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Optimum feeding rate of solid hazardous waste in a cement kiln burner

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Abstract

Solid hazardous waste mixed with wood chips (SHW) is a partly CO_2 neutral fuel, and hence is a good candidate for substituting fossil fuels like pulverized coal in rotary kiln burners used in cement kiln systems. SHW is used in several cement plants, but the optimum substitution rate has apparently not yet been fully investigated. The present study aims to find the maximum possible replacement of coal by SHW, without negatively affecting the product quality, emissions and overall operation of the process. A full-scale experiment was carried out in the rotary kiln burner of a cement plant by varying the SHW substitution rate from 0 to 3 t/hr. Clinker quality, emissions and other relevant operational data from the experiment were analysed using fuel characteristics of coal and SHW. The results revealed that SHW could safely replace around 20% of the primary coal energy without giving negative effects. The limiting factor is the free lime content of the clinker. Results from the present study were also compared with results from a previous test using meat and bone meal.

Keywords: Cement kiln burner; Free lime; Full-scale test; Solid hazardous waste; Wood chips.

1. Introduction

Cement manufacturing is an energy-intensive process due to the high temperatures required in the kilns for clinkerization. Depending on the process, cement production typically requires 3.2-5.0 MJ/kg clinker of thermal energy [1]. The energy is supplied to the process through combustion of different types of fuel.

Due to decarbonation of carbonates in the raw materials and the fuel combustion, cement production generates an average world carbon emission of 0.81 kg CO_2 per kg cement produced [2]. The calcination of carbonates accounts for roughly 60% of the CO_2 emitted, while the remaining CO_2 results from energy usage during the production process [3].

Although coal, petroleum coke, and other fossil fuels have been traditionally burned in cement kilns, because of the high energy usage and high environmental impact of the process, many cement companies have turned to energy-rich alternative fuels. Further, due to their high burning temperatures, cement kilns are well-suited for accepting and efficiently utilizing a wide range of wastes that can present a disposal challenge. Besides, this integrated activity offers additional revenues to the cement industry as the disposal of wastes normally receives a financial incentive. The replacement of coal by carbon dioxide neutral fuels 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 [4].

The two major energy consumption units in the cement manufacturing process are the precalciner burner and the rotary kiln burner. In modern precalciner cement kilns typically 60 % of the fuel energy is supplied in the precalciner, whereas the remaining 40 % is supplied via the rotary kiln burner. The precalciner has the greatest potential for using alternative solid fuels, but when the replacement potential in the precalciner is fully utilized, one may turn to the kiln burner to try to increase the overall fossil energy replacement ratio even more.

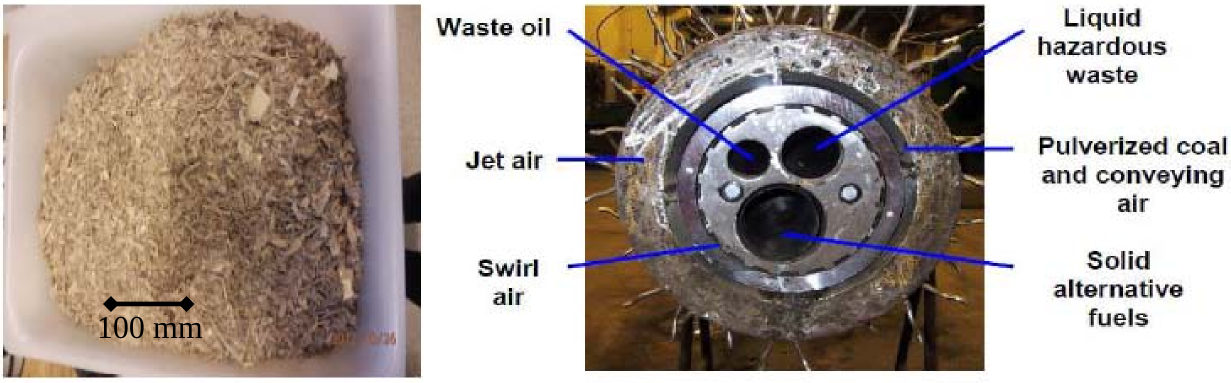
Cement plants have been utilizing certain approved hazardous wastes as an alternative fuel since the 1970s. Because the characteristics and types of chemical and hazardous wastes vary greatly, it is difficult to specify a typical analysis and generalize about the impacts of burning of chemical and hazardous waste. Some researchers have focused on emissions and pollution due to hazardous waste combustion in cement kilns [5-10]. The cement kiln dust production has been compared by some authors, and it has been found that wet kilns that burn hazardous wastes generate significantly more cement kiln dust waste, and with higher toxicity; this is however not the case for dry kilns [11]. In still another study, the destruction efficiency and pollutant formation have been studied for hazardous waste combustion in cement kilns [12, 13]. The optimum feeding rate, destruction removal efficiency and emissions have been investigated in a pesticide trial burn in a Chinese cement kiln [14].

The main objective of the present study was to find the maximum possible replacement of coal by a mix of wood chips and solid hazardous waste (SHW) without negatively affecting the 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. Finally, the optimum feed level was concluded for the investigated kiln system. The results were also compared with a similar study on meat and bone meal (MBM), previously carried out by the current authors [15].

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 [16], whilst coal is fully fossil.



(a) (b)

Figure 1. (a) Solid hazardous waste mixed with wood chips, (b) Rotary kiln burner tip

Coal and SHW 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 Ika Calorimeter System C5000. The bulk density was measured by weighing a known freely distributed volume. The particle size was analyzed 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 has several years of experience using SHW in the precalciner, but less experience in using it as a coal replacement in the rotary kiln 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 1(b). The solid alternative fuel is fed via a Pfister feeder system designed to control mass feeding of solid secondary fuels up to 7 t/hr.

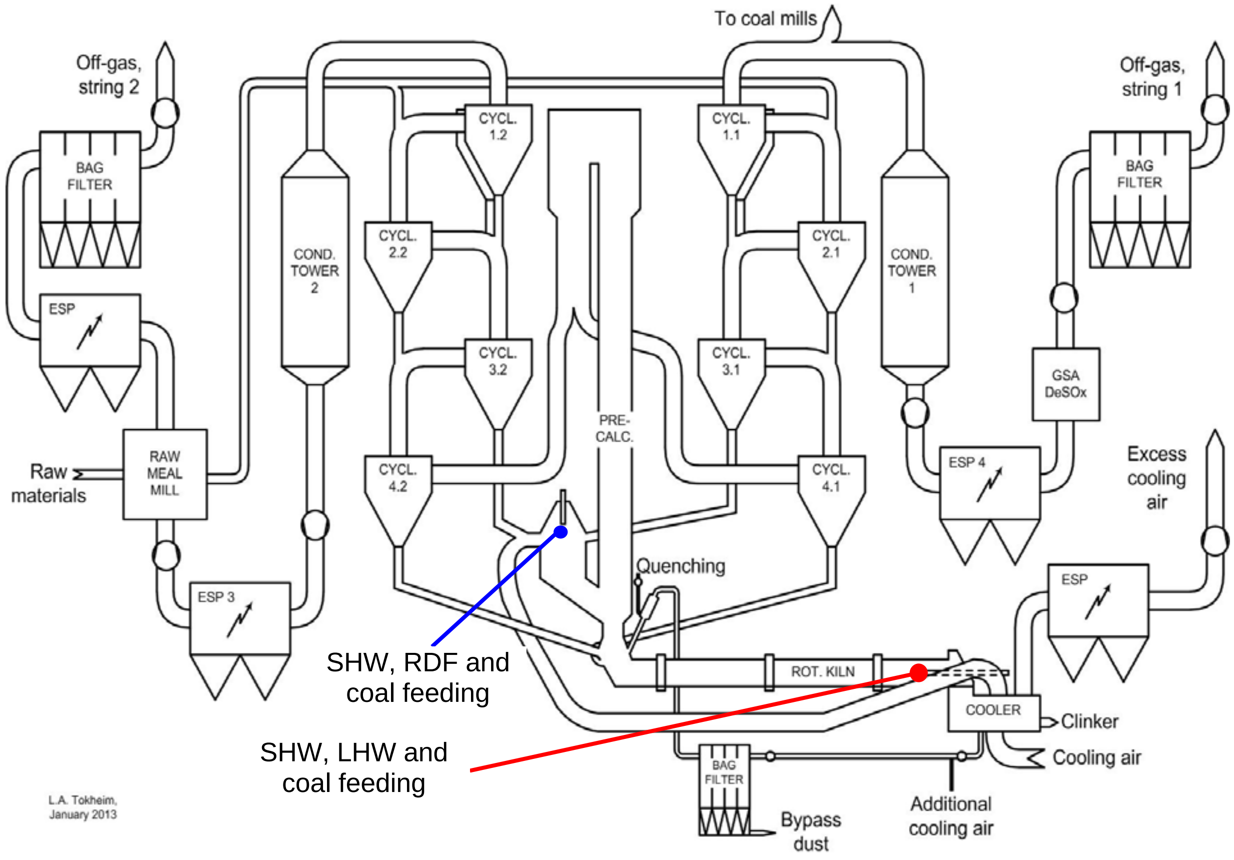


Figure 2. The cement kiln system [17]

The test was carried out for 20 hrs by varying the feeding rate of SHW in particular time intervals. SHW was fed via the Pfister system described above. In addition to coal 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 14 MJ/kg. Ordinary portland cement (OPC) clinker was produced during the test period. The raw meal feeding rate was kept around 226 t/hr; however, had to be reduced during the later stages of the experiment to keep the clinker quality within the desired range.

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 (refuse derived fuel (RDF) and SHW) supply rates in the precalciner 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 [3] constant during the test. The total alternative fuel feeding in precalciner was kept around 13 t/hr. The ratio of thermal energy consumption between rotary kiln and precalciner was kept at 39:61. The feeding rate of SHW was gradually increased by reducing the coal supply to the rotary kiln burner (Table 1) in order to keep the thermal energy consumption of the kiln 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 by both SHW and LHW in the rotary kiln burner. Step 1 and step 10 correspond to reference cases, i.e. only coal and LHW were fed. Fuel characteristics are given in Table 2.

Table 1. Experimental schedule (each step is 2 hours)

Step number	Feeding rate of SHW [t/hr]	Coal feeding rate [t/hr]	Coal energy substitution [%]
1	0.0	6.9	7.7
2	0.5	6.3	11.9
3	1.0	6.0	17.6
4	1.5	5.7	21.4
5	2.0	5.0	26.7
6	2.5	4.9	29.9
7	2.5	5.2	28.6
8	2.5	5.2	28.6
9	3.0	5.0	31.5
10	0.0	6.7	10.3

Table 2. Properties of coal, SHW and MBM

Property	Coal	SHW	MBM [15]
Moisture [wt. %]	1.7	30.0	4.0
Volatiles [wt. %]	27.5	51.4	60.8
Fixed carbon [wt. %]	51.4	1.0	8.0
Ash [wt. %]	19.4	17.6	27.2
Lower heating value [MJ/kg]	27.1	15.0	18.5
Freely settled density [kg/m^3]	640	310	720

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 along the points in kiln length 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 [18]. The 1hr spot measurements were collected from short term historical data of the system for the day of the experiment and the day before.

Raw meal was analyzed for oxides and sulphur content whereas precalcined meal was analyzed for degree of calcination, sulphur and chloride contents; all in 2 hr time intervals. Key clinker properties were analyzed 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 analyzed with a Philips PW 2404 x-ray spectrometer using the x-ray fluorescence (XRF) method, and the SO_3 content was analyzed 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. Results and discussion

This section presents the results from laboratory and full-scale experiments. First the fuel characteristics determined in the lab are given. Then impacts on the clinker quality, process and then on shell temperature are discussed.

4.1 Fuel characterization

The analysed properties of coal and SHW are given in Table 2. It is observed that the moisture content of SHW is very high in comparison with with coal. However, this is quite typical of alternative fuels containing biogenic matters. In contrast, the fixed carbon is extremely low in SHW. The bulk density is around half of that of coal, which might give volumetric restrictions when feeding.

The cumulative distributions of coal and SHW particle sizes are shown in Figure 3. The particle size will affect the burnout time of the particles in the kiln; this is further discussed later.

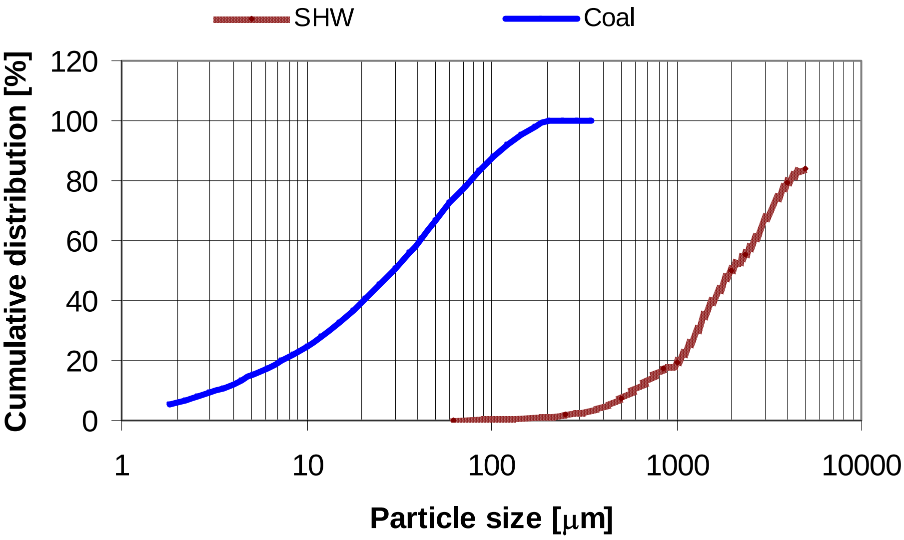


Figure 3. Cumulative particle size distribution

4.2 Analyses of raw meal, precalcined meal and clinker

The variation of the measured raw meal properties during the test period was insignificant. The degree of calcination of the precalcined meal was constant around 96-97%. Similarly, the SO_3 content and the Cl content of the precalcined meal were 1.5-2.2 % and 1.0-1.7 %, respectively. These properties have not been impacted by SHW feeding at the rotary kiln burner.

Figure 4 shows that the main oxides in clinker were all at desirable levels to maintain an acceptable clinker quality throughout the experiment. SHW does not have high concentrations of sulphur (average around 0.5 wt.%), however minor changes in the clinker SO_3 might be due to process-disturbing changes in the internal sulphur cycles in the kiln system [3], potentially induced by changes in the combustion conditions in the rotary kiln burner as a result of the SHW feeding. However, the SO_3 content is in an acceptable range (less than 1.5%) for the standard clinker, and the level appears not to be impacted by the feeding of SHW.

The main issue indicated is the increase in free lime content with increments of SHW feeding (Figure 5). The free lime content is always higher than in the reference cases (step 1 and step 10), implying that there is a significant impact from SHW feeding on the clinker quality. However, in step 1 and step 10, the raw meal feed rate was somewhat lower than the planned feed rate for the test. The feed rate had to be reduced due to high CO content in the stack. This was not related to the operation in main burner, but was rather due to poor burn out of alternative fuels in the precalciner (Figure 6).

When the feeding of SHW is 2 t/hr, the free lime content is almost at the maximum allowable limit, 2.5%. It is even higher (3.2%) when the SHW feeding rate is 2.5 t/hr. The high free lime content reveals improper burning of the raw meal and poorer quality of the clinker. The raw meal feed rate was reduced totally by 10 t/hr (from 226 t/hr) in step 7 in order to counteract the increase in free lime. The response to this action is seen as a considerable reduction in free lime in step 7, as shown in Figure 5. In step 8, while keeping the SHW feed rate at 2.5 t/hr, the raw meal feeding was again increased by 5 t/hr (i.e. a total raw meal feeding rate of 221 t/hr). A slight decrease in free lime could be observed, indicating that a reduction of 10 t/hr in raw meal feeding rate was actually more than required to recover the kiln process. The free lime content in step 9 was quite similar to that of step 8, even if the SHW feeding rate was increased to 3 t/hr in step 9. It can be concluded that more than 2 t/hr of SHW feeding is not appreciable, when the raw meal feed rate is as high as 226 t/hr. However, even 3 t/hr of SHW feeding can be handled with a slightly (around 2%) lower production rate compared to 226 t/hr. This also illustrates that fine tuning is necessary when burning this type of fuel in the rotary kiln burner.

One possible reason for an 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 lower heating value and fixed carbon, and also due to very high moisture content (Table 2). A larger particle size of the SHW (Figure 3) 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. While the maximum size of the coal particles is around 200 µm, the SHW distributes to even more than 5000 µm. However, even if the burnout time of large particles is higher, this may be partly offset by a higher content of volatiles in SHW (Table 2) via faster fuel ignition.

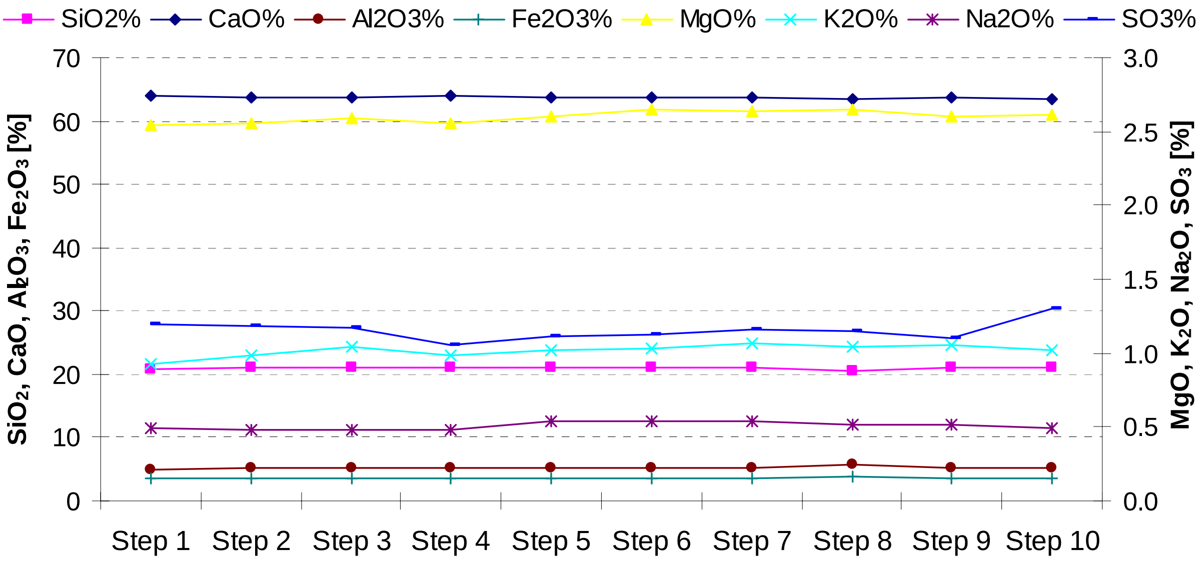


Figure 4. Clinker oxide composition during the test

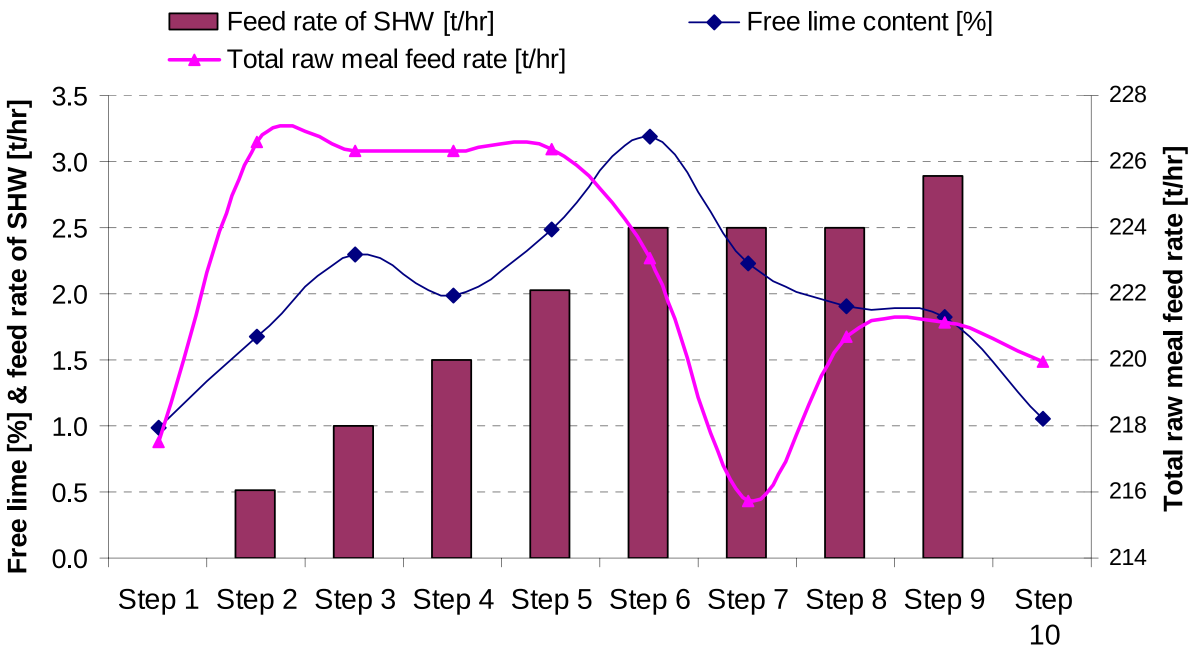


Figure 5. Free lime content of clinker variation according to feeding rate of SHW

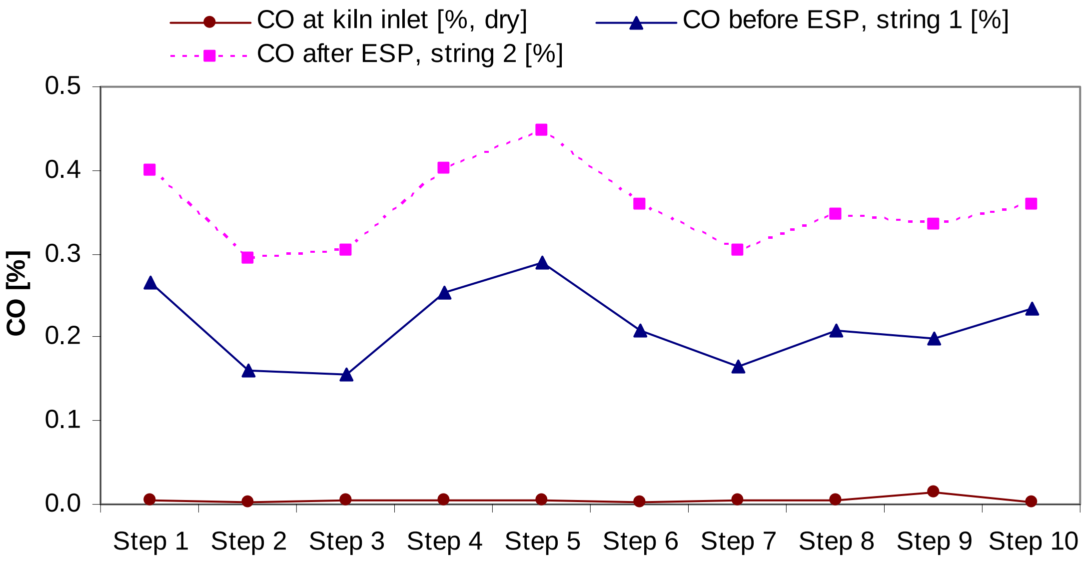


Figure 6. CO content at the kiln inlet and in the two stacks

A similar type of test was previously carried out by the current authors using meat and bone meal (MBM) as the coal replacement fuel. Results from the present study can be compared with those findings [15].

The MBM test concluded that for long term operation, the MBM feed rate should not exceed 5 t/hr for a raw meal feeding of 220 t/hr. In the present study, for 220 t/hr of raw meal feeding, the authors recommend 3 t/hr feeding of SHW in the rotary kiln burner in order to achieve desired clinker quality. The feeding rates of these two fuels correspond to 39% and 20% primary energy substitution, respectively.

The characteristics of MBM and SHW (Table 2) can give an explanation to the different allowable feeding rates. As explained above, one reason for an increase in free lime content is reduced flame temperature. Higher moisture content, lower calorific value and lower content of volatiles in SHW are likely to give a lower flame temperature. Additionally, for a given percentage, the particle size of SHW is four times that of MBM [15]. However, it should be noted that these effects may be partly counteracted by the comparatively high Ca content of MBM, which may contribute to an increase in clinker free lime content when MBM is burnt in the rotary kiln burner.

4.3 Process data

The O_2 concentration in the kiln inlet was kept rather high (around 5 %), so the CO concentration in the kiln inlet was close to zero throughout the experiment (Figure 6): Also, it did not increase as a result of SHW feeding.

It is observed in Figure 7 that the NO_x level at the kiln inlet dropped when feeding SHW. That means the sum of thermal NO_x formation and fuel NO_x formation in the kiln was lower in steps 2-9. This is a clear indication that the (maximum) temperature in the kiln dropped when SHW was fed (lower thermal NO_x formation).

The kiln drive current (Figure 7) 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 3 and 4, which is likely due to the increase in SHW feeding. The subsequent increase in kiln drive current is likely due to a decrease in raw meal feeding. The graph also shows that the thermal NO_x formation in the kiln was considerably lower during feeding of SHW. This is an indication of reduced flame temperature, which explains the reduced kiln drive current (lower melt phase fraction) and hence the higher free lime content.

The CO concentration in the stack (not shown) was around 0.2% during the entire test. The TOC emissions were in the range 10-35 mg/Nm³, but the concentration variation was apparently not linked to the SHW feeding, but was rather due to the conditions in the precalciner.

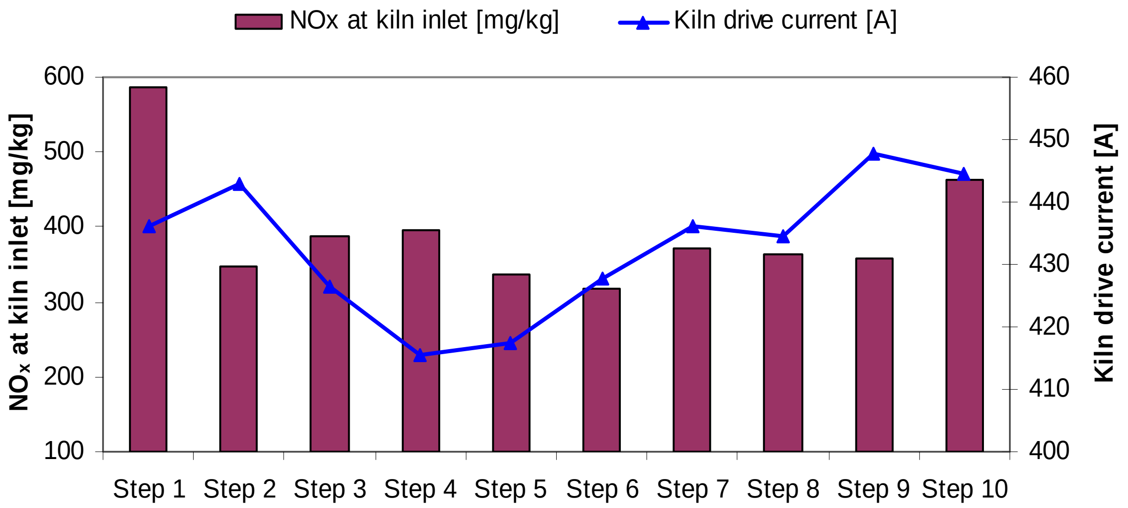


Figure 7. NO_x concentrations and kiln drive current

4.4 Shell temperature

The 1hr spot measurements from the shell 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 check for deviations from normal operation. The shell temperature is shown in Figure 8 (0 m corresponds to the kiln outlet). Large deviations are not observed except in the region 16-22 m. The average shell temperature on the test date is 40-60 °C lower than on the day of normal operation in that region. However, this is because the day before the test, the plant produced a different type of clinker, and a change in shell temperature is quite typical of such situations.

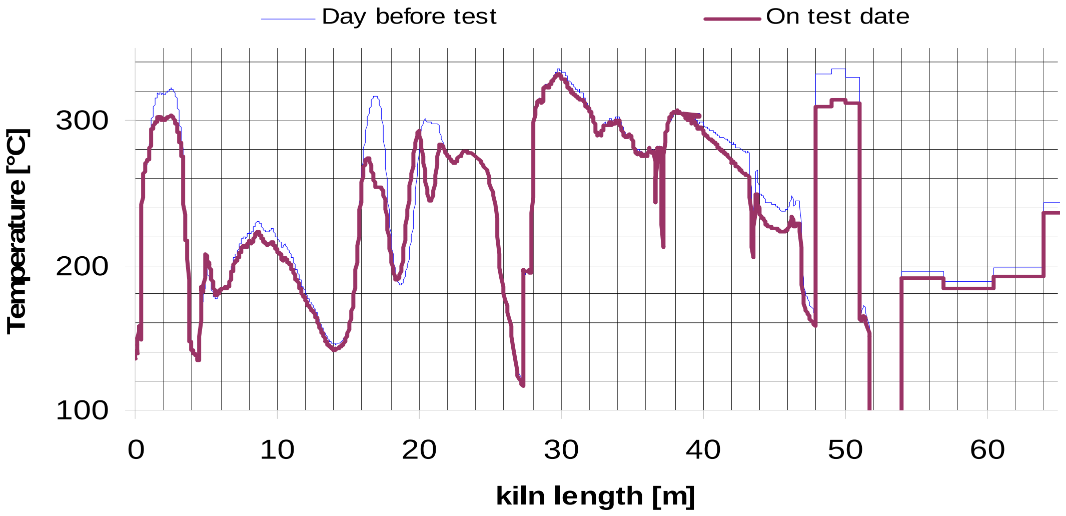


Figure 8. Average kiln shell temperature data for the test date and for the day before test

5. Conclusion

The test results demonstrate the possibility of significant replacement of coal by a mix of solid hazardous waste and wood chips (SHW) in the rotary kiln burner without negatively affecting product quality, production rate, emissions or overall operation. No significant impacts on emissions or kiln operation were observed, regardless of SHW feeding rate. The most important impact of the SHW feeding was on the free lime content of the clinker. Replacement of 20% of the coal energy in the rotary kiln burner (3 t/hr of SHW feeding) proved acceptable. This coal energy replacement of 20% is lower compared to 39% found in a test with meat and bone meal previously carried out. Different fuel characteristics can explain this difference.

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References

[1] Lemieux P., Stewart E., Realff M., Mulholland J.A. Emissions study of co-firing waste carpet in a rotary kiln. Journal of Environmental Management 2004, 70(1), 27-33.

[2] Huntzinger D.N., Eatmon T.D. A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies. Journal of Cleaner Production 2009, 17(7), 668-675.

[3] Tokheim L.A. The impact of staged combustion on the operation of a precalciner cement kiln. Ph.D. thesis, Telemark University College / Norwegian University of Technology and Science, Norway, 1999.

[4] Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC 2003. European Commission, 2003.

[5] Tsiliyannis C.A. Alternative fuels in cement manufacturing: Modeling for process optimization under direct and compound operation. Fuel 2012, 99, 20-39.

[6] Karstensen K.H. Formation, release and control of dioxins in cement kilns. Chemosphere 2008, 70(4), 543-560.

[7] Zemba S., Ames M., Green L., Botelho M.J., Gossman D., Linkov I., Palma-Oliveira J. Emissions of metals and polychlorinated dibenzo(p)dioxins and furans (PCDD/Fs) from Portland cement manufacturing plants: Inter-kiln variability and dependence on fuel-types. Science of the Total Environment 2011, 409(20), 4198-4205.

[8] Ames M., Zemba S., Green L., Botelho M.J., Gossman D., Linkov I., Palma-Oliveira J. Polychlorinated dibenzo(p)dioxin and furan (PCDD/F) congener profiles in cement kiln emissions and impacts. Science of the Total Environment 2012, 419, 37-43.

[9] Loo W.v. Dioxin/furan formation and release in the cement industry. Environmental Toxicology and Pharmacology 2008, 25(2), 128-130.

[10] Guo Q., Eckert J.O. Heavy metal outputs from a cement kiln co-fired with hazardous waste fuels. Journal of Hazardous Materials 1996, 51(1-3), 47-65.

[11] Jacott M., Reed C., Taylor A., Winfield M. Energy Use in the Cement Industry in North America: Emissions, Waste Generation and Pollution Control, 1990-2001. 2nd North American Symposium on Assessing the Environmental Effects of Trade, Commission for Environmental Cooperation, 2003.

[12] Ottoboni A.P., Souza I.D., Menon G.J., Silva R.J.D. Efficiency of destruction of waste used in the co-incineration in the rotary kilns. Energy Convers. Mgmt 1998, 39(16-18), 1899-1909.

[13] Mournighan R.E., Branscome M. Hazardous Waste Combustion in Industrial Processes: Cement and Lime Kilns. Project summary. United States Environmental Protection Agency, 1988.

[14] Li Y., Wang H., Zhang J., Wang J. Disposal of Obsolete Pesticides Including DDT in a Chinese Cement Plant as Blueprint for Future Environmentally Sound Co-Processing of Hazardous Waste Including POPS in the Cement Industry. Procedia Environmental Sciences 2012, 16, 624-627.

[15] Ariyaratne W.K.H., Melaaen M.C., Eine K., Tokheim L.A. Meat and bone meal as a renewable energy source in cement kilns: Investigation of optimum feeding rate. International Conference on Renewable Energies and Power Quality, Spain, 2010.

[16] Ariyaratne W.K.H., Asgautsen Ø., Melaaen M.C., Eine K., Tokheim L.A. Determination of fossil fraction of refuse derived fuel by the selective dissolution method in calorific value basis: Development of simplified method. Fuel 2012, 98, 41-47.

[17] Tokheim L.A., Kiln system modification for increased utilization of alternative fuels at Norcem Brevik. Cement international 2006, 4(4), 52-59.

[18] Manjula E.V.P.J. Evaluation of rotary kiln modeling results by experimental data from full-scale tests. M.Sc. Thesis, Telemark University College, Norway, 2011.

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