introduction of SPL into the raw meal.

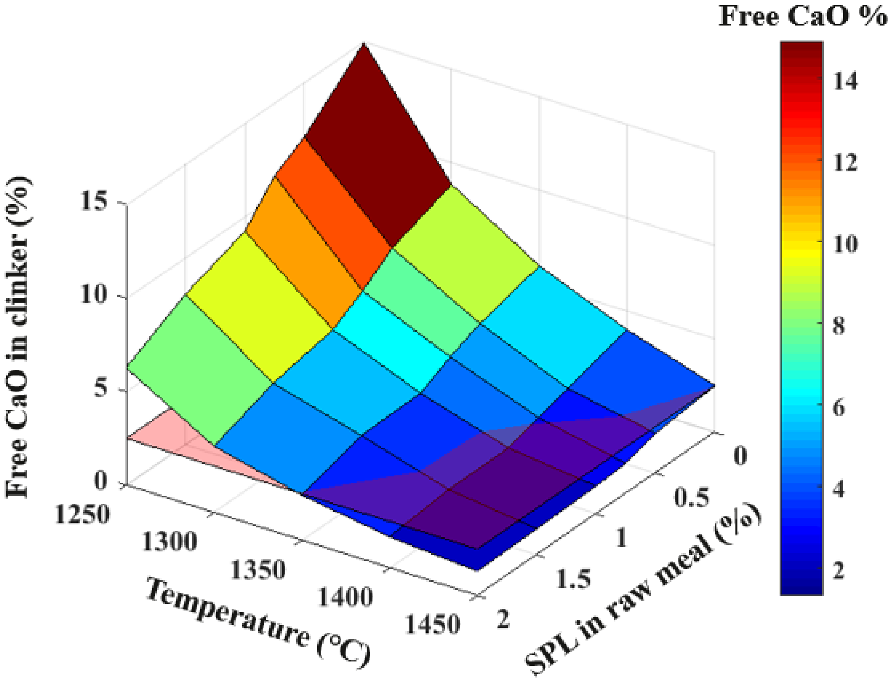


Figure 2. Burnability test: Effect of temperature and SPL addition on free CaO % in clinker.

An alternate representation of the surface plot (Figure 2) is shown in Figure 3 as a contour plot. The contour lines and their corresponding values represent the free CaO content in the clinker. Figure 3 illustrates that if the process begins at the control case of 1450 °C and 0 % SPL, holding the free CaO content in the clinker constant at 2.5 %, an addition of 0.6 % SPL (currently adopted by the cement facility) can lead to a 30 °C decrease in required temperature. Furthermore, the required temperature in the kiln decreases more if more SPL is added. Hence, the burnability test results demonstrate the potential for significant kiln temperature reduction as a result of SPL (and thus fluoride) addition to the cement raw meal, which is around -50 °C/% SPL.

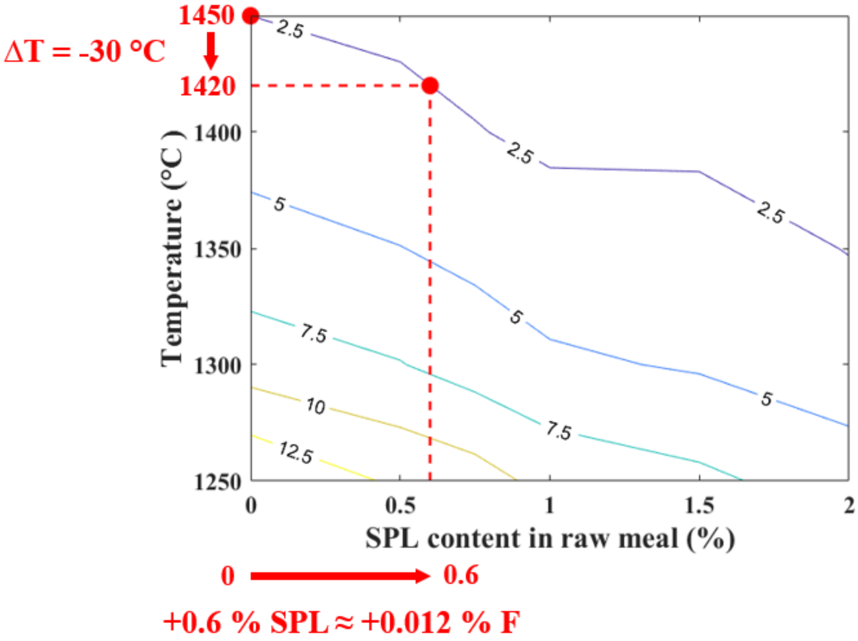


Figure 3. Burnability test: Contour plot of free CaO in clinker (%) as a function of temperature and SPL content in raw meal. The arrows show the effect of adopting SPL content of 0.6 % in raw meal vs. no SPL addition in this cement facility.

3.2 Fuel Consumption

There are two ways SPL can reduce fuel consumption. First, SPL contains carbon, which burns at high temperatures to release heat. The additional heat provided by SPL means less coal is needed as a fuel to provide heat to the process. Using SPL composition data and calorific values determined by the cement plant, and assuming 0.6 % of the raw meal is SPL and other components in the SPL do not change the reaction energy (i.e. the metal oxides are of the same energy as the other raw materials SPL displaces), the heat released by SPL carbon oxidation is 1.63 MJ/h for this cement plant producing 347 $t_{clinker}$/h. This corresponds to a reduction in heat requirement of 4.70 kJ/$t_{clinker}$. Assuming the heating efficiency is the same for coal combustion and SPL carbon decomposition, the corresponding coal reduction for 0.6 % SPL in feed is 1.85 kg coal/$t_{clinker}$. Thus, coal reduction by the presence of SPL carbon is approximately 3.07 kg coal/$t_{clinker}$ per % SPL in raw meal.

Second, there is a relationship between the process temperature in the kiln and the amount of fuel required. Adding SPL increases the amount of fluoride in the raw meal, decreasing the temperature requirement as evident in the burnability test. This in turn lowers the coal requirement. Assuming a linear relationship between temperature and coal consumption around the operation regime, the reduction in coal consumption is approximately 20 kg coal/h per °C. From the burnability test's result of -50 °C/% SPL for a given free lime content, this translates to a reduction of 2.87 kg coal/$t_{clinker}$ per % SPL in raw meal. Thus, the total effect of SPL on coal usage is -5.93 kg coal/$t_{clinker}$ per % SPL, or a net CO_2 emission reduction of 8.8 kg/$t_{clinker}$ per % SPL in raw meal.

3.3 NO_x

The cement production process produces significant NO_x emissions due to its high operating temperature and use of nitrogen (N)-containing fuel. NO_x primarily consists of NO and NO_2, with NO being the dominant species in cement production since it contributes to > 90 % of flue gas

NO_x [12]. Thus, this study focuses on NO formation to determine NO_x emissions, as NO_2 is formed mainly through the oxidation of NO by O_2. NO_x can be classified into two major categories based on its source of production: fuel NO_x, where nitrogen in the fuel or raw material is converted into NO through oxidation with O_2, and thermal NO_x, where high process temperatures of the combustion air cause its N_2's N-N triple bonds to break more easily to form NO [13].

Fuel NO_x

The oxidizing (fuel-lean) condition in the kiln and calciner indicates that a significant amount of nitrogen in the fuel (fuel-N) is likely to be oxidized to form NO [14]. One study indicates that approximately 60 % of fuel-N is converted to NO_x, but this depends highly on oxygen levels and temperature profiles in the flame [12]. The complex kinetics of fuel combustion and fuel-N formation makes it hard to predict the conversion of fuel-N to NO_x theoretically [13], but from the mass balance sheets of the cement production process, the combustion oxygen to carbon ratio is less than 1.3 (mol/mol). Furthermore, the fuel used in this plant, bituminous coal, typically results in less NO_x emissions compared to other types of coal [15 – 16]. Using this information, the conversions of fuel-N to fuel NO_x were estimated to be 32 % (kiln, higher temperature) and 24 % (calciner, lower temperature). Due to the reduced coal consumption and lower nitrogen content of SPL compared to coal, the amount of fuel-N entering the process decreases. The corresponding reduction in fuel NO_x was determined to be 571 mol/h or 75.7 $g/t_{clinker}$ per % SPL in raw meal, or approximately 35 ppm_v NO_x reduction (5.8 %) per % SPL in raw meal from the stack.

Thermal NO_x

Thermal NO_x production, which is highly temperature dependent, is also expected to decrease with the addition of SPL since the fluoride flux effects reduce the kiln operation temperature. To determine the effect of temperature reduction on thermal NO_x emissions, a kinetic model was used to estimate thermal NO_x production at various kiln temperatures. The model was developed only for the kiln because thermal NO_x production is only significant at temperatures higher than 1200 °C, which occurs only in the kiln [13]. Using a material balance model and extended Zeldovich mechanisms that describe NO formation kinetics, along with process information to estimate the temperature, pressure, and flow profiles within the kiln, the amount of thermal NO_x exiting the kiln was calculated using MATLAB. Figure 4 shows the predictions of the thermal NO_x model. NO is produced mainly at the highest temperature region of the kiln (at above ~1300 °C), and production decreases as oxygen level drops and combustion gases dilute the mixture as they move towards the kiln exit.

The combustion zone temperature was varied between 1350 and 1650 °C to determine how the temperature reduction via fluoride flux effect can affect thermal NO_x emissions (Figure 5). The results indicate that thermal NO emissions are highly temperature dependent, which is supported by literature [12 – 13]. In the cement plant of interest, the kiln operates at a relatively low temperature (combustion zone temperature reaches around 1450 °C), thus the kiln outlet thermal NO_x concentration is low at around 14.1 ppm_v. For 0.6 % SPL addition, which corresponds to 30°C reduction in flame temperature to 1420 °C, the thermal NO_x concentration exiting the kiln will only decrease by 6.9 ppm_v to 7.2 ppm_v. Overall, the emission reduction in thermal NO_x is approximately 8.6 $g/t_{clinker}$ per % SPL in raw meal in this cement plant's operating regime. This reduction is less than 0.4 % of total NO_x through the stack, indicating that temperature reduction has a relatively small effect on reducing total NO_x emissions through the thermal NO_x pathway. This is supported by a study by Haus, where fuel NO_x was found to be 70 – 100 % of the total NO_x emissions for kilns using coal as a fuel [17]. However, for cement manufacturing plants with initially high kiln combustion zone temperatures, an equivalent addition of SPL that allows for lower kiln operating temperature will yield a substantial amount of thermal NO_x reduction. Thus, the potential for SPL to reduce NO_x produced in the kiln is highly dependent on the kiln process temperature.

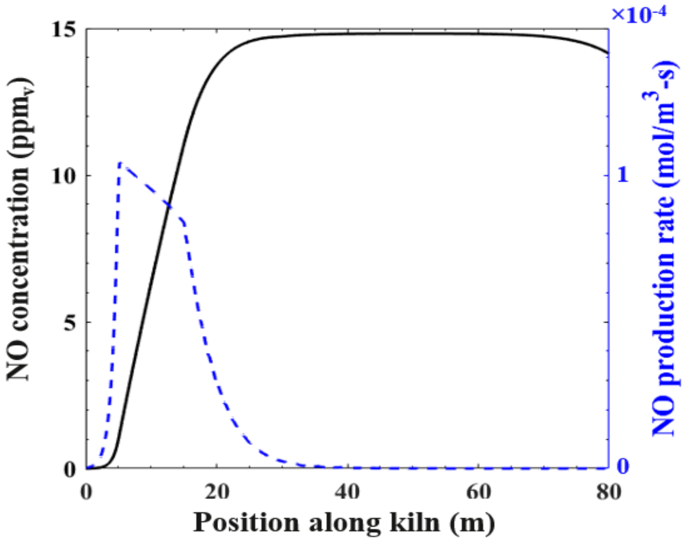


Figure 4. NO concentration and production rate profiles across the kiln for combustion zone temperature of 1450 °C. The gas inlet (clinker outlet) is on the left at position 0.

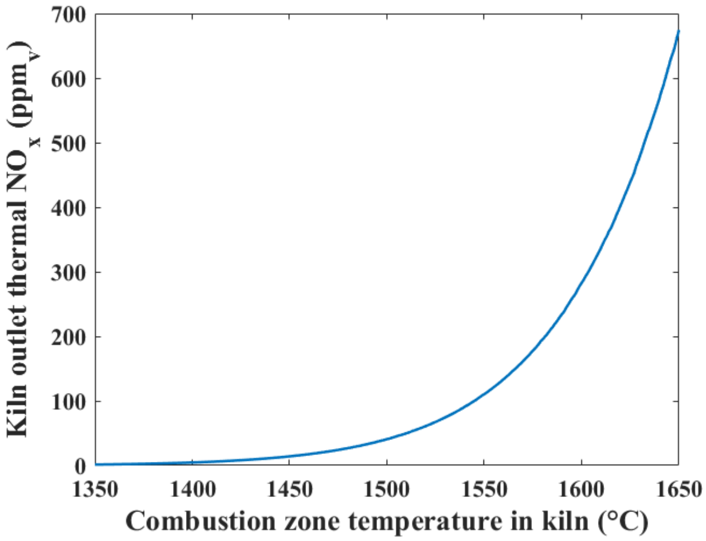


Figure 5. Dependence of thermal NO_x emissions on combustion zone temperature.

Cyanide Effect on NO_x

Cyanide is present in SPL mainly in the form of sodium cyanide (NaCN) and to some extent as metal complexed cyanides, and is formed inside the pot during the high temperatures and high current electrolysis in aluminium smelting [18]. Because of its toxicity, handling of cyanide is a challenge and much efforts have been spent on reducing cyanide formation or destroying cyanide for the aluminium manufacturing wastes [19 – 20]. The use of SPL in cement production is hypothesized to destroy the cyanide. Furthermore, cyanide-containing compounds in SPL have the potential to scrub NO_x but also produce NO_x [9].

Cyanide conversion or scrubbing reactions follow two major pathways – the HCN or NH_3 routes (Table). This study focuses on the major cyanide species, NaCN, in SPL. At the introductory point (SPL storage bin), there is no moisture. In the subsequent raw material handling processes, including the conveyor belt, mixer, and raw mill grinder, moisture could enter the SPL to trigger conversion reaction. The pH of the raw material mix for 0.6 % SPL is 10.6, so HCN production is thermodynamically limited. The basic decomposition reactions are limited by slow kinetics at this low temperature as confirmed by kinetics calculations performed using Aspen Plus. At the elevated temperature in the raw meal silo at 65 – 70 °C, NaCN conversion into ammonia and nitrogen gases is estimated to be significant (~25 %). The remaining solid NaCN enters the preheater and into the calciner to undergo heterogeneous reactions. At the preheater exhaust gas lines and raw mill, ammonia scrubbing (non-catalytic) is ineffective due to the low temperatures of around 65 – 250 °C, suggesting that there would be limited NO_x scrubbing due to the slow kinetics [21].

Table 1. NaCN Formation and Conversion (Scrubbing) Reactions [20]

Pathways	Formation Reaction	Conversion Routes
HCN	**"Acidic" (pH < 10)**	1. $HCN + O_2 \rightarrow NO$ + Products
	$NaCN + H_2O \rightarrow HCN + NaOH$	2. $HCN + NO \rightarrow N_2$ + Products
NH_3	**Basic (pH > 10)**	
	1. $NaCN + 2\ H_2O \rightarrow NH_3 + HCOONa$	1. $NH_3 + O_2 \rightarrow NO$ + Products
	2. $NaCN + 3\ H_2O \rightarrow CO_2 + 0.5\ N_2 + NaOH + H_2$	2. $NH_3 + NO \rightarrow N_2$ + Products

From mass balance, at the low SPL addition of 0.6 % in the raw meal, the maximum impact that cyanide can have on NO_x emissions is 0.08 %, which suggests cyanide scrubbing of or conversion into NO_x is negligible in cement manufacturing facilities.

3.4 Toxic Substance Destruction

SPL contains two major toxic substances: cyanide (CN) and fluoride (F). In general, fluoride is present in both carbon and refractory layers at around 1 - 2 wt % [25]. CN content in SPL is low and also varies across cuts, though on average CN is around 60 ppm by weight [18].

Fluoride typically reacts with the metal cations and is fixed in the final clinker product, whereas all CN is destroyed at the high temperatures of cement production [3],[4].

EGA Laboratory analysis of final clinker composition found leachable fluoride remained below 0.003 % for clinker samples with and without SPL, whereas total fluoride concentration increased from 0.030 % for clinker sample without SPL to 0.053 % for clinker sample with SPL, confirming that fluoride is fixed in the clinker product as non-leachable fluoride. Laboratory analysis for cyanide content in the clinker samples could not be completed due to laboratory instrument limitation.

3.5 Limits to SPL Addition

From the information presented above, the overall trend for cement manufacturing is that higher levels of SPL addition are beneficial primarily due to reduced temperatures and fuel consumption. However, there are several factors that place hard upper limits on SPL addition to the raw meal.

The first factor is the total alkali limit in the clinker product. High alkalinity in the clinker leads to concrete strength and degradation issues, and is stipulated by ASTM standards as 0.6 % total alkali in cement [22]. SPL contains around 20 % total alkalis compared to the 0.5 % in the raw meal used by the cement plant [23]. If the raw meal to clinker factor, defined as the weight ratio of raw meal to clinker product, is 1.6, and the raw meal without SPL does not contain any alkalis, then the maximum SPL addition to the raw meal, based on upper limits on clinker alkali content provided in ASTM guidelines, is 1.93 %. Since limestone and other additives do include alkalis, the maximum SPL addition will be much less than that figure. Our partner cement plant is currently adhering to BS EN cement standards which have no total alkali limit. However, due to market demands they are limiting their SPL addition to 0.75 % of raw meal. Nonetheless, it should be noted that SPL addition could yield operational benefits related to SO_3 removal as its alkali-containing compounds (such as Na_2O and K_2O) balance SO_3 off-gas production in the end of the calciner and at the beginning of the kiln. SPL's alkali content lower the boiling point of SO_3 and reacts with SO_x to form alkali sulphates [24], which are observed to reduce maintenance costs required to dislodge solid SO_3 build-up in the calciner section.

Another issue that limits SPL addition in cement production is the need to stay within targets for three parameters – the lime saturation factor (LSF), silica modulus (SM), and alumina modulus (AM). LSF is the ratio between the actual quantity of lime to the theoretical quantity of lime required by the other main oxides in the raw meal, SM is the weight ratio of silica to the summation of alumina and ferric oxide in the raw meal, and AM is the weight ratio of alumina to ferric oxide in the raw meal [10], An LSF greater than 100 will cause free CaO to remain in the clinker. Using established mass-balance algorithms, when SPL is added, the addition of other raw material components such as limestone, shale, sand, and copper slag were adjusted to maintain the target LSF, SM, and AM. Based on the laboratory experiments, high SPL addition of 5 % fails to achieve adequate LSF values for the raw meal, and this presents another upper limit for SPL addition.

The third factor that bounds the quantity of SPL addition is a maximum fluoride content in the clinker. From literature and discussions with our cement partner, this limit was identified to be 0.5 % fluoride in clinker to maintain cement quality [10]. Analysis of SPL showed a maximum fluoride content of 2 % [25]. Using the 1.6 raw meal to clinker factor, this restricts the SPL addition to raw meal to 15 % with respect to fluoride limits.

A final reason that SPL addition may be limited is due to potential issues with grinding of raw meal with high SPL content. SPL is significantly harder than limestone or the other additives and consequently requires much more energy to grind. In addition, the reliability and operations of the raw mill equipment may be affected. It is not possible to quantify the limit on SPL addition due to grinding currently as this will depend on the specific raw mill and process.

Table summarizes the factors that may limit SPL addition in cement production.

Table 2. Limits on SPL Addition in Cement Production.

	This Cement Plant	Total Alkali in Clinker	LSF	Maximum F in Clinker	Grinding Restrictions
Upper Limit of SPL in Raw Meal (%)	0.75	1.93	5	15	-

3.6 Cement Production Summary

Figure 6 summarizes the effect of SPL on reducing coal consumption, CO_2, and NO_x emissions from the cement production process with 0.6 % SPL in the raw meal.

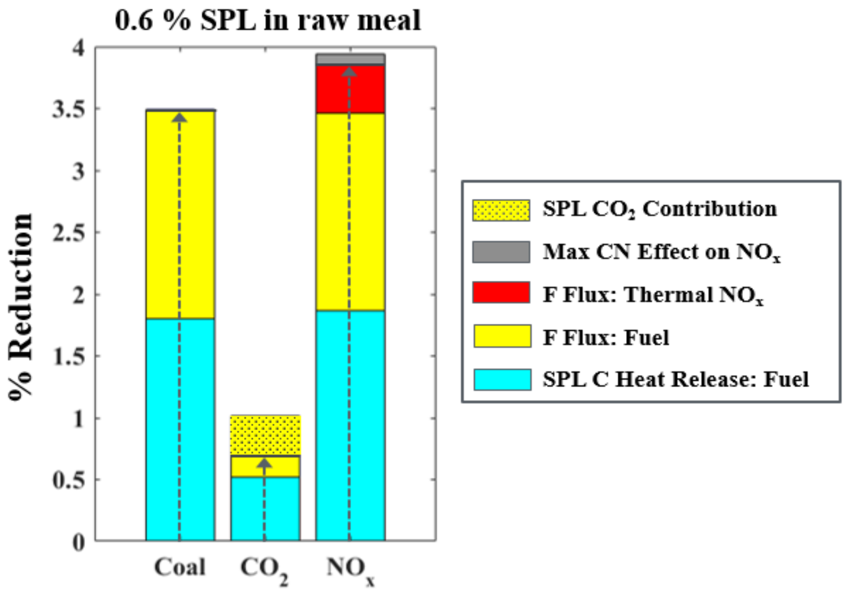


Figure 6. Summary of SPL addition's effect on cement production on fuel consumption, CO_2 and NO_x emissions. The arrow indicates the net reduction.

Using 0.6 % SPL in raw meal, the cement manufacturing facility is able to reduce coal consumption around 3.5 %. There are equal contributions to this reduction from the heating value of carbon in SPL and the fluoride flux effect that lowers the required kiln temperature. The same two factors are able to reduce CO_2 emissions by 1 %. This reduction is less than the coal reduction because around 70 % of the CO_2 emission comes from limestone calcination, and fuel CO_2 emissions contribute to only ~30 %. However, due to the carbon content in SPL, additional CO_2 is released. This culminates in a total CO_2 reduction of around 0.65 %. Finally, using 0.6 % SPL in raw meal, NO_x emissions are expected to drop 3.8 %. There are contributions due to reductions in nitrogen from coal and fluoride flux effects leading to lower fuel and thermal NO_x generation.

3.7 Overall Footprint Analysis

To investigate the impact of SPL addition on the power consumption and emissions (CO_2 and NO_x) for a cement manufacturing plant, this paper considered our partner cement plant's case study. The overall process from sourcing raw materials to producing the clinker was compared for two cases, one using 0 % SPL and the other using 0.6 % SPL. Changes in raw material usage (primarily limestone and shale) and coal consumption due to SPL addition were translated to changes in power consumption and emissions related to mining, transportation, and crushing of these materials. Crushing of SPL and transportation to the cement plant in Ras Al Khaimah, UAE were also included in the analysis. Similarly, impacts on power consumption and emissions from the cement process were analyzed. The overall emissions due to generation of the power consumed in the process are reported. Except SPL crushing which uses electricity generated using diesel, all other electricity is produced using natural gas.

In addition to the direct effects on fuel consumption and CO_2 and NO_x emissions shown in section 3.5, the power consumption also changes in cement production. Due to the different grindability of SPL compared to traditional cement raw materials, electricity usage of the raw mill is affected on addition of SPL. Raw mill power consumption data for varying amounts of SPL, from 0 to 5 %, was obtained as a result of preparation of raw meal for the burnability tests. For 0.6 % SPL, raw mill power was approximately 2 % higher compared to 0 % SPL. In addition, the total air flow rate required in the kiln is also reduced as a result of reduction in the coal requirement. For 0.6 % SPL addition, taking into account the 3.5 % coal reduction and the air required for the combustion of carbon in SPL, the total air flow rate required in the kiln is reduced by 2.2 % from the base value, and the reduction in power consumption can be obtained through the fan characteristic curve provided by our partner.

3.7.1 Raw Materials

Using 0.6 % SPL in raw meal reduces coal consumption by around 3.5 %, increases limestone requirement by 1 %, and decreases shale requirement by 17.4 % from their base values. Changes in electricity usage and emissions from raw material and coal sourcing can be considered under three main activities: mining, transportation, and crushing. Data for power, emission, distance, etc. were obtained from various sources and were used to calculate or estimate electricity consumption and emissions [26 – 36].

The cement facility sources its coal from mines in South Africa and Mozambique. Considering all mining related activities, on average, coal mining produces 440 kg CO_2 eq/ tonne of coal mined [26]. This mined coal is then shipped from South Africa to UAE, a distance of ~8000 km, leading to considerable CO_2 and NO_x emissions [27]. Finally, crushing of the coal before introducing it into the kiln also consumes electricity.

The limestone required in the process is sourced from mines located adjacent to the cement plant. The limestone is mined using explosives that result in emissions. Electricity is consumed when the limestone is crushed at the mine and transported to the cement plant via conveyor belts. Emissions from trucks used to transport limestone to the crusher are neglected due to the very short distances involved.

The shale required for the process is sourced from within a 50 km radius of the cement plant and is mined and crushed in a way similar to limestone. Hence estimates from limestone mining are used for shale. Emissions from transporting shale over 50 km are considered.

The SPL from EGA is crushed at a third-party crushing facility which consumes electricity. Emissions from transporting this SPL from EGA to our partner cement plant, an average distance of 200 km, is included in the analysis.

3.7.2 Overall Changes in Power Consumption and Emissions

The power consumption and emissions from raw materials sourcing and cement process described above were combined to determine the overall footprint of adding 0.6 % SPL to raw meal. The percentage change in electricity and emissions from their base values for 0 % SPL addition were calculated. Electricity requirement increased by 1.3 %, CO_2 emissions decreased by 0.72 %, and NO_x emissions decreased by 3.7 %. This corresponds to an overall increase in 160 kW of electricity, 2300 kg/h decrease in CO_2, and 19 kg/h decrease in NO_x from the base case values for 0 % SPL for this cement plant producing 347 $t_{clinker}$/h. The CO_2 emission reduction is significantly higher than the CO_2 that would be produced from the increase in electricity requirement [37]. The following figures show the % breakdown of each contribution.

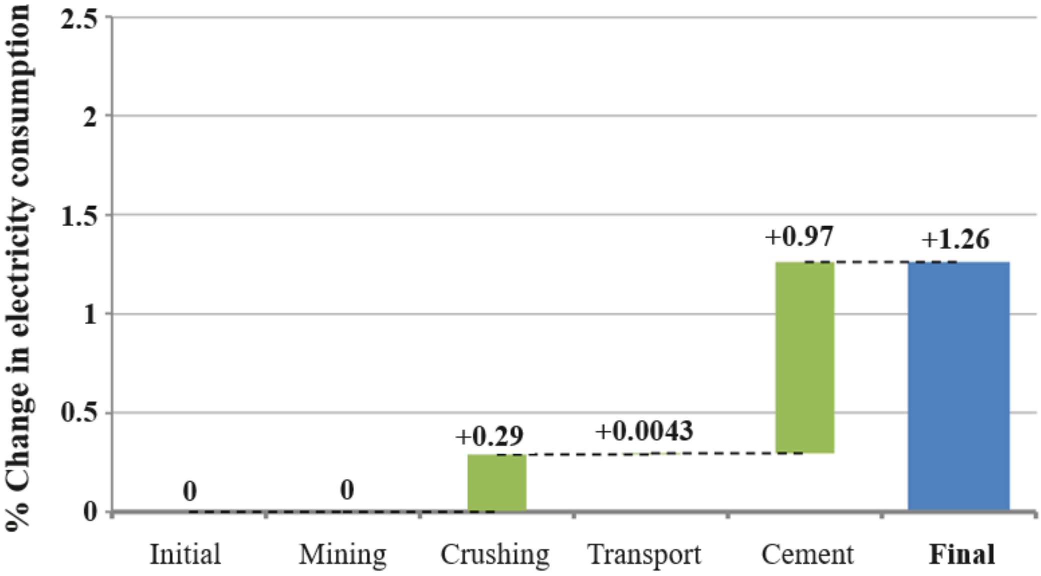


Figure 7. Percentage change in electricity from base case of 0 % SPL.

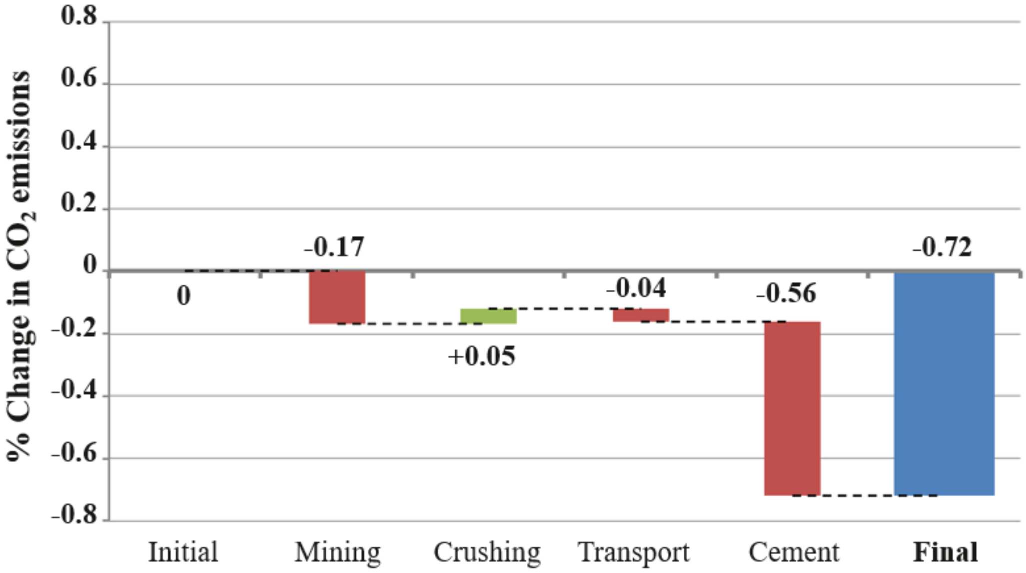


Figure 8. Percentage change in CO_2 emissions from base case of 0 % SPL.

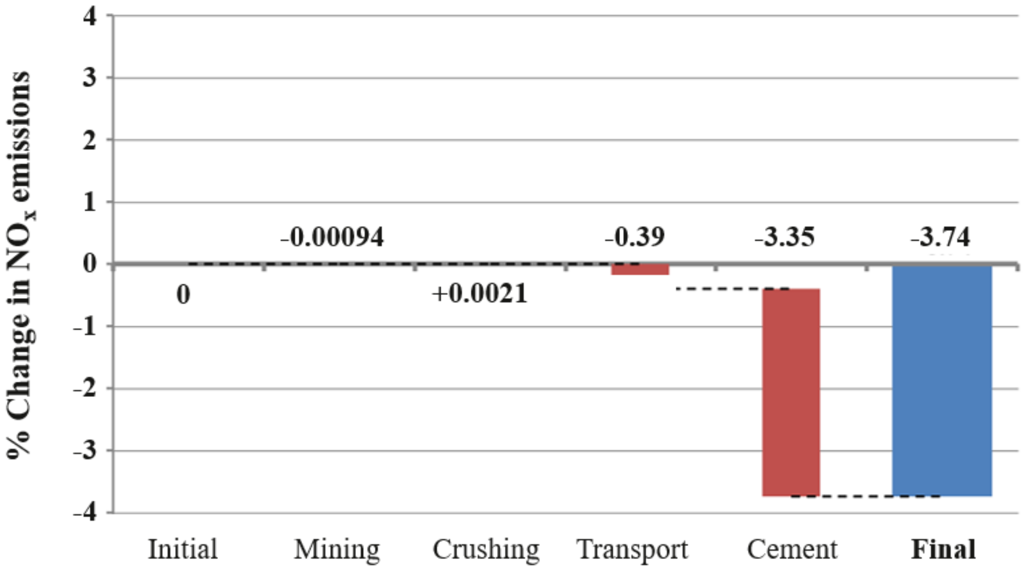


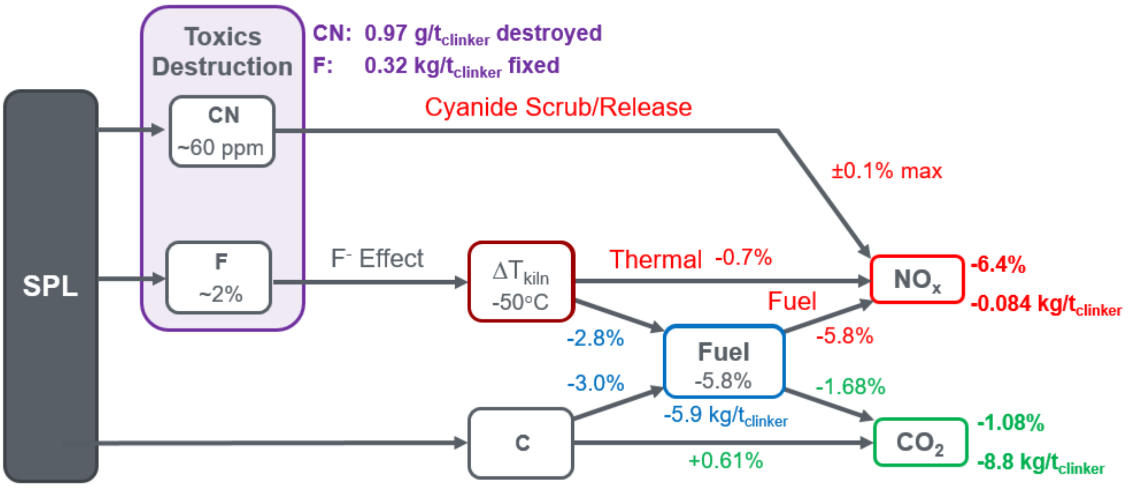
Figure 9. Percentage change in NO_x emissions from base case of 0 % SPL.

4. Conclusions

This paper presents a comprehensive assessment of the environmental effects of using spent pot lining, a waste generated during pot line replacement in aluminum industry, as an alternative raw material (ARM) in cement production. The case study examines the benefits realized in the cement plant by substituting existing raw materials with SPL, including changes in fuel consumption, CO_2 and NO_x emissions, and the fate of toxic materials within SPL.

Burnability tests results indicate that SPL usage can reduce the maximum kiln temperatures by around 50 °C per % SPL addition in the raw meal through the fluoride fluxing effect enabled by the fluoride in SPL. The lower kiln temperature leads to lower thermal NO_x production and fuel consumption, which in turn result in lower CO_2 and fuel NO_x emissions. For a cement production facility with 0.6 % SPL addition, this translates to a 3.5, 0.65, and 3.8 % reduction in coal consumption, CO_2 emissions, and NO_x emissions, respectively. On a 1 % SPL addition basis, this corresponds to decreases of 5.9 kg coal/$t_{clinker}$ (5.8 %), 8.8 kg $CO_2/t_{clinker}$ (1.08 %), and 0.084 kg $NO_x/t_{clinker}$ (6.4 %) per % SPL in raw meal. Material balance and kinetic modeling of NO_x emissions suggest that NO_x emission reduction occurs mainly through the fuel NO_x, not the thermal NO_x, pathway for kilns operating with combustion zone temperatures below ~1500 °C. Complete destruction and fixation of toxic compounds such as cyanide and fluoride, introduced by SPL into the cement production line, are expected to take place based on the probable reactions of cyanide in its pathway and the fixing of fluoride in the clinker.

Overall, the study results illustrate that SPL utilization as an alternative raw material in cement production can yield environmental benefits to the cement production plant – emission reduction in CO_2 and NO_x – on top of the monetary benefits which include savings in the form of fuel and raw material. Furthermore, the aluminium industry can also benefit from this collaboration, since the waste disposal of SPL has been a challenge for years. The repurposing of SPL in cement production can ultimately facilitate cross-industrial collaboration and foster further development of a circular economy to create a sustainable society.



* $t_{clinker}$ = clinker production in tonnes

Figure 10. Summary of the environmental impact of SPL addition on cement production within the cement facility. All values are on a per % SPL in raw meal basis.

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