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Abstract

The present study aims to find the maximum possible replacement of coal by combined feeding of plastic waste and solid hazardous waste mixed with wood chips (SHW) in rotary kiln burners used in cement kiln systems. The coal replacement should be achieved without negative impacts on product quality, emissions or overall operation of the process. A full-scale experiment was carried out in the rotary kiln burner of a cement kiln by varying SHW and plastic waste feeding rates. Experimental results were analysed using fuel characteristics of coal, SHW and plastic waste. The results revealed that feeding 3 t/hr of SHW plus 2.5 t/hr of plastic waste was acceptable, although giving a slightly lower production rate. This waste feeding rate is equivalent to 52% of coal energy replacement in the main burner. The limiting factor is the free lime content of the clinker. A comparable result for the reduction in production rate could be found from a simulation using a mathematical model of the kiln. Results from the present study were also compared with results from two previous studies, in which SHW and meat and bone meal were the solid alternative fuels used.

Keywords: Mix of Plastic Waste and Solid Hazardous Waste, Full-scale Test, Mathematical Modelling, Free Lime

1. Introduction

Cement plants have been utilizing certain approved hazardous wastes as an alternative fuel since the 1970s. Since hazardous waste is a partly CO_2 neutral fuel, the replacement of coal by hazardous waste will reduce net carbon dioxide emissions to the atmosphere, while letting the manufacturer gain economic advantages by possibly earning CO_2 allowances under an Emissions Trading scheme (Europian Directive, 2003). However, lower flame temperature inside the cement kiln and quality issues of the product due to admission of a mix of solid hazardous waste and wood chips (SHW) into kiln burner in comparatively high rates have been described by the current authors in a previous study (Ariyaratne et al, 2013). The higher moisture content, lower calorific value and larger particle size of the alternative fuel has a significant effect on the combustion characteristics (Ariyaratne et al, 2013). Maxiumum 20% of coal energy replacement in the rotary kiln burner was recommended based on that study (Ariyaratne et al, 2013).

It could also be mentioned that, although not experienced in the particular SHW test mentioned above (Ariyaratne et al, 2013), the SHW particles are quite sticky and have a tendency of blocking the pipelines used for pneumatically conveying the alternative fuel into the burner. Hence, operating with SHW will require regular cleaning of the feeding system.

Admission of plastic waste in addition to SHW could provide an enhancement in coal energy replacement in kiln burner, both because the plastic waste has higher calorific value than SHW, and because the plastic particles may mechanically clean the pipeline and hence prevent blocking due to deposits of sticky SHW fragments.

Though the plastic waste substitution in cement kilns does not give a direct reduction in net CO_2 emissions (compared to biomass waste incineration with energy recovery), burning plastic waste in cement kilns is a well-proven waste management technique in the world (Al-Salem et al, 2009; Al-Salem et al, 2010; Patel et al, 2000; Briassoulis et al, 2012). The effect of plastic waste combustion on key process parameters and emissions in cement kilns were investigated by some authors (Tsiliyannis, 2012; Karstensen, 2008). Life cycle assessments for end-of-life treatments of post-consumer plastic wastes have been carried out by some researchers (Lazarevic et al, 2010; Chilton et al, 2010), whereas fuel production from waste plastic has been studied by others (Panda et al, 2010; United Nations Environment Programme, 2009). In still other studies, the possibility of energy recovery from electrical and electronic waste, basically composed of different plastic types and other constituents, in cement kilns has been investigated (Tange and Drohmann, 2005; Fink, 1999; Kang and Schoenung, 2005; Nnorom and Osibanjo, 2008; Ravi, 2012; Fisher et al, 2005). Furthermore; composition, thermal and other properties of different waste plastics can be found in (Martinho et al, 2012; Jiao et al, 2009; Fujino and Honda, 2009; Othman et al, 2008).

The main objective of the present study was to investigate the impact of mixing SHW with plastic waste, and to find the maximum possible replacement of coal by such a mixture, taking into account product quality, emissions and overall operation of the process.

A full-scale experiment was carried out in a cement plant which annually produces 1.3 million tons of cement. The bottleneck for using this fuel mix in the rotary kiln burner was investigated, and possible reasons were discussed by evaluating process and quality data as well as by comparing the physiochemical properties of the fuels. The optimum feed level was concluded for the investigated kiln system. The reduction in production rate due to a certain amount of coal replacement in kiln burner was verified through simulations using a mathematical model of the kiln. The results were also compared with a similar study on meat and bone meal (MBM) and on SHW previously carried out by the current authors (Ariyaratne et al, 2010; Ariyaratne et al, 2013).

2. Materials

The hazardous waste used in the test, is a mixture of organic solvents, paint, glue and many other organic hazardous waste types. This mixture is quite pasty and difficult to handle, and is therefore mixed with about 30 wt% of wood chips to improve handling properties, see Figure 1(a). The resulting mix, here abbreviated SHW, is a partly biogenic fuel (Ariyaratne et al, 2012). The plastic waste is a mixture of different types of plastics originated from industries and households, and it might contain packaging waste, electronic waste, etc, see Figure 1(b). The plastic mix can be regarded as fully fossil.

Figure 1: (a) Solid Hazardous Waste Mixed with Wood Chips (b) Plastic Waste

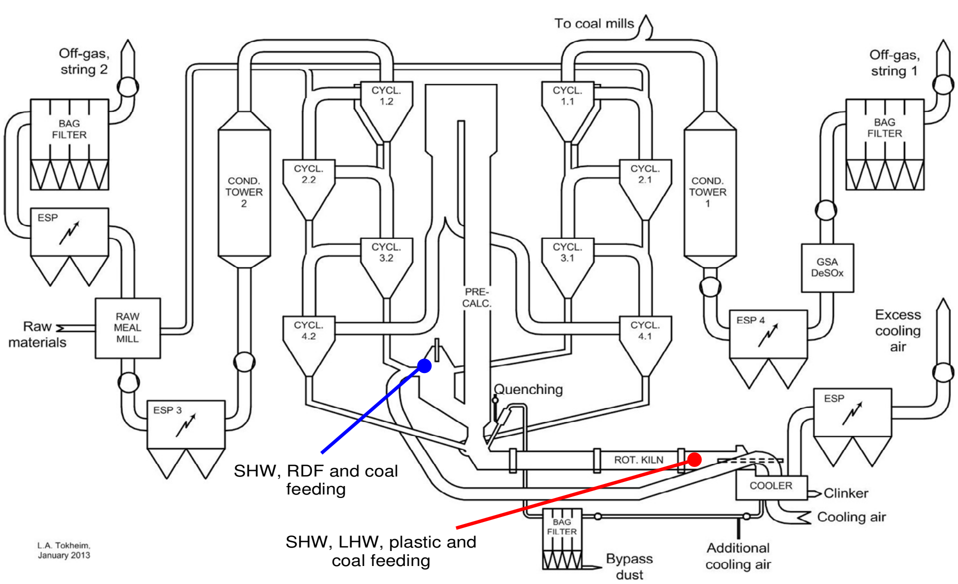
Coal, SHW and plastic waste were characterised through laboratory experiments, including determination of proximate analysis, heating value, bulk density and particle size distribution. The proximate analysis was carried out using a Las Navas Automatic Multiple Sample Thermogravimetric Analyzer TGA-2000 by applying different temperature steps up to 750 °C. The heating value was determined by an Ika Calorimeter System C5000. The bulk density was measured by weighing a known freely distributed volume. The particle size was analysed by mechanical sieving using a Retsch AS200 instrument. Additional chemical analyses of the fuels were available from the plant laboratory.

3. Full-Scale Test

A full-scale test was carried out in a modern 4-stage, 2-string precalciner cement kiln system at a Norwegian cement plant, see Figure 2. The plant had some experience in using SHW as a coal replacement in the rotary kiln burner, but virtually no experience in using plastic waste in this burner.

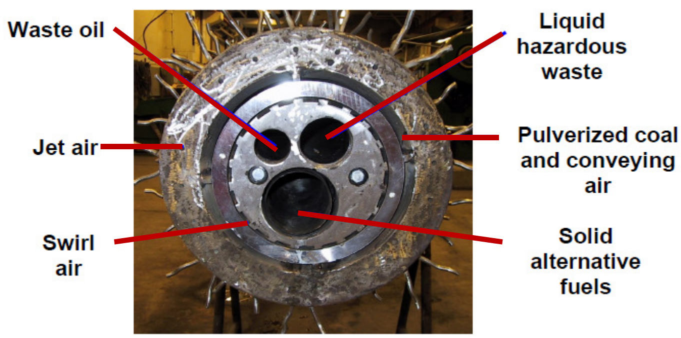
The kiln is 68 m long and 4.4 m in diameter. It is equipped with a modified KHD Pyrojet burner at the kiln outlet (where the hot clinker is discharged from the kiln), with three different tubular fuel inlets for solid and liquid alternative fuels and one annular inlet for coal, see Figure 3. The solid alternative fuels are fed into the kiln burner via a Pfister feeding system.

Figure 2: The Cement Kiln System (Tokheim, 2006)



The test was carried out for 16 hrs by varying the feeding rate of SHW and plastic waste in particular time intervals. In addition to coal, plastic waste and SHW, liquid hazardous waste (LHW) was fed to the rotary kiln burner at a constant rate of 1.5 t/hr. The lower heating value of LHW was around 17 MJ/kg. Ordinary portland cement (OPC) clinker was produced during the test period. The raw meal feed rate in steps 2 and 3 were around 225 t/hr but had to be reduced to 221 t/hr in step 4 due to lower kiln drive current (an indication of reduced temperature inside the kiln). There was a break (5 hours) in the test between steps 4 and 5 due to high CO concentration in the stack (Figure 7). The CO problem was caused by a waste combustion issue in precalciner and a mechanical problem in the coal mill, and was not related to the rotary kiln burner conditions. Step 5 was started with 215 t/hr of raw meal feeding and from this step onwards the raw meal feed rate was around 215 t/hr (Figure 5).

Figure 3: Rotary Kiln Burner Tip



The conditions in the precalciner and in the kiln were kept as stable as possible throughout the experiment. The raw material composition and feeding rate, the conventional (coal) and alternative fuel supply rates in the precalciner (refuse derived fuel (RDF) and SHW) and the bypass stream were all maintained at almost constant levels in order to keep the degree of calcination of hot meal, the thermal energy consumption and the circulation of alkalis, sulphur and chlorine (Tokheim, 1999) constant during the test. The total alternative fuel feeding in the precalciner was kept around 13 t/hr. The thermal energy consumption ratio between rotary kiln and precalciner was kept at 41:59. The feeding rate of SHW was increased in three steps from 1 t/hr to 3 t/hr, and in each step the plastic waste is supplied in two different feed rates (Table 1). The thermal energy consumption of the kiln was at an almost constant level. Simultaneously, material samples were collected and analyzed, and process data were collected.

3.1. Experimental Plan

Table 1 shows the experimental schedule and the thermal energy replacement totally by SHW, plastic waste and LHW in the rotary kiln burner. Step 1 and step 8 correspond to reference cases, i.e. only coal and LHW were fed. Solid fuel characteristics are given in Table 2.

Table 1: Experimental Schedule (Each Step is 2 Hours)

Step Number	Feeding Rate of SHW [t/hr]	Feeding Rate of Plastic Waste [t/hr]	Coal Feeding Rate [t/hr]	Coal Energy Substitution [%]
1	0.0	0.0	6.7	10.3
2	1.0	0.4	5.9	23.8
3	1.0	1.0	5.4	30.3
4	2.0	1.0	4.9	37.1
5	2.0	2.0	3.8	49.0
6	3.0	2.5	2.6	64.0
7	3.0	3.0	2.3	68.6
8	0.0	0.0	6.5	12.5

3.2. Data Collection

Process data (fuel and raw meal feed rates, emissions, Pfister feeder characteristics, bypass and cooler data, etc) were collected through a plant database system in one minute intervals during the whole experiment.

Kiln shell temperature data were collected from a CS210 temperature monitoring system. The system gives average circumference temperature at selected axial positions as a scan number. An in-house developed procedure was used to convert scan numbers into corresponding kiln lengths according to the scanners located along the kiln (Manjula, 2011). The 1hr spot measurements were collected from short term historical data of the system for the day of the experiment and the day after.

Raw meal was analysed for oxides and sulphur content, whereas precalcined meal was analysed for degree of calcination as well as sulphur and chloride contents; all in 2 hr time intervals. Key clinker properties were analysed in 1hr time intervals and averaged for each step for plotting purposes. The clinker samples were collected from the apron conveyor after the cooler. The oxides were analysed with a Philips PW 2404 x-ray spectrometer using the x-ray fluorescence (XRF) method, and the SO_3 content was analysed by means of an ELTRA CS 800 carbon-sulphur analyzer. The ethylglycol method was used for analysis of free lime (uncombined CaO) in the clinker.

4. Model

A previously developed mathematical model was used to simulate the kiln system (Ariyaratne et al, 2013 (1); Ariyaratne et al. 2013 (2)). The model was based on the steady state mass and energy balance of the rotary kiln as well as mass balance of the precalciner. The process parameters were taken from the full-scale cement plant described above. The model was used to investigate the reduction in clinker production rate when 3 t/hr of SHW and 2.5 t/hr of plastic waste are used as solid alternative fuels in rotary kiln burner. These maximum feed rates were bottlenecks found in the current full-scale test.

In the first step of the modeling, a mix of coal and solid alternative fuel (3 t/hr of SHW and 2.5 t/hr of plastic waste) was supplied to the main burner. This mass flow rate of alternative fuel replaced around 47% of the primary coal energy in the model. It should be noted that in the full-scale test, this energy replacement was around 52% when 3 t/hr of SHW and 2.5 t/hr of plastic waste were supplied. This discrepancy can be explained: First; in the model, the heating value of coal was kept similar to that of previous publications (Ariyaratne et al, 2013 (1); Ariyaratne et al. 2013 (2)) in order to keep consistency, but was not exactly similar to the heating value of the coal used in the real test. Second; in the real test, the total energy consumption at the kiln burner was not perfectly constant during a given step, but in the model it was assumed as a constant value.

In the second step, the energy input to the main burner was increased by increasing the coal flow rate of the mixture in order to obtain the same kiln gas temperature as in the coal reference case (in which only coal is supplied as primary fuel). Keeping the high temperature is crucial for maintaining the clinker mineral formation rate in the rotary kiln and hence maintaining the product quality. Increasing the fuel input however means that the clinker-specific fuel energy requirement in the main burner was increased.

The third and final step was to adjust the coal mass flow rate and the clinker production rate in order to obtain the same kiln gas temperature and the same volumetric flow rate of total exhaust gas from the precalciner as in the coal reference case. This was done in order to find the reduction in production rate due to replacement of part of the coal by an alternative fuel. The reason for keeping the total exhaust gas flow rate at the reference case level is that the major gas flow resistance is in the preheater and precalciner, and this resistance typically represents a bottleneck for the production capacity. The excess O_2 for the combustion in the calciner was kept equal to the value used in the rotary kiln. The clinker-specific energy supply to the precalciner was kept constant in both cases; 90% of that energy was provided via RDF and the rest through coal.

Basic analyses used for the model are shown in Table 2. Further information about the model is given in previous publications (Ariyaratne et al, 2013 (1); Ariyaratne et al. 2013 (2)).

Table 2: Ultimate Analysis of Different Fuels Used in the Model (as Received Basis)

Parameter	Unit	Coal	SHW	Plastic Waste	RDF
Net calorific value (NCV)	[MJ/kg]	28.30	15.00	25.10	18.20
C	[kg/kg]	0.729	0.339	0.587	0.431
H	[kg/kg]	0.039	0.050	0.057	0.062
O	[kg/kg]	0.056	0.118	0.118	0.304
S	[kg/kg]	0.014	0.011	0.000	0.004
N	[kg/kg]	0.017	0.006	0.028	0.007
Ash	[kg/kg]	0.136	0.176	0.093	0.121
Moisture	[kg/kg]	0.010	0.300	0.117	0.071

5. Results and Discussion

This section presents the results from laboratory and full-scale experiments as well as the results from the model simulation. First the fuel characteristics determined in the lab are given. Then impacts on the clinker quality, process and then on shell temperature are discussed. Finally, the reduction in production rate was compared with model simulation results.

5.1. Fuel Characterization

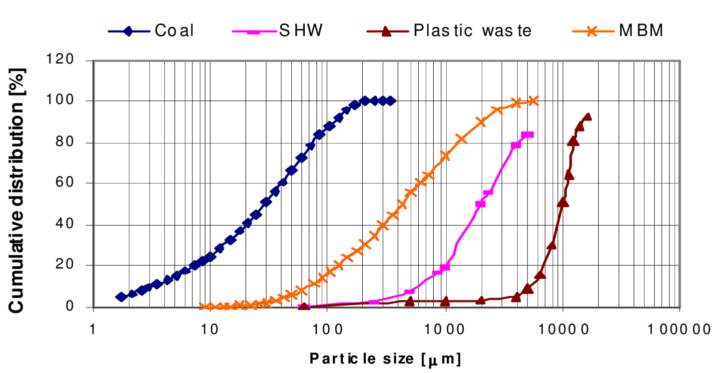
The analysed properties of coal, SHW and plastic waste are given in Table 3. It is observed that SHW has the highest moisture content, then comes the plastic waste. In contrast, the fixed carbon is extremely low in SHW and in plastic waste. However, the volatile content of both solid alternative fuels are significantly higher than that of coal. The bulk densities of both fuels are less than that of coal, which might give volumetric restrictions when feeding.

Table 3: Properties of Coal, SHW, Plastic Waste and MBM Used in the Full-scale Test (as Received Basis)

Property	Coal	SHW	Plastic waste	MBM
Moisture [wt. %]	1.7	30.0	11.7	4.0
Volatiles [wt. %]	27.5	51.4	77.8	60.8
Fixed carbon [wt. %]	51.4	1.0	0.6	8.0
Ash [wt. %]	19.4	17.6	9.9	27.2
Net calorific value [MJ/kg]	27.1	15.0	25.1	18.5
Freely settled density [kg/m^3]	640	310	480	720

The cumulative distributions of coal, SHW, plastic waste and MBM particle sizes are shown in Figure 4. The particle size will affect the burnout time of the particles in the kiln; this is further discussed later.

Figure 4: Cumulative Particle Size Distribution



5.2. Analyses of Raw Meal, Precalcined Meal and Clinker

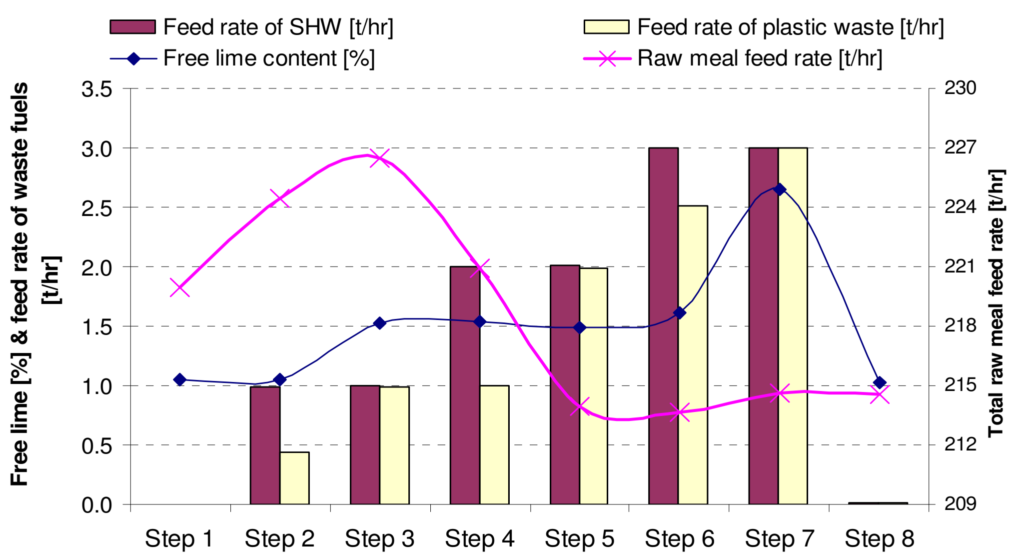
The variation in the measured raw meal properties during the test period was insignificant. The degree of calcination of the precalcined meal was around 95-98%. Similarly, the SO_3 content and the Cl content of the precalcined meal were 1.5-2.3 % and 1.1-1.5 %, respectively. These properties were not impacted by SHW feeding at the rotary kiln burner.

The main oxides in clinker were all at desirable levels to maintain an acceptable clinker quality throughout the experiment and appear not to be impacted by the feeding of solid alternative fuel feeding.

The main issue indicated is the increase in free lime content with increments of solid waste feeding (Figure 5). The free lime content is always higher than in the reference cases (steps 1 and 8), implying that there is a significant impact from solid waste feeding on the clinker quality. The deviations in raw meal feeding were described in section 3.

When the feeding of SHW is 3 t/hr and of plastic waste is 3 t/hr (step 7), the free lime content (2.7%) is higher than the maxium allowable concentration (2.5%). The high free lime content reveals improper burning of the raw meal and implies poorer quality of the clinker. Therefore, from the available information, it cannot be recommended to operate with more than 5.5 t/hr (3 t/hr SHW and 2.5 t/hr plastic waste) of total solid fuel burning at a raw meal feed rate of 214 t/hr, which is a slight decrease in production rate. This also illustrates that fine tuning is necessary when burning this type of fuel in the rotary kiln burner.

Figure 5: Free Lime Content of Clinker Variation according to Feeding Rate of Solid Waste Fuels



One possible reason for the increase in free lime content is reduced flame temperature: If the temperature is not sufficiently high, part of the CaO in the raw materials may not combine with other oxides, and the free lime level increases. Reduced flame temperatures could be due to the combined characteristics of the solid waste fuels. Both fuels have very high moisture content and very low fixed carbon content compared to coal (Table 3). Even if the heating value of plastic waste is comparable with that of the coal, the heating value of SHW is considerably lower, which causes a lower flame temperature. The larger particle size of the SHW and plastic waste (Figure 4) also contributes to that phenomenon, as larger particles increase the burnout time, which will most likely reduce the maximum flame temperature and hence the local heat flux from the flame to the material bed in the kiln. For a given percentage, the particle size of SHW is more than 50 times that of coal, whereas the particle size of plastic waste is more than 150 times that of coal. While the maximum size of the coal particles is around 200 μm, the SHW and plastic waste distribute to more than 5000 μm and 15000 μm, respectively. However, even if the burnout time of large particles is higher, this may be partly offset by a higher content of volatiles and comparatively lower content of ash in SHW and plastic waste (Table 3).

5.2.1. Comparison with Previous Tests

Similar types of tests were previously carried out by the current authors using MBM (Ariyaratne et al, 2010) and SHW (Ariyaratne et al, 2013) as the coal replacement fuel. Results from the present study can be compared with those findings.

The MBM test and the SHW test indicated that for long term operation, the alternative solid fuel feed rate should not exceed 5 t/hr and 3 t/hr, respectively, for a raw meal feeding of 220 t/hr. In the present study, for 214 t/hr of raw meal feeding, the authors recommend 5.5 t/hr feeding of SHW and plastic waste in the rotary kiln burner in order to achieve the desired clinker quality. This corresponds to 3 t/hr of SHW feeding and 2.5 t/hr of plastic waste feeding; see step 6 in Figure 5. The feeding rates of this mixture of solid waste fuel correspond to 52% primary energy substitution. The figure for the MBM and SHW tests are 39% and 20%, respectively, but with 2.8% higher production than in the present test.

Pure SHW has the lowest replacement potential, which can be explained by the low heating value, the low volatile content and the high moisture content of that fuel (Table 3). Adding plastic waste to the SHW will increase the possibility of primary energy substitution because of the high heating value, the high content of volatiles and the low moisture content in plastic. Indeed, plastic waste is not a CO_2 neutral fuel, so mixing plastic with SHW means that the alternative fuel mixture will have a lower biomass fraction than will pure SHW. But plastic will replace coal (another fossil material), and hence not contribute to increased CO_2 emissions in itself. Moreover, if addition of plastic is required to facilitate feeding of the partly CO_2-neutral SHW, then the use of plastic can indeed be justified as it can be seen as a prerequisite to achieve a net reduction in fuel-related CO_2 emissions.

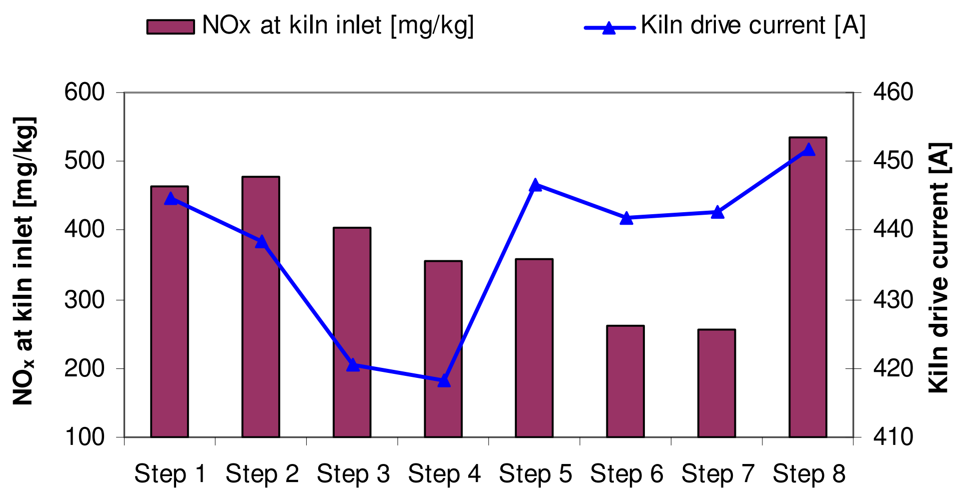
MBM gives almost the same feeding possibility as the SHW/plastic mix, but slightly higher production rate. This can be explained by the positive impact on the combustion characteristics following from the lowe moisture content, the relatively high volatiles content (Table 3) and the small particle size (Figure 4) of the MBM. For a given percentage, the particle size of SHW is four times that of MBM and plastic waste is 12 times that of MBM.

5.3. Process Data

It is observed in Figure 6 that the NO_x (sum of thermal NO_x and fuel NO_x) in the kiln dropped when feeding solid alternative fuels, in particular, in steps 6 and 7. This is a clear indication that the (maximum) temperature in the kiln dropped when solid waste fuels were fed (lower thermal NO_x formation).

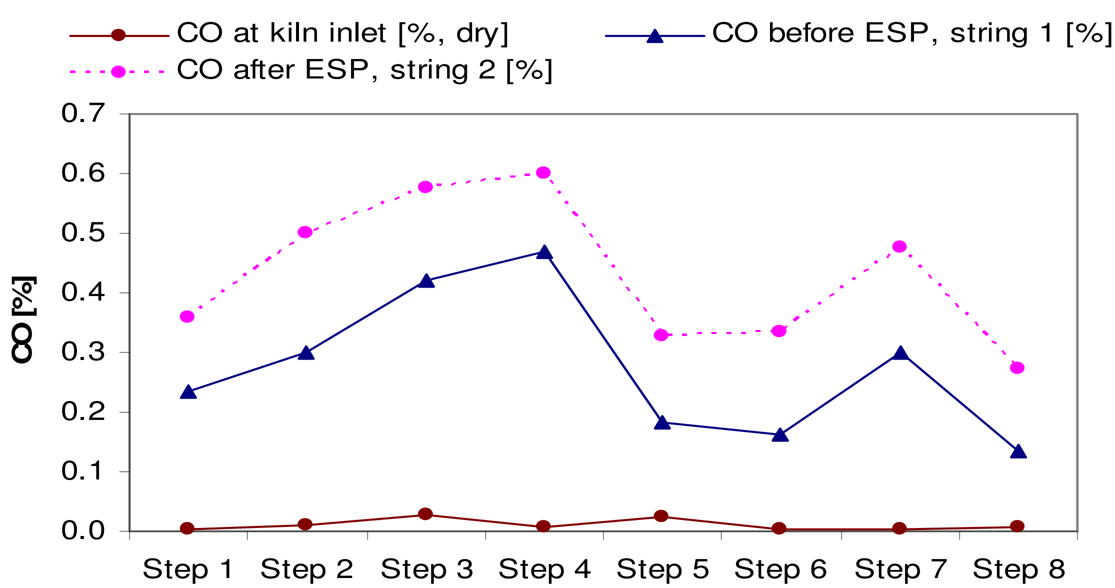
The kiln drive current (Figure 6) is in a typical range for smooth operation, i.e. 400-500 A for OPC clinker production. A drop in the kiln drive current would be an indication of reduced melt formation in the kiln, which would give a poorer clinker quality. The kiln drive current appears to be decreasing in steps 2-4, likely due to the increase in solid alternative fuel feeding, and then it increases due to a decrease in raw meal feeding. Figure 6 also suggests that the thermal NO_x formation in the kiln gets lower in particular when increments of SHW occur (steps 3-4 and 5-6), but not when plastic waste increments occur (steps 4-5 and 6-7). This is an indication of reduced flame temperature and hence a higher free lime content due to higher SHW feeding.

Figure 6: NO_x Concentrations and Kiln Drive Current



The O_2 concentration in the kiln inlet was kept rather high (around 6%), so the CO concentration in the kiln inlet was close to zero throughout the experiment (Figure 7). Also, it did not increase as a result of solid alternative fuel feeding.

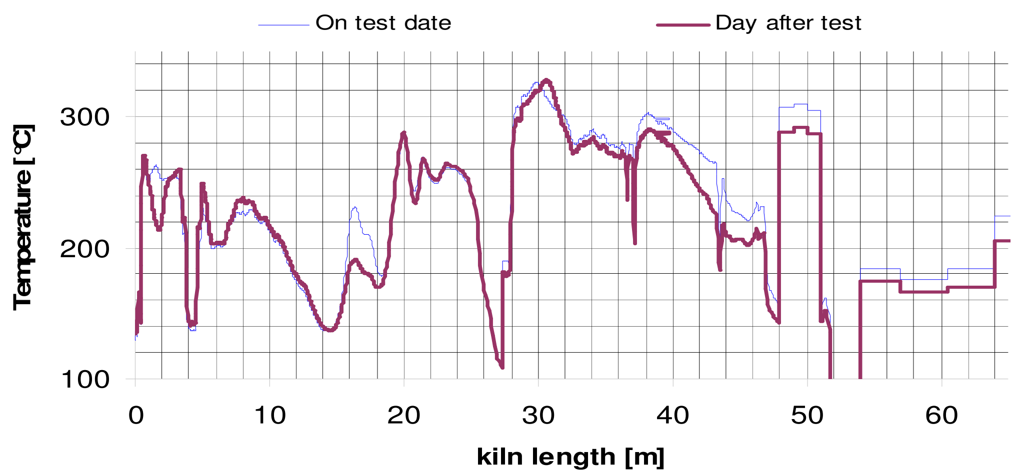
Figure 7: CO Content at the Kiln Inlet and in the Two Stacks



5.4. Shell Temperature

The 1hr spot measurements from the temperature monitoring system are used to calculate daily averages. These are plotted for the test date and for the day before the test date in order to identify any deviations from normal operation of the plant. The result is shown in Figure 8 (0 m corresponds to the kiln outlet). In the region close to the burner (16-18 m), the average shell temperature on the test date is 40 °C higher than on the day of normal operation. This could be interpreted as an indication of sudden heat release from plastic waste combustion which has a lower burnout time due to higher content of volatiles in the waste fuel.

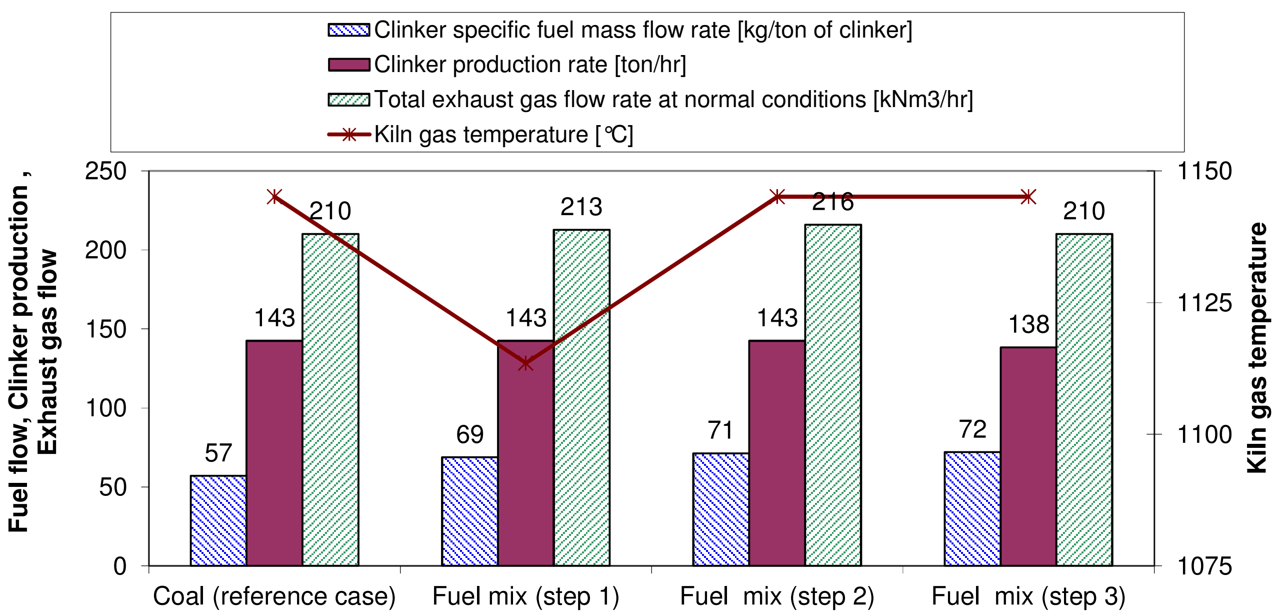
Figure 8: Average Kiln Shell Temperature Data for the Test Date and for the Day after Test



5.5. Results from Model Simulation

Figure 9 shows the main results from the simulation.

Figure 9: Fuel Mass Flow, Clinker Production Rate, Exhaust Gas Flow Rate and Gas Temperature for Fuel Mix Compared with the Coal Reference Case



The kiln gas temperature in step 1 is 31°C lower than in the reference case when 3 t/hr of SHW and 2.5 t/hr of plastic waste are used as primary fuels in addition to coal. The total exhaust gas flow rate at normal conditions is also quite higher in step 1. In step 2, the specific fuel consumption is increased to obtain the same kiln gas temperature as in the reference case (1145 °C). The clinker-specific energy consumption in the main burner is increased by 4.4% in this step. The air requirement for the combustion increases with the increase in fuel consumption, hence the kiln gas flow rate is further increased causing an increase in the total exhaust gas flow rate. The total exhaust gas flow rate is increased from 213 to 216 kNm^3/hr. In step 3, the total exhaust gas flow rate is the same as in the reference case (210 kNm^3/hr), however, the penalty is a reduced clinker production rate. Around 2.9% reduction in clinker production is calculated. In this case, the raw meal requirement is lower, hence the fuel energy requirement and CO_2 release due to calcination is lower in the precalciner, resulting in reduced exhaust gas from the precalciner, compensating for the increased exhaust gas from the kiln. (The sum of the two is equal to the total flow rate in the reference case.) This reduction in production rate (2.9%) is comparable with reduction in raw meal feed rate found from the full-scale test (2.7%) where 3 t/hr of SHW and 2.5 t/hr of plastic waste are fed to the main burner.

6. Conclusion

The test results demonstrate the possibility of significant replacement of coal by a mix of solid hazardous waste and wood chips (SHW) and plastic waste in the rotary kiln burner without negatively affecting product quality, emissions or overall operation. No significant impacts on emissions or kiln operation were observed, regardless of feeding rates of solid alternative fuels. The most important impact of that fuel feeding was on the free lime content of the clinker. Replacement of 52% of the coal energy in the rotary kiln burner (3 t/hr of SHW and 2.5 t/hr of plastic waste feeding) proved acceptable, however, the raw meal feed rate had to be reduced by 2.7%. This coal energy replacement of 52% in the present test is higher compared to 39% and 20% found in tests with meat and bone meal and SHW, respectively which were previously carried out. Different fuel characteristics can explain this difference. Results from a mathematical model simulation also gave comparable result for the reduction in production rate (2.9%) when 3 t/hr of SHW and 2.5 t/hr of plastic waste are fed to the rotary kiln burner.

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