The Effect of Fuel Emulsion on Fuel Saving in Cement Kilns

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Abstract: In this work, the combustion of heavy oil and its emulsions with water, in the cement kilns, was investigated in experiments on an industrial scale. The performance of the cement rotary kilns, used in Tartous Company for cement and construction materials, was studied when they were employed to be operated with heavy fuel oil (HFO) and with the water phase of emulsified heavy oil containing 8 vol. % water and 92 vol. % heavy fuel oil (HFO). The emulsified water/heavy fuel oil (W/HFO) with 8 vol. % of water content showed no separation and contained the smallest and most homogeneous water-in-HFO (W/HFO) droplets after stability tests. Four rotary kilns have been operated for 4 months with a regular heavy fuel oil HFO and $W_{0.08}/HFO_{0.092}$. It has been found that the micro-explosion, observed in $W_{0.08}/HFO_{0.092}$, improved the kiln efficiency and reduced the fuel consumption by 10.31% in the case of normal feeding while the fuel saving increases with decreasing the feeding rate and reaches 12.99 at low feeding rate. The effect of emulsified fuel on the composition of Portland cement clinker that produced in Tartous Company for cement and construction materials using these two types of fuels is investigated. It is found that the influence is practically negligible on the Alite and Ferrite phases of clinker composition while the influence on the other two phases is important.

Keywords: W/HFO emulsion, Fuel saving, Experiment, Clinker composition.

1. INTRODUCTION

Cement production consumes large quantities of raw materials and energy (thermal and electrical). The manufacturing process is very complex. This complexity is due to the many constituents and phases present in the process as well as the mineralogical and physical changes that occur simultaneously. Thus, the production of clinker includes a large number of raw materials (with different material properties), heat treatment technologies, and a variety of fuel sources. The phases present in the process include a gas phase, pure liquids and solids, and solutions of liquids and solids. The physical obstacles to the production of good-quality clinker involve too coarsely ground raw materials and fuels as well as insufficiently homogenized material. The clinker production process requires about 3.2–6.3 GJ of energy and 1.7 tons of raw materials (mainly limestone) per ton of clinker [1, 2]. Being an energy-intensive industry, thermal energy accounts for about 20-25% of cement production cost [3]. Typical electrical energy consumption for modern cement manufacturing is about 110-120 kWh per ton of cement. In this process, the heat energy is mainly used during combustion, while the maximum share of the electrical energy is used to grind cement [3]. 30-40% of the total cement costs are attributable to energy costs (3.3 GJ per 1 ton of cement) [4].

There is a general trend around the world to produce cement using Alternative Fuels (AF). The economic and environmental benefits of replacing fossil fuels with alternative fuels are clearly being felt [5]. Many alternative fuels are used in the cement industry [6-12]. The list of these types includes biological waste, *i.e*. combustible materials derived from biomass, paper waste, agricultural cellulose waste, agricultural plastic waste from horticulture and wood, waste treatment plants for residential waste, textile industry waste, plastic materials industry, wooden, plastic and paper packages, expired tires, oil tanks waste and secondary animal products waste, automotive plastics, biological and industrial sludge, oil emulsions, cable waste, demolition waste, refinery sludge, spent solvents, waste frying oils, and much more others. The clinker industry consumes about 40% of the total energy needs of cement plants. This energy is spent on the oven / pre-firing / preheating system. This convection is usually covered by the use of fossil fuels (coal and crude oil derivatives). Therefore, one can seriously think about improving the environmental factor and taking advantage of the carbon dioxide credits by using alternative fuels.

In the cement production, the main processes vary depending on the design of the manufacturing equipment, the method of operation and fuel consumption [13]. The cement manufacturing process mainly includes quarrying, raw materials preparation, raw materials preheating, kilns, clinker cooling, milling, storage and dispatching. A schematic diagram of the cement manufacturing is shown in Figure **1** [14] which shows the operations from the initial quarry to the shipment of the final product.

To secure the required heat energy, the fuel is burned in the furnace as well as in the preheater tower.

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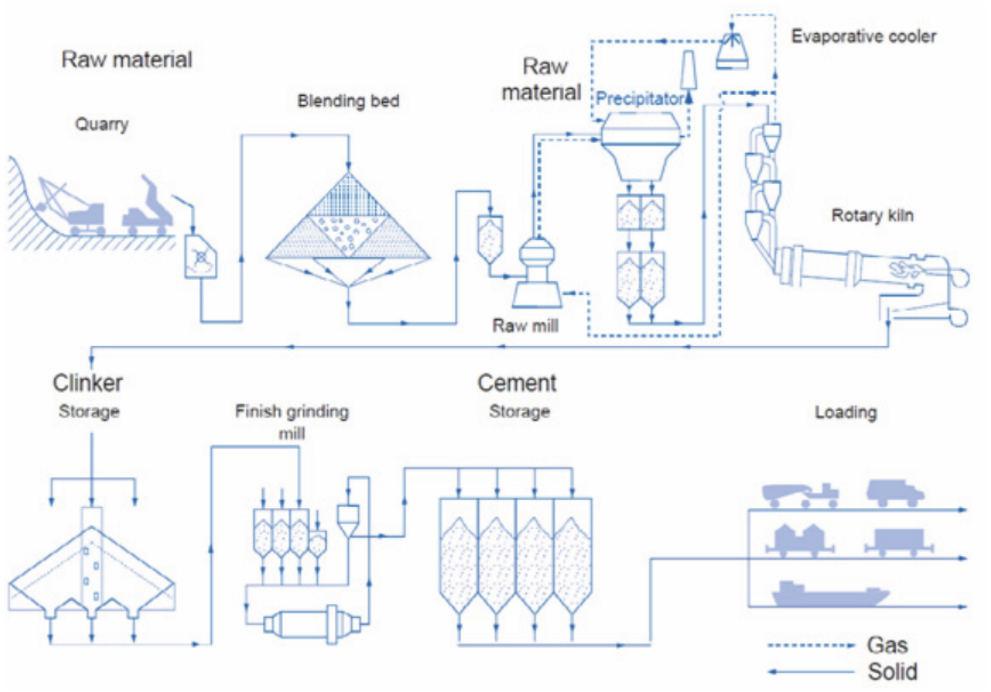

Figure 1: Schematic presentation of the cement manufacturing process from quarry to dispatch [14].

The cement kiln is capable of burning a wide range of materials. The process begins with the dissociation of calcium carbonate ($CaCO_3$) at about 900 °C into calcium oxide (CaO) and carbon dioxide. This process is known as calcination. The process of formation of clinker in a furnace takes place by reacting calcium oxide with silica, alumina and ferrous oxide to form silicates, aluminates and ferrites of calcium respectively at a high temperature (usually 1400 - 1500 ° C) [15]. These materials are the main components of the clinker material. This clinker is cooled and then ground with gypsum and other additives to produce cement. Because of the long stay of the clinker in the oven at high temperatures and the alkalinity of the oven environment, the clinker is able to absorb the pollutants and lock them in [16]. It should also be noted here that the physical properties of the furnace feedstock (density and homogeneity), grinding characteristics and storage/feeding capabilities should be taken into consideration when studying the effect of the alternative fuel on the produced clinker.

Currently, studies focus on using energy efficient fuels and reducing greenhouse gas emissions. One of the most popular fuels is emulsified fuel. Emulsified heavy fuel oil (HFO) with water (water/HFO) is considered as an alternative fuel. The definition of water/HFO emulsion, its brief history and benefits of its use as an alternative fuel in boilers are given elsewhere (see for example [17-21]).

The technical conditions of operation with alternative fuel should be asked in the case of its use in the cement manufacturing process. So, can the technical conditions for operating using alternative fuels be changed so that the environmental and economic benefits of using this fuel are achieved without causing significant losses in the production rate? Indeed, practical experience with emulsified HFO can be relied upon to achieve complete combustion of the used fuel - which will lead to reducing the amount of excess air in the gases emitted from the kiln chimney while achieving the required level in the rate of clinker production. Thus, the technical requirements, which are related to gas emissions from kiln chimneys in the cement industry, could be totally achieved.

The present manuscript is devoted to investigate the effects of emulsified HFO use on the performance of the kilns and on the composition of Portland cement clinker and its main phases: Belite (approximately dicalcium silicate or C2S ($2CaO.SiO_2$)), Alite (approximately tricalcium silicate or C3S ($3CaO.SiO_2$)), Aluminate (very Approximately tricalcium aluminate or C3A ($3CaO.Al_2O_3$)) and Ferrite (very approximately tetra calcium Alumina ferrite or C4AF ($4CaO.Al_2O_3.Fe_2O_3$). Moreover, Although the calorific value of the emulsified fuel decreases with increasing mixing rate with water, the amount of conventional fuel, which is in the emulsion, required to produce the same amount of heat produced from pure fuel is less than the amount of pure fuel by a percentage that will be determined in this work when the kilns are employed at 8% of water content in the W/HFO emulsion. This is a ratio that directly falls in the efficiency improvement rate of the used kilns. Therefore, the secondary goal of the present work is to investigate the performance of the rotary kilns at $W_{0.08}/HFO_{0.92}$ emulsion.

2. MATERIALS

2.1. Tartous Company for Cement and Construction Materials

The Tartous Company for cement and construction materials is located about 1.5 km from the beach of Mediterranean sea 10 km North of Tartous city. There are four rotary kilns in this company. During this study the kilns have been operated for 4 months with a regular heavy fuel oil HFO and W/HFO.

2.2. Heavy Fuel Oil Characterization

The dehydrated HFO was characterized according to ASTM D1298 for the specific gravity, ASTM D1552 for sulphur content, ASTM D92 for flash point, ASTM D97 for pour point, ASTM D445 for kinematic viscosity, ASTM D482 for ash content and ASTM D240 for the heat of combustion. Asphaltenes and vanadium contents were characterized according to UOP614 and UOP391 respectively. The results are given in [17].

2.3. Gas Emissions Characterization

The temperature of the gas emissions from the chimney T_f (^oC), the ambient temperature T_a (^oC) and the concentration of each of the emitted gases (oxygen O_2; carbon monoxide CO; carbon dioxide CO_2; nitrogen oxides: NO, NO_2 and NO_x; hydrogen H_2; sulphur dioxide SO_2; and H_2S) were measured using Testo 350XL.

2.4. HFO Consumption

HFO consumption was measured during the experiment using the Yokogawa Coriolis flow meter. This kind of flow meters allows measuring the volumetric and mass flow as well as temperature and density. So, it can be used easily in both cases: HFO and W/HFO.

2.5. Clinker and Raw Materials Composition

Portland cement is made by mixing substances containing lime, silica, alumina, and iron oxide and then heating the mixture until it almost fuses. During the heating process di-calcium and tri-calcium silicate, tri-calcium aluminate, and a solid solution containing iron are formed. X-ray fluorescence (XRF), a standard technique across the cement industry, is used to determine metal-oxide concentrations and oxide stoichiometry.

2.6. Crystalline Structures

X-ray diffraction (XRD) provides quantitative analysis of free lime in clinker, which is critical to the production process. Kiln parameters are monitored and adjusted continuously, based on XRD and XRF analytical results.

3. METHODOLOGY

The cement industry is greatly affected by the presence of sulfur oxide and magnesium oxide [22]. In the chemical analysis of cement, certain mathematical relations exist between the percentage of lime and the combination of compounds like silica, alumina and iron oxide [23]. These relations are:

3.1. Lime Saturation Factor

The lime saturation factor (LSF) is the ratio of the actual amount of lime to the theoretical lime required by the other major oxides in the clinker. This factor is an important criterion in the preparation of feeding materials according to British standards. This factor is given by:

$$LSF = 100\frac{[CaO-0.7SO_3]}{[2.8SiO_2+1.18Al_2O_3+0.65Fe_2O_3]} \tag{1}$$

For the production of clinker, LSF is given by the following relationship:

$$LSF = 100\left\{\begin{matrix} \frac{CaO}{[2.8SiO_2+1.18Al_2O_3+0.65Fe_2O_3]}; if\ MgO\ concentration\ is\ less\ than\ 2\% \\ \frac{[CaO+0.75MgO]}{[2.8SiO_2+1.18Al_2O_3+0.65Fe_2O_3]}; if\ MgO\ concentration\ is\ greater\ than\ 2\% \end{matrix}\right\} \tag{2}$$

The LSF factor is used to control the concentration of calcium oxide CaO required to react with the other three oxides (SiO_2, Al_2O_3, and Fe_2O_3) on the condition that no unified (free) lime remains in the cement produced to avoid the risks and damages caused by the instability of the cement in the concrete or mortar represented by the cracks caused On the volumetric expansion of free lime when interacting with water during hydration of cement and forming hydroxide larger than the original oxide. As for the decrease in the lime level in the crude mixture, this leads to a decrease in the content of the (C3S) phase, and thus a decrease in the compressive strength of the cement.

3.2. Liquid Phase

The concentration of the liquid phase, at normal burning conditions (1450°C), ranges between 25 and 28%. Usually, the temperature is increased to increase the speed of chemical reactions, and the materials that increase the viscosity of the liquid phase are the oxides Al_2O_3, K_2O and Na_2O, while iron oxide Fe_2O_3 and sulfur oxide SO_3 reduce the viscosity of the liquid phase. This parameter is given by:

$$\text{Liquid phase} = 3.0Al_2O_3 + 2.25Fe_2O_3 + MgO + K_2O + Na_2O + SO_3 \quad (3)$$

3.3. Silica Moduli

Silica Moduli (SM) which gives an idea of the amount of melt phase present in the burning zone of the kiln. The mentioned parameter is given by:

$$SM = \frac{SiO_2}{Al_2O_3 + Fe_2O_3} \quad (4)$$

It should be noted here that, the high value of this parameter up to 3.0 makes the burning of the raw mixture difficult to form clinker due to the increase in the proportion of silica in it, especially if silica is free because it is more difficult in the thermal reaction than silicates or aluminous silicates and the low liquid phase concentration. It also makes the solid time of the produced cement relatively long, makes the packaging unstable and weak to thermal changes, as well as provides the opportunity to form dust clinker. If SM is less than 2.0, the concentration of the liquid phase in the clinker increases, which leads to a decrease in the combustion coefficient and thus the burning process is easier and the clinker formed is tough, solid and difficult to grind, but the produced cement has low durability and the period of cohesion is short and the temperature of its hydration is high.

3.4. Alumina Moduli

The Alumina Moduli (AM) which determines the composition of liquid phase in the clinker. AM is given by:

$$AM = \frac{Al_2O_3}{Fe_2O_3} \quad (5)$$

Some authors use Iron Moduli FM=1/AM. So, it is sufficient to use one of these two factors to control the iron and aluminum oxides (Al and Fe) in the raw mixture and thus control the liquid phase content. The appropriate limits for the change of AM are between 1.3 and 2.5. With increasing AM, the reaction becomes more difficult, as in the case of white cement. As for the decrease of AM coefficient, as in the case of sulfate-resistant cement, it leads to the emergence of some difficulties due to the fluidity of the materials and the low viscosity of the molten mixture and thus makes the furnace temperature above its operating temperature. Also, decreasing AM leads to an increase in ferritic content (C4AF) and a decrease in the aluminate phase.

It should be noted here that increasing the AM value of 2.5 makes the liquid phase with high viscosity and easy to burn, and makes the cement produced with early strength and high hydration temperature, and the produced cement has low resistance to sulfur salts. Decreasing the coefficient AM value less than 0.64 reduces the viscosity of the liquid phase and increases its density value and leads to difficulty in burning the clinker and prevents the presence of the (C3A) phase in the clinker produced. The cement is resistant to salts and its hydration temperature is low.

3.5. Conversion Rate (Feeding Materials➔Clinker)

When the feedstock is burned, every 100 parts of calcium carbonate decomposes into 44 parts carbon dioxide and 56 parts calcium oxide as the water in the feed material evaporates. Hence the combustion losses consist of water vapor and carbon dioxide gas. Assuming the proportion of water in the feedstock is x, this ratio can be calculated based on experimental measurements of the general loss of the feed material and the possible loss of calcium carbonate with the following relationship:

$$x = (LI - 0.44 * CaCO_3\%)/(100 - CaCO_3\%) \quad (6)$$

where LI is lost by ignition. Then, the amount of clinker produced from one kilogram of feeding material, a, is given by the following relationship:

$$a = 1 - 0.01 * [0.44 * CaCO_3\% + x * (100 - CaCO_3\%)] \quad (7)$$

Thus, the necessary amount of feeding material, b, to produce one kilogram of clinker is given by the following relationship:

$$b = \frac{1}{a} \tag{8}$$

The percentage of calcium oxide, *C*, in the clinker material is determined by the following relationship:

$$C = \frac{CaCO_3\%*56}{100*a} \tag{9}$$

3.6. Portland Cement Clinker - Principal Minerals

According to [24] Portland cement clinker contains four principal minerals: Alite (typically about 65 percentage of the total), Belite (typically about 15 percentage of the total), Aluminate (typically about 7 percentage of the total) and Ferrite (typically about 8 percentage of the total). Alite is a solid solution series of trigonal, monoclinic and triclinic. Alite may include up to approximately 4 percent impurity. Belite is a solid solution series of trigonal, orthorhombic and monoclinic. Aluminate and the ferrite or interstitial phases crystallize from the melt with a degree of separation which increases with decreasing rate of cooling.

Long time ago, namely on 1929, Bogue proposed a method for calculating the main four principal minerals of the Portland cement clinker basing on the chemical analysis of the feeding raw materials [25]. This method was frequently used through the years, and within the numerous citations one can mention [26-29]. In the present work, the normalized calcination saturation factor K:

$$K = \frac{CaO\% - (1.65*Al_2O_3\% + 0.35*Fe_2O_3\%)}{2.8*K_{max,exp}SiO_2\%} \tag{10}$$

Is used:

$$C3S = 3.8 * SiO_2 * (3K - 2) \tag{11}$$

$$C2S = 8.6 * SiO_2 * (1 - K). \tag{12}$$

$$C3A = 2.65 * (Al_2O_3\% - 0.64 * Fe_2O_3\%) \tag{13}$$

$$C4AF = 3.04 * Fe_2O_3\% \tag{14}$$

3.7. Fuel Saving

By defining the specific consumption as the amount of HFO needed to produce one kilogram of clinker, the fuel-clinker conversion rate can be calculated. The saving rate that any new fuel can provide in comparison with HFO can be evaluated according to the following relationship:

$$Saving\ rate = 100x\ \frac{(new\ fuel\ consumption - old\ fuel\ consumption)}{old\ fuel\ consumption} \tag{15}$$

4. RESULTS AND DISCUSSIONS

4.1. Normal Feeding Rate

4.1.1. Raw Materials Composition

In order to determine the conversion rate (feeding materials➔ clinker) the chemical analysis of the feeding materials were done using XRF technique and the LI at 950°C was measured also. The results are given in Tables **1** and **2**. Then, by applying the relationships (6) - (9) to the data of Tables 1 and 2, the numerical values of *x, a, b*, and *C* are determined. Table (3) shows the values of these parameters in addition to the measured values of calcium oxide C_m in the clinker samples produced from the studied feeding

Table1: Raw Material Composition of the First Series of Experiments at Kiln No. 2

75.1	75.19	75.1	75.2	76.3	75.6	76.1	76.6	76.2	76.1	$CaCO_3$
2.58	3.06	3.33	3.07	2.98	2.97	2.96	2.87	2.89	2.87	Al_2O_3
2.28	2.87	2.97	2.94	2.81	2.76	2.69	2.62	2.65	2.63	Fe_2O_3
44.42	42.58	42.18	42.68	42.91	43.26	43.52	43.61	43.44	43.51	CaO
1.7	2.17	2.27	2.16	2.04	1.98	1.92	1.79	1.83	1.76	MgO
0.13	0.13	0.13	0.13	0.13	0.13	0.12	0.12	0.12	0.11	K_2O
11.29	12.60	12.79	12.49	12.29	11.93	12.03	11.93	11.84	11.94	SiO_2
0.34	0.15	0.16	0.13	0.13	0.15	0.12	0.11	0.11	0.08	SO_3
36.22	34.91	34.55	34.81	34.96	35.3	41.3	35.5	35.41	35.5	LI-950°C

Table 2: Raw Material Composition of the Second Series of Experiments at Kiln No. 1

75.3	76.3	76.4	76.3	75.1	76.3	75.4	75.8	75.3	76.1	76.3	$CaCO_3$
2.84	2.77	2.58	2.7	2.6	2.64	2.65	2.65	2.59	2.6	2.58	Al_2O_3
2.77	2.67	2.54	2.64	2.6	2.63	2.62	2.65	2.67	2.59	2.6	Fe_2O_3
43.11	43.36	43.37	43.43	43.07	43.02	42.94	43.2	43.05	43.87	43.66	CaO
2.38	2.32	2.34	2.31	2.62	2.11	2.02	2.13	2.28	2.1	2.08	MgO
11.61	11.71	11.52	11.65	12.01	12.75	12.27	11.89	11.79	11.35	11.34	SiO_2
0.22	0.33	0.21	0.18	0.27	0.07	0.15	0.08	0.02	0.05	0.06	SO_3
35.3	35.6	35.7	35.5	35.4	35	34.9	34.8	35	35.4	35.2	LI-950°C

Table 3: The Estimated Values of *x, a, b* and *C*. C_m is the Measured Value of *C*

0.076	0.063	0.072	0.085	0.075	0.078	x
0.650	0.654	0.651	0.647	0.645	0.646	a
1.538	1.529	1.535	1.546	1.549	1.548	b
64.75	64.31	64.66	65.47	66.46	66.07	C
62.50	64.71	61.86	62.92	64.89	64.56	C_m
3.60	-0.61	4.52	4.05	2.42	2.34	*RE*

materials. It is clear from Table **3** that, the relative difference (RE) between the measured values of calcium oxide C_m and the proportions calculated C on the basis of relationship (5) acceptable.

4.1.2. Feeding Materials➔Clinker Conversion Rate

It is seen from Table **3** that average amount of feeding materials to produce 1 kg of clinker is 1.542 kg.

4.1.3. Clinker Composition

During the provided experiments, the measured percentages of oxides and losses in the produced clinker material are determined using XRF technique. The results are shown in Tables **4**, which corresponds to the clinker produced using ordinary fuel HFO, and 5, which corresponds to the clinker produced using emulsified fuel $W_{0.08}/HFO_{0.92}$.

4.1.4. Clinker Phases

The provided data in Tables **4** and **5** can be used to determine the main clinker phases following equations (10) to (14). The results are given in Tables **6**, which corresponds to the clinker produced using ordinary fuel HFO, and **7**, which corresponds to the clinker produced using emulsified fuel $W_{0.08}/HFO_{0.92}$.

Table 4: Clinker Composition of the First Series of Experiments with HFO at Kiln No. 2

1050	1150	1170	1210	1150	1230	1000	1040	1000	Liter weight
4.96	4.97	5.00	4.84	4.97	4.98	4.92	4.90	4.96	Al_2O_3
4.08	4.08	4.07	4.07	4.08	4.07	4.11	4.12	4.09	Fe_2O_3
61.98	62.50	64.71	61.86	62.49	62.92	63.73	64.89	64.56	CaO
3.33	3.13	3.87	3.59	4.00	3.15	2.75	2.62	2.97	MgO
0.19	0.16	0.17	0.17	0.13	0.17	0.17	0.15	0.14	K_2O
19.16	19.86	19.15	19.73	20.11	19.23	19.54	20.01	19.65	SiO_2
2.97	2.47	2.75	2.53	1.31	2.59	2.37	2.19	1.69	SO_3
0.18	0.16	0.36	0.20	0.11	0.09	0.09	0.33	0.17	LI-950°C

Table 5: Clinker Composition of the Second Series of Experiments with W/HFO at Kiln No. 1

1200	1180	1160	1230	1220	1160	1120	1180	1210	1140	1120	Liter weight
4.83	4.44	4.82	4.8	4.8	4.8	4.79	4.77	4.8	4.8	4.78	Al_2O_3
4.08	4.07	4.06	4.09	4.09	4.1	4.09	4.11	4.1	4.09	4.09	Fe_2O_3
60.48	60.99	60.96	62.41	63.16	62.64	61.49	62.29	62.45	61.83	61.97	CaO
4.43	4.44	5.23	3.97	3.75	3.58	3.65	3.44	3.63	3.39	3.31	MgO
0.19	0.17	0.15	0.19	0.18	0.22	0.21	0.19	0.21	0.19	0.18	K_2O
20.11	20.09	19.95	19.2	19.46	19.6	18.5	19.35	19.21	18.84	18.26	SiO_2
2.05	1.52	0.99	1.68	1.69	2.41	2.56	1.86	2.38	1.46	1.28	SO_3
0.34	0.1	0.09	0.04	0.9	0.05	0.1	0.14	0.33	0.27	0.34	LI-950°C

Table 6: Clinker Main Phases with HFO

0.94	0.95	0.94	0.92	0.97	0.94	K
56.19	56.71	55.65	53.89	60.59	55.41	C3S
9.21	7.90	8.44	12.41	3.94	8.77	C2S
3.67	5.07	5.01	5.09	4.89	4.90	C3A
14.90	14.23	14.20	14.01	14.23	14.26	C4AF

Table 7: Clinker Main Phases with $W_{0.08}/HFO_{0.92}$

0.96	0.96	0.94	0.98	0.95	0.96	0.97	K
63.81	64.80	61.67	65.56	62.37	63.88	64.26	C3S
6.90	6.90	9.67	3.58	8.42	6.88	5.53	C2S
5.78	5.78	5.77	5.76	5.67	5.77	5.78	C3A
14.59	14.59	14.59	14.56	14.50	14.59	14.59	C4AF

4.1.5. Fuel Specific Consumption

Basing on the specific consumption definition, the amount of HFO needed to produce one kilogram of clinker (the fuel-clinker conversion rate can be calculated) was found with pure HFO to be 0.126 dm^3 while it was found to be 0.113 dm^3 with $W_{0.08}/HFO_{0.92}$. Thus, according to equation (15), the fuel saving is 10.32%.

4.2. Low Feeding Rate

4.2.1. Raw Materials Composition

In order to determine the conversion rate (feeding materials ➔ clinker) the chemical analysis of the feeding materials were done using XRF technique and the LI at 950°C was measured also. The results are given in Tables **8** and **9**. Then, by applying the relationships (6) - (9) to the data of Tables 8 and 9, the numerical values of *x, a, b*, and *C* are determined. Table (10) shows the values of these parameters in addition to the measured values of calcium oxide C_m in the clinker samples produced from the studied feeding materials. It is clear from Table 10 that, the results are similar to those of Table 3 and the relative difference (RE) between the measured values of calcium oxide C_m and the proportions calculated C on the basis of relationship (5) acceptable.

Table 8: Raw Material Composition of the Third Series of Experiments at kiln No. 1

75.8	76.82	77.47	76.57	$CaCO_3$
3.43	3.21	3.2	3.26	Al_2O_3
2.94	2.77	2.74	2.87	Fe_2O_3
43.21	43.93	44.08	43.52	CaO
2.31	2.26	2.18	2.34	MgO
0.19	0.19	0.2	0.19	K_2O
12.19	11.97	11.76	12.23	SiO_2
0.51	0.62	0.47	0.59	SO_3
35.72	35.37	36.14	35.31	LI-950°C

Table 9: Raw Material Composition of the Fourth Series of Experiments at Kiln No. 1

76.6	76.1	75.3	75.44	$CaCO_3$
3.46	3.24	3.27	3.07	Al_2O_3
2.93	2.84	2.86	2.63	Fe_2O_3
42.74	43.62	43.67	44.12	CaO
2.8	2.33	2.34	2.23	MgO
0.17	0.17	0.17	0.16	K_2O
14.17	11.86	11.96	11.78	SiO_2
0.99	0.29	0.26	0.28	SO_3
35.19	35.08	35.64	35.72	LI-950^{o}C

Table 10: The Estimated Values of *x, a, b* and *C* in the Low Feeding Experiments

3	2	1	Experiment
0.11	0.09	0.08	x
0.64	0.67	0.65	a
1.56	1. 5	1.54	b
66.63	63.46	66.45	C
64.6	64.42	65.79	C_m
2.03	-0.96	0.66	*RE(%)*

4.2.2. Feeding Materials➔Clinker Conversion Rate

It is seen from Table **10** that the average amount of feeding materials to produce 1 kg of clinker is 1.533 kg.

4.2.3. Clinker Composition

During the provided experiments, the measured percentages of oxides and losses in the produced clinker material are determined using XRF technique. The results are shown in Tables **11**, which corresponds to the clinker produced using ordinary fuel HFO, and **12**, which corresponds to the clinker produced using emulsified fuel $W_{0.08}/HFO_{0.92}$.

4.2.4. Clinker Phases

When calculating the main clinker phases in the case of low feeding, it is found that, see Table **13**, the main influence of the W/HFO is on the Belite and Aluminate phases. Thus, our finding that the clinker itself is a mixture of at least four distinct compounds, called alite, belite, aluminate and ferrite is (see Table **13**), which are discharged from the kiln and cooled in the cooler, is in agreement with available literature (see for example [30]). Even so, the percentage of each phase could be different depending on the percentages of main oxides in the feeding materials.

Table 11: Clinker Composition of the Third Series of Experiments with HFO at Kiln No. 1

1210	1170	1150	1050	1280	1240	1220	1190	1170	Liter weight
5.23	5.29	5.13	5.09	5.25	5.16	5.24	5.14	5.29	Al_2O_3
4.44	4.45	4.43	4.43	4.42	4.42	4.43	4.41	4.45	Fe_2O_3
65.4	65.76	66.89	65.83	64.71	64.71	65.58	66.35	65.76	CaO
3.51	3.51	3.35	3.29	3.38	3.36	3.46	3.31	3.51	MgO
0.17	0.17	0.12	0.2	0.27	0.27	0.24	0.22	0.17	K_2O
20.35	20.49	20.38	20.63	19.95	19.58	19.58	19.71	19.98	SiO2
1.37	1.26	0.98	1.43	2.27	2.25	1.97	1.81	1.26	SO_3

Table 12: Clinker Composition of the Fourth Series of Experiments with W/HFO at Kiln No. 1

1170	1150	1120	1200	1230	1240	1280	1210	Liter weight
5.21	5.12	5.11	5.09	5.12	5.18	5.22	4.97	Al_2O_3
4.44	4.42	4.42	4.42	4.43	4.43	4.44	4.41	Fe_2O_3
64.03	64.86	64.05	64.39	64.78	64.93	63.61	66.25	CaO
3.47	3.52	3.8	3.6	3.6	3.62	3.61	3.41	MgO
0.19	0.19	0.2	0.19	0.17	0.18	0.23	0.16	K_2O
19.65	19.84	19.64	19.74	20.71	20.66	20.44	19.96	SiO2
1.8	1.71	1.77	1.69	1.42	1.49	1.85	1.46	SO_3

Table 13: Clinker Main Phases with $W_{0.08}/HFO_{0.92}$ at Low Feeding Case

0.94	0.98	0.96	0.95	0.96	0.93	0.93	0.94	0.95	0.96	0.95	K
59.96	65.62	61.83	62.08	64.12	58.31	57.12	59.14	60.91	62.35	61.14	C3S
3.15	1.34	2.42	2.55	2.35	3.78	3.74	3.20	2.81	2.34	2.77	C2S
5.87	5.78	5.94	5.91	5.81	5.85	6.12	6.07	5.93	5.94	5.92	C3A
13.38	13.44	13.44	13.44	13.44	13.41	13.41	13.44	13.41	13.44	13.42	C4AF

4.2.5. Fuel Saving

In the case of low feeding rate, it was found that the specific consumption with pure HFO is 0.154 dm^3 while it was found to be 0.134 dm^3 with $W_{0.08}/HFO_{0.92}$. Thus, according to equation (15), the fuel saving is 12.99%.

5. CONCLUSIONS

Analysis of the obtained results allows the following conclusions:

1. The role of emulsified fuel in reducing the specific consumption value of rotary kilns is proven experimentally. The use of $W_{0.08}/HFO_{0.92}$ leads to a fuel saving of 10.30% at normal feeding rate while the fuel saving is of 12.99% at low feeding rate.

2. It also showed that the use of $W_{0.08}/HFO_{0.92}$ saves the amount of fuel needed to ensure the smooth operation of the kilns.

3. Observations showed that the use of HFO in kilns leads to problems resulting from the lack of complete combustion of the HFO, which leads to a rise in the heat of the preheaters after the rotary kiln to about 750°C and the occurrence of problems that lead to the stoppage of the production line for maintenance, while the use of the emulsified fuel makes the combustion complete and greatly reduces these problems.

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REFERENCES

[1] Van Oss HG, Padovani AC. Cement manufacture and the environment, Part I: Q5 chemistry and technology. J Ind. Ecol 2002; 6(1): 89-105. https://doi.org/10.1162/108819802320971650

[2] Van Oss HG, Padovani AC. Cement manufacture and the environment, Part II: environmental challenges and opportunities. J Ind. Ecol. 2003; 7(1): 93-126. https://doi.org/10.1162/108819803766729212

[3] Madlool NA, Saidur R, Hossain MS, Rahim NA. A critical review on energy use and savings in the cement industries. Renew Sustain Energy Rev, 2011; 15(4): 2042-2060. https://doi.org/10.1016/j.rser.2011.01.005

[4] Aranda Usón A, López-Sabirón AM, Ferreira G, & Llera Sastresa E. Uses of alternative fuels and raw materials in the cement industry as sustainable waste management options. Renewable and Sustainable Energy Reviews, 2013; 23: 242-260. https://doi.org/10.1016/j.rser.2013.02.024

[5] Ngadi Z, Lahlaouti ML. Impact of using Alternative fuels on cement rotary kilns: Experimental study and modeling. Procedia Engineering, 2017; 181: 777-784. http://creativecommons.org/licenses/by-nc-nd/4.0/ https://doi.org/10.1016/j.proeng.2017.02.465

[6] Genon G, & Brizio E. Perspectives and limits for cement kilns as a destination for RDF. Waste Management, 2008; 28(11): 2375-2385. https://doi.org/10.1016/j.wasman.2007.10.022

[7] Mokrzycki E, & Uliasz- Bocheńczyk A. Alternative fuels for the cement industry. Applied Energy, 2003; 74(1-2): 95-100. https://doi.org/10.1016/S0306-2619(02)00135-6

[8] Zabaniotou A, & Theofilou C. Green energy at cement kiln in Cyprus-Use of sewage sludge as a conventional fuel substitute. Renewable and Sustainable Energy Reviews 2008; 12(2): 531-541. https://doi.org/10.1016/j.rser.2006.07.017

[9] Rahman A, Rasul MG, Khan MMK, & Sharma S. Recent development on the uses of alternative fuels in cement manufacturing process. Fuel, 2015; 145: 84-99. https://doi.org/10.1016/j.fuel.2014.12.029

[10] Schuhmacher M, Nadal M, & Domingo JL. Environmental monitoring of PCDD/Fs and metals in the vicinity of a cement plant after using sewage sludge as a secondary fuel. Chemosphere, 2009; 74(11): 1502-1508. https://doi.org/10.1016/j.chemosphere.2008.11.055

[11] Conesa JA, Gálvez A, Mateos F, Martín-Gullón I, & Font R. Organic and inorganic pollutants from cement kiln stack feeding alternative fuels. Journal of Hazardous Materials, 2008; 158(2-3): 585-592. https://doi.org/10.1016/j.jhazmat.2008.01.116

[12] Mei S, Xie J, Chen X, He F, Yang H, & Jin M. Numerical simulation of the complex thermal processes in a vortexing precalciner. Applied Thermal Engineering, 2017; 125: 652-661. https://doi.org/10.1016/j.applthermaleng.2017.07.041

[13] European Commission. Reference Document on the Best Available Techniques in the Cement and Lime Manufacturing Industries. BAT Reference Document (BREF), European IPPC Bureau, Seville, Spain 2011.

[14] Vdz Media release (2009). Environmental Data of the German Cement Industry, www.vdz-online.de/uploads/media/Environmental_data_2009.pdf

[15] Kaantee U, Zevenhoven R, Backman R, Hupa M. Cement manufacturing using alternative fuels and the advantages of process modelling. Fuel Process Technol 2004; 85(4): 293-301 https://doi.org/10.1016/S0378-3820(03)00203-0

[16] Rahman A, Rasul MG, Khan MMK, & Sharma S. Recent development on the uses of alternative fuels in cement manufacturing process. Fuel, 2015; 145: 84-99. https://doi.org/10.1016/j.fuel.2014.12.029

[17] Soulayman S, El-Khatib R. The Effect of Fuel Emulsion on Fuel Saving in Fire Tube Boilers of Tartous Company for Cement and Construction Materials. Journal of Solar Energy Research Updates, 2019; 6: 69-77.

[18] Li YY, Hou SS, & Sheu WJ. Investigation on boiler efficiency and pollutant emissions of water/heavy oil emulsions using edge-tone resonant homogenizer. Fuel, 2014; 119: 240-251. https://doi.org/10.1016/j.fuel.2013.11.029

[19] Katin V, Kosygin V, Akhtiamov M, & Vol'khin I. Mathematical Models of the Output of Major Pollutants in the Process of Burning Water Fuel Oil Emulsions in Boiler Plants. Advances in Intelligent Systems and Computing, 2017; 987-997. https://doi.org/10.1007/978-3-319-70987-1_107

[20] Lin SL, Lee WJ, Chang SS, Lee C, Lee LF, Lin CS, & Loong H. Energy Savings and Emission Reduction of Traditional Pollutants, Particulate Matter, and Polycyclic Aromatic Hydrocarbon Using Solvent-Containing Water Emulsified Heavy Fuel Oil in Boilers. Energy & Fuels, 2011; 25(4): 1537-1546. https://doi.org/10.1021/ef200083g

[21] Chelemuge Namioka T, Yoshikawa K, Takeshita M, & Fujiwara K. Commercial-scale demonstration of pollutant emission reduction and energy saving for industrial boilers by employing water/oil emulsified fuel. Applied Energy, 2012; 93: 517-522. https://doi.org/10.1016/j.apenergy.2011.12.018

[22] Staněk Theodor, Sulovský Petr. The Impact of Basic Minor Oxides on the Clinker Formation. Materials Science Forum, 2017; 908: pp 3-9. https://doi.org/10.4028/www.scientific.net/MSF.908.3

[23] Alemayehu, F. and Sahu, O. Minimization of Variation in Clinker Quality. Advances in Materials, 2013; 2: 23-28. https://doi.org/10.11648/j.am.20130202.12

[24] Ghosh SN (2002) Advance in cement technology; chemistry, manufacture and testing, (2ndedn), published by Tech Books International, New Delhi, India.

[25] Bogue RH. Calculation of the Compounds in Portland Cement. nd. Eng. Chem. Anal. Ed. 1929; 1(4): 192-197. https://doi.org/10.1021/ac50068a006

[26] Morten Nedergaard Pedersen, Mads Nielsen, Sønnik Clausen, Peter Arendt Jensen, Lars Skaarup Jensen, and Kim Dam-Johansen. Imaging of Flames in Cement Kilns To Study the Influence of Different Fuel Types. Energy & Fuels, 2017; 31 (10): 11424-11438. https://doi.org/10.1021/acs.energyfuels.7b01954

[27] LE. Copeland, Stephen. Brunauer, DL. Kantro, EG. Schulz, and CH. Weise. Quantitative Determination of Four Major Phases of Portland Cement by Combined X-Ray and Chemical Analysis. Analytical Chemistry, 1959; 31(9): 1521-1530. https://doi.org/10.1021/ac60153a032

[28] Islem Labidi, Sonia Boughanmi, Houcine Tiss, Adel Megriche. Critical research study of quantification methods of mineralogical phases in cementitious materials. Journal of the Australian Ceramic Society, 2019; 55 (4): 1127-1137. https://doi.org/10.1007/s41779-019-00327-5

[29] Yonggang Yao, Wenlong Wang, Zhi Ge, Changzai Ren, Xingliang Yao, Shuang Wu. Hydration study and characteristic analysis of a sulfoaluminate high-performance cementitious material made with industrial solid wastes. Cement and Concrete Composites, 2020; 112: 103687. https://doi.org/10.1016/j.cemconcomp.2020.103687

[30] Fellaou S, Harnoune A, Seghra MA, Bounahmidi T. Statistical Modeling and Optimization of the Combustion Efficiency in Cement Kiln Precalciner, Energy 2018. https://doi.org/10.1016/j.energy.2018.04.181

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