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Evaluating the potential of waste plastics as fuel in cement kilns using bench-scale emissions analysis

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ABSTRACT

In an effort to reduce emissions and lower fuel costs, cement plants have explored the use of waste materials to displace coal and petroleum coke. A potential candidate is non-recyclable waste plastics. Knowledge of potential changes in cement kiln parameters with a change in the composition of operating fuel prior to full-scale application is necessary for obtaining permits and for plant preparedness. Most bench-scale performance studies have targeted the prediction of full-scale stack emissions with variable degrees of success. In this work, a bench-scale tube furnace and a heated grid reactor (HGR) have been used to compare combustion and emission changes when waste plastics displace an equivalent amount of heat from the coal/coke blend. Trends in the results from bench-scale experiments on residual volatile organic compound (VOC) emissions matched full-scale observations on kiln thermal performance. Bench-scale particulate matter (PM) emissions indicated that no significant changes were likely in full-scale stack PM emissions when using waste-derived fuel (WDF). This bench-scale fuel characterization approach has been used to study the potential impact of waste plastics on the performance of a local cement kiln.

1. Introduction

Approximately 2.8 million tonnes of plastic waste is disposed of annually in Canada. Of this, an estimated 719,000 tonnes are from residential sources and the rest are from non-residential sources including the industrial, commercial and institutional sector which includes grocery stores and goods manufacturing plants [1,2]. According to the Clean Foundation [3], 490 million plastic bags are used in Atlantic Canada each year. At 5 g per bag, this represents a potential energy estimate of 101 PJ/year based on reported calorific values for plastic film. Most of these plastics end up in landfills since they are usually unrecyclable. Redirecting such waste to a local cement kiln for co-processing presents a dual solution to both cost and environmental concerns.

Clinker is produced in cement kilns heated to about 1450 °C. In rotary kilns, raw materials are introduced into the slightly elevated end of large rotating drums inclined downward towards the burner through which fuel is fed to supply heat for the reactions. The blending of different fuels with coal in thermal processes such as clinker production for economic, environmental and chemical benefits has been discussed in literature [4–6]. Factors considered for alternative fuels for co-firing include moisture and ash content, calorific value, volatile content, and reactivity. The alternative fuel is also evaluated based on the potential for ambient air pollution, slagging and fouling, and corrosion. Generally, the performance of WDF depends upon their ability to influence the reactivity of a coal-fuel blend, and to reduce the formation of potentially harmful emission such as nitrogen oxides (NO_x), sulphur dioxide (SO_2), airborne PM and polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs). These emissions and their environmental and human health effects have also been discussed in the literature [6–8]. Most cement plants undergo rigorous trials to ascertain the suitability of a selected alternative fuel. These trials may interfere with normal plant operations and need to be carried out over long periods before definitive trends can be observed. This is due to the complex changes that regularly occur in kiln operations. Knowing the composition of the potential fuel before industrial trials does not adequately inform operators, regulators and communities with sufficient data to manage potential changes for a given fuel.

The overall objective was to use a combination of previous studies, ultimate analysis, tube furnace emission tests and HGR combustion tests to evaluate and correlate fuel properties and bench-scale emission behavior to expected changes in full-scale cement kiln parameters.

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Nomenclature

C&D	Construction and Demolition
Coal-coke	1:1 mixture of coal and petroleum coke by mass
EPS	Expanded Polystyrene
ESP	Electrostatic Precipitator
GCMS	Gas Chromatography Mass Spectroscopy
HDPE	High Density Polyethylene
HGR	heated grid reactor
LDPE	Low Density Polyethylene
LHW	liquid hazardous waste
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
PCDD/F	polychlorinated dibenzo(dioxin/furan)
PDF	plastic-derived fuel
PM	particulate matter
RDF	refuse-derived fuel
SHW	solid hazardous waste
TDT	Thermal Desorption Tubes
VOC	volatile organic compound
WDF	waste-derived fuel
WMR	Wire Mesh Reactor

2. Kiln emissions and thermal performance

Approximately 50–60% of the CO_2 is related to calcination of $CaCO_3$, and the rest is as a result of fuel combustion [9,10]. SO_2, carbon dioxide (CO_2) and fuel NO_x generated during combustion are governed primarily by the sulphur, carbon and nitrogen content of the fuel. Based on a simple stoichiometric mass balance, the expected mass (m_e) of gaseous oxide (xO) with molecular mass (MM_{xO}) produced from the oxidation of element x (N, C, S or H) with molecular mass (MM_x) is given by:

$$m_e = \left[\frac{n \times Y_x \times MM_{xO}}{E_f \times MM_x}\right] \times E_t \quad /[\mathrm{kg}] \tag{1}$$

where n is the stoichiometric mole ratio of x to xO, E_t is the energy required for the process [kJ], E_f is the energy content of the given fuel [kJ/kg], and Y_x is the percent composition of x in the fuel on a dry basis from the ultimate analysis. When heated, a solid fuel loses moisture and then releases volatile components, which ignite and form a flame. The extent of thermal degradation of produced VOC such as benzene, xylene and toluene is dependent on temperature and the retention time within this zone. At elevated temperatures (>1000 °C) the mixture of organic vapor and air is oxidized to form CO, CO_2, NO_x and H_2O [11]. The more extensive the degradation, the lesser the VOC content in the combustion products. Given the variables related to the emission of residual VOC, theoretical calculations based on stoichiometry fall short in predicting their quantities in combustion products.

Similar to residual VOC, it is difficult to theoretically quantify PM emissions even where the composition and stoichiometry of combustion are well known. Changes in fuel such as using WDF may influence PM emissions, especially PM with a median aerodynamic diameter $\leqslant 10\ \mu m$ (PM_{10}) [12]. Total suspended particulates are a function of the percentage of ash, or mineral matter, in the fuel, coupled with the unburned carbon resulting from combustion and firing method used [6]. Fuels such as waste plastics with low ash content can therefore be blended with high-ash coals to reduce suspended particulates. It is also expected that a higher volatile content will reduce unburned carbon in the products of combustion. Gases such as SO_2, NO_x, and VOC emitted from cement kilns can transform in the atmosphere to form secondary fine airborne particulate matter with a median aerodynamic diameter $\leqslant 2.5\ \mu m$ ($PM_{2.5}$) and ozone (O_3) [6,13–16]. Carrasco et al. [17] and CRA [18] report a broad variation of expected changes in gaseous emissions such as SO_2, NO_x and CO in their literature review on effects of Tire-derived fuels on cement kiln emissions. Both groups confirm that the variation in results show that emissions generally do not only depend on the quantity of their parent elements in the fuel but also on their presence in raw materials, and the efficiency of the combustion process. This makes ascertaining the contribution of fuel combustion to gaseous and particulate emission of a cement kiln stack by field measurements challenging. Many sources of similar emissions are present throughout the cement making process. It also makes the scale-up of bench-scale experiments based on emissions unsuccessful in many cases. The work of Jeschar et al. [7] for example showed that the challenge of replicating actual kiln conditions on small-scale may sometimes lead to full-scale emissions results which do not conform to theoretical expectations. Despite these limitations, bench-scale experiments are useful for the comparative analysis of materials under similar controlled conditions. The degree to which full-scale predictions from bench-scale observations are acceptable depend on (1) the reasonable simulation of the actual kiln burning zone conditions by the smaller scale test as can be obtained in a heated grid or entrained flow reactor [19] and (2) the full-scale kiln parameters of interest. Parameters such as flue gas flow rate and kiln gas temperature, which are not easily masked by the presence of other materials can be reasonably linked to properties determined from bench-scale analysis.

Predictive methods based on flue gas flow rates have been used successfully by Ariyaratne et al. [20] to study effects of fuel composition, moisture content, calorific value and state on actual kiln performance. In their work the effect of substituting coal with refuse-derived fuel (RDF), waste wood, solid hazardous waste (SHW) and liquid hazardous waste (LHW) using models on overall heat and mass balances of the cement kiln, were validated by full-scale trials. The characteristics of the fuels as received, satisfactorily explained trends in the results on temperature, flue gas flow rates and their consequent effect on clinker production rates. For example, kiln gas temperatures were 24 °C, 28 °C, 22 °C and 95 °C lower than the temperature in the coal reference case for RDF, waste wood, SHW and LHW respectively [20]. According to Ariyaratne et al. [20] this drop in temperature matched the fuel heating values obtained from ultimate analysis. The higher the heating value and lower the ash content for the solid fuels, the higher the kiln gas temperature. An increase in the required mass of fuel increases gaseous combustion products and leads to an overall increase in flue gases. This increase in the total flue gas leads to a reduction in thermal performance which translates to a reduction in kiln gas temperature. In a second paper by Ariyaratne et al. [21], the kiln gas temperature was impacted by the air requirement for fuel combustion, which can also be deduced from the ultimate analysis of the fuel. Additionally, the secondary air requirement of a cement kiln generally increases with an increase in volatiles to ensure complete combustion. This can be countered by a decrease in mass for a fuel with a high energy content. Fuel air requirement is also affected by a combined effect of the presence of O and the molar H/C ratios for the given fuel [21]. Generally, the higher the molar H/C ratio of a fuel, the lesser the molar air requirement.