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Environmental impact assessment of alternative fuels co-processing in rotary cement kilns

This study focuses on comparison of potential negative environmental impact of the coal combustion and its partial substitution by alternative fuels from combustible wastes (used tires and solid alternative fuel TP-1) during Portland cement clinker production in rotary cement kiln. Environmental impact assessment was carried out based on the fuels chemical composition and operating parameters of a rotary cement kiln in accordance with EURITS and IMPACT 2002+ methodologies. Chemical composition and physical properties of used tires and solid alternative fuel from plastic, paper and wood waste mixture (TP-1) were studied. Available data shows that hard coal from Ukrainian deposits has high level of some pollutants (S = 3.1 wt. %, As = 135 ppm, Hg = 0.7 ppm). The high content of Zn (up to 4100 ppm) in used tires limits their usage as alternative fuel in cement kiln. Solid alternative fuel TP-1 was prepared in accordance with the EURITS and Lafarge Cement Group requirements. In comparison with the usage of exclusively Ukrainian coal, the use of a composite fuel, which includes up to 10 energy-eq % of used tires leads to an increase of the negative environmental impact by 8% on aquatic ecotoxicity and 5% on terrestrial ecotoxicity, respectively. But, the negative impact on global warming, aquatic eutrophication and acidification, terrestrial acidification and nutrification, respiratory effect and human toxicity was decreased. The partial substitution of coal by solid alternative fuel TP-1 in equal proportions with used tires reduces the negative environmental impact of fuel combustion in cement kiln compared to the use of coal only and in case of coal with used tires usage. Coal substitution by alternative fuels in all proposed scenarios caused less damage to human health, ecosystem quality and climate change compared to the usage of coal alone. Increase of the part of co-processed alternative fuels led to environmental damage decreases.

Keywords: **environmental impact assessment, midpoint level, damage level, rotary cement kiln, alternative fuel, used tires, solid alternative fuel (TP-1), coal, combustion, co-processing, pollutants**

Introduction

Cement production life cycle includes high energy-consuming process of raw materials sintering in a rotary kiln and this causes emissions. The burning of Portland cement clinker requires a material temperature of about 1450°C, gas temperature in the flame zone of about 2000°C, a long residence time with the strong turbulence in a rotary kiln. Such conditions are also optimal for a comprehensive utilization of a wide range of combustible wastes as alternative fuels. The practice of waste co-processing in cement kilns has been successfully applied in the EU countries, USA, Japan etc. For example in the nearest to Ukraine European neighbouring country, Poland, 14 years ago only 1.2% of thermal energy in cement industry was replaced by alternative fuel, now they replace more than 50% of coal by alternative fuels from waste (1.0 Mt per year). Some wastes such as used tires are co-processed in rotary kilns separately but 78% of all thermal energy from wastes that are used in Polish cement industry are obtained from prepared alternative fuels from combustible wastes [1-3]. The co-processing of waste has been officially recognised by the European Commission as a resource efficient best practice under its flagship initiative for a resource-efficient Europe under the Europe 2020 strategy and an optimum way of reducing dependency on fuels and raw materials as well as lowering CO_2 emissions [4].

Nowadays in Ukraine about 18 Mt of combustible wastes are unused every year. The main method of waste management is its storage in landfills, most of which are overloaded or do not meet the requirements of environmental safety. Only 30% of industrial and 4% of domestic wastes are utilized [5]. Most cement plants in Ukraine tend to reduce fuel costs and to substitute up to 40% of fossil fuels by alternative fuels from wastes. Today they are co-processing with coal only few percent of wastes, mostly used tires, sawdust, plastic and agricultural wastes. Thus, it would be reasonable to separately collect and process combustible wastes into solid alternative fuels and apply them in the cement industry.

Emissions from the cement kiln come from the physical and chemical reactions of the raw materials and from the combustion of fuels. The main constituents of the exit gases from a cement kiln are nitrogen from the combustion air, CO_2 from calcination and combustion, water from the combustion process and the raw materials, and excess oxygen. The exit gases also contain small quantities of dust, chlorides, fluorides, sulphur dioxide, NO_x, carbon monoxide, and still smaller quantities of organic compounds and heavy metals [6]. In the cement industry, a multi-stage emission cleaning is widely applied. During the sintering process, heavy metals (except for mercury, cadmium and thallium) are almost completely immobilized in clinker minerals structure, while their leaching-out from the hardened concrete was not observed [7]. However, rotary cement kilns significantly contribute to air pollution. Cement industry is responsible for about 5% of global CO_2 emissions [8] and about 5% of global mercury emissions [9].

1. Estimation of air emissions

Portland cement clinker production consists of two parallel processes - fuels combustion and raw materials sintering. The production of cement clinker releases pollutants emissions both directly and indirectly: the heating of raw materials releases pollutants directly, while the burning of fossil fuels to heat the kiln indirectly results in pollutants emissions. A typical 4x150 m wet process rotary kiln with the capacity of 34 t/h of Portland cement clinker emits approximately 350 thousand m^3/h of flue gases (10 thousand m^3/t of clinker).

Chemical composition and physical properties of used tires and solid alternative fuel TP-1 are presented in Table 1. Solid alternative fuel TP-1 was prepared in accordance with the EURITS and Lafarge Cement Group requirements by mixing wastepaper processing waste, PET-bottles waste and sawdust followed by shredding it to a size of ≤ 10 mm [10]. Available data shows that hard coal from Ukrainian deposits has increased pollutants content (S = 3.1 wt.%, As = 135 ppm, Hg = 0.7 ppm). The high content of Zn (up to 4100 ppm) in used tires is limiting their usage as alternative fuel in cement kiln.

Table 1. **The fuels characteristics**

Parameters	Coal [11, 12]	Used tires	TP-1
As, ppm	135.0	2.2	1.0
Cd, ppm	1.0	0.2	0.1
Cr, ppm	23.0	37.0	0.1
Cu, ppm	30.0	230.0	4.0
Hg, ppm	0.7	0.1	0.01
Ni, ppm	18.0	28.0	2.0
Pb, ppm	13.0	19.0	8.0
Zn, ppm	48.0	4100.0	12.0
S, wt. %	3.1	1.3	0.9
Cl, wt. %	0.1	0.3	0.3
Ash content, wt. %	16.5	16.6	4.8
Moisture content, wt. %	6.9	5.0	9.3
LHV, MJ/kg	23.3	29.6	25.9

To calculate the amounts of pollutants from the fuels combustion (coal, used tires, shredded solid alternative fuel (TP-1)) in the rotary kiln there was used stoichiometric Eq. (1) [13]:

$$C_xH_yO_zN_uCl_vS_w + \left(x + \frac{y-v}{4} - \frac{z}{2} + w\right) \cdot O_2 \rightarrow \rightarrow x \cdot CO_2 + \left(\frac{y-v}{2}\right) \cdot H_2O + \left(\frac{u}{2}\right) \cdot N_2 + v \cdot HCl + w \cdot SO_2 \quad (1)$$

where C + H + O + N + Cl + S = 100 wt.%.

A specific emission A_{ij} of j-th pollutant from combustion of the i-th fuel (kg/t_{fuel}) was calculated by the Eq. (2):

$$A_{ij} = \frac{(V_m \cdot v_{ij} \cdot \rho_j \cdot TK_j)}{100\%} \quad (2)$$

where:
V_m - overall molar volume, m^3/mol;
v_{ij} - amount of substance, mol/kg_{fuel};

ρ_j - density of the pollutant, kg/m^3;
TK_j - transfer coefficient of the pollutant, % [14].

Specific emission B_{ij} of j-th pollutant from combustion of the i-th fuel during clinker production (kg/$t_{clinker}$) was calculated by the Eq. (3):

$$B_{ij} = \frac{A_{ij} \cdot Q_{clinker}}{Q_i} \tag{3}$$

where:
A_{ij} - specific emission of pollutant from combustion of the fuel, kg/t_{fuel};
Q_i - fuel net calorific value (GJ/t_{fuel});
$Q_{clinker}$ - specific heat for clinker sintering, GJ/$t_{clinker}$.

The output specific emissions were estimated by the use of (linear) transfer coefficients, which gives the ratio of the emissions of an element in one specific output flow, relative to the total amount of that element in the input.

2. Environmental impact assessment

A potential environmental impact of coal usage and alternative fuels from combustible wastes co-processing was evaluated in accordance with the life cycle impact assessment methodology IMPACT 2002+ (ver. 2.1) [15].

Algorithm of environmental impact assessment is derived by multiplying the amount of consumed/emitted compounds from different elementary flows with respective characterization factors, corresponding to impact categories (Fig. 1). An elementary flow can have an impact on different midpoint categories within a same damage category, as well as on different damage categories.

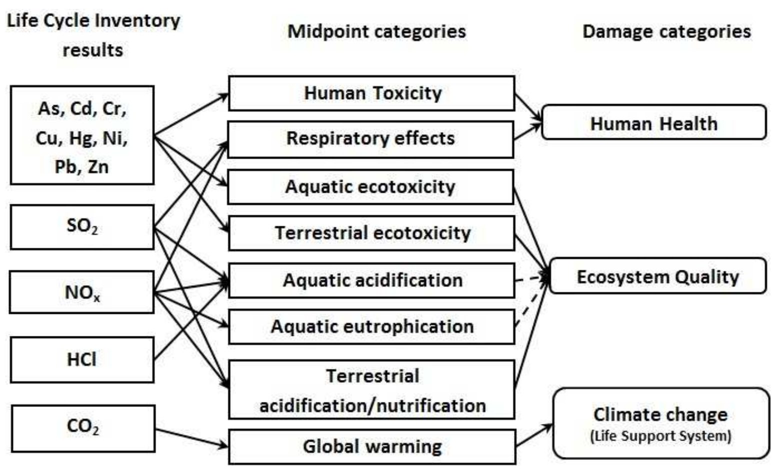


Fig. 1. The scheme demonstrates environmental impacts of fuel combustion in rotary cement kiln based on the IMPACT 2002+ methodology and links life cycle inventory results, midpoint categories and damage categories

In most cases, pollutants from fuel combustion had a simultaneous negative effect on several environmental categories (Fig. 1). An arrow shows a quantitatively modelled impact pathway. The impact pathways between midpoint and damage categories, presented by dotted arrows, presumably exist, however, due to the missing data that were not quantitatively modelled [15].

A midpoint score characterizes the elementary flows and other environmental interventions that contribute to the same impact and calculated as following [15]:

$$S_M = \sum (emission_i \cdot CF_i^m) \tag{4}$$

where:
S_M - a midpoint score, kg_{eq} substance X;
$emission_i$ - the amount of emitted pollutant X, kg;
CF_i^m - midpoint characterization factor, kg_{eq} substance X/$kg_{emitted}$.

The normalized damage score is calculated as following:

$$S_{DN} = \sum (emission_i \cdot DF_i^n) \tag{5}$$

where:
S_{DN} - normalized damage score, points = pers·yr;
$emission_i$ - the amount of emitted pollutant X, kg;
DF_i^n - normalized damage factor, points/$kg_{emitted}$.

A "point" represents the average impact in a specific category "caused" by a person during one year in Europe. It is calculated as the total yearly damage score due to emissions and extractions in Europe divided by the total European population.

Presented results of the environmental impact assessment were calculated for different scenarios (Fig. 2) and do not take into account emissions from clinker raw materials sintering.

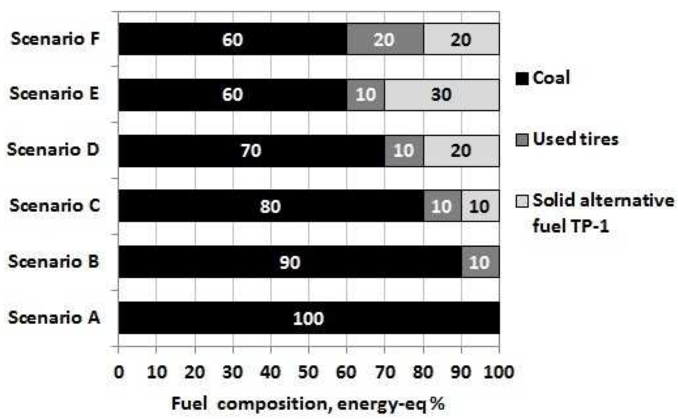


Fig. 2. Different scenarios of the fuel mixture composition

The impact in relative units (%) for wet process kilns is the same as for dry process kilns at the midpoint as well as at the damage level. An environmental impact assessment results at the midpoint level of fuels combustion by the scenarios shown in Figure 3.

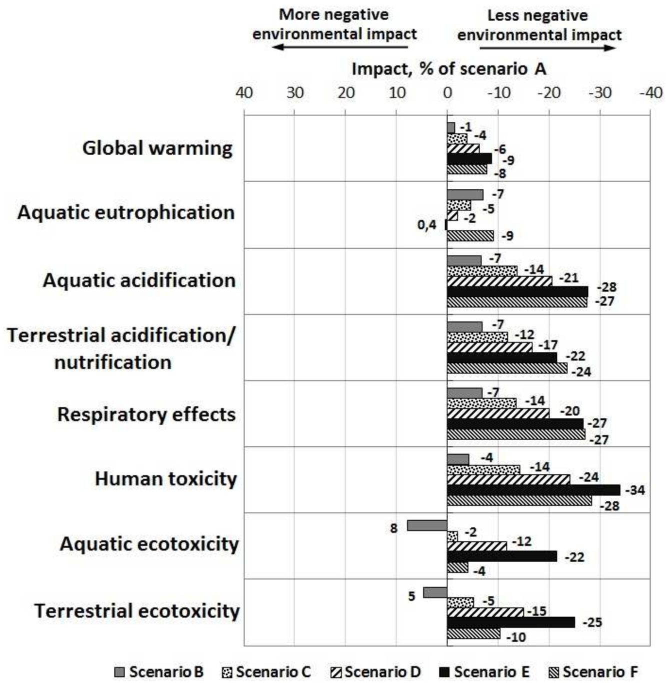
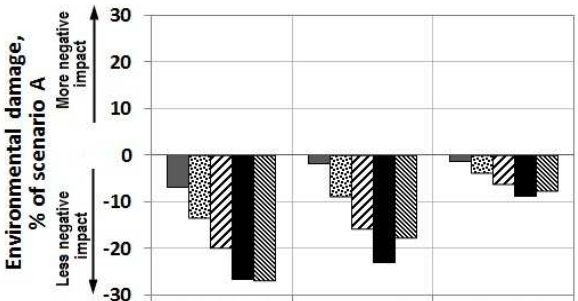


Fig. 3. The scheme of midpoint categories used for the environmental impact assessment of alternative fuels co-processing versus coal combustion in rotary cement kiln

The higher the value, the greater impact on the environment, negative values (below zero) reflect the best environmental outcomes compared to the baseline scenario. As shown in Figure 3, coal substituting by 10 energy-eq % of used tires (Scenario B) increased by 8% impact on aquatic ecotoxicity and by 5% on terrestrial ecotoxicity, compared to Scenario A (baseline scenario). Meanwhile, impact on global warming, aquatic eutrophication and acidification, terrestrial acidification/nutrification, respiratory effects and toxicity to humans were decreased, compared with the baseline scenario. Usage of 10÷20 energy-eq % of solid alternative fuel TP-1 (Scenarios C, D, F) reduced the impact on all eight midpoint environmental categories compared to the baseline scenario and scenario B. In the midpoint level coal substitution by solid alternative fuel TP-1 in equal proportions with used tires (Scenarios C, F) reduces the potential negative impact of fuel combustion in cement kiln on the environment compared to the baseline scenario and in case of coal with used tires usage (Scenarios A, B).

In consequence, a further step of environmental impact assessment allocated all eight midpoint categories, without aquatic acidification and aquatic eutrophication taken into account, to one or more damage categories (Fig. 1). A damage indicator result is the quantified representation of this quality change. It was evaluated that coal substitution by alternative fuels in all proposed scenarios caused less damage to human health, ecosystem quality and climate change compared to the baseline scenario (Fig. 4). Increase of the part of alternative fuels in the fuel mixture led to decreased environmental damage.



	Human health	Ecosystem quality	Climate change
Scenario C	-6,9	-1,8	-1,5
Scenario D	-13,5	-8,9	-3,9
Scenario G	-20,1	-16,0	-6,4
Scenario H	-26,8	-23,1	-8,8
Scenario F	-27,0	-17,8	-7,8

Fig. 4. The scheme of damage categories used for the environmental impact assessment of fuel combustion in rotary cement kiln

Conclusion

Waste utilization as alternative fuels in cement industry reduces the usage of non-renewable natural resources (coal) and reduces the amount of accumulated waste. Thus, the main objectives of the Sustainable Development Strategy, a harmonious combination of benefits to the industry (cement), society and environment, are implemented. It was revealed that partial coal substitution by alternative fuels causes less negative impact on the environment than coal combustion in rotary cement kiln. The results of environmental impact assessment allow us to optimally decrease the usage of non-renewable natural fuels in cement industry.

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Ocena oddziaływania na środowisko współspalania paliw alternatywnych w obrotowych piecach cementowych

Przeprowadzone badanie skupia się na porównaniu potencjalnego negatywnego oddziaływania na środowisko spalania węgla i jego częściowej substytucji paliwem alternatywnym z odpadów palnych (zużyte opony samochodowe i paliwo alternatywne stałe TP-1) podczas produkcji klinkieru portlandzkiego w obrotowych piecach cementowych. Ocena oddziaływania na środowisko została przeprowadzona na podstawie składu chemicznego paliw i parametrów pracy obrotowego pieca cementowego zgodnie z metodologią EURITS i IMPACT 2002+. Zbadano skład chemiczny i właściwości fizyczne zużytych opon samochodowych i paliwa alternatywnego stałego (TP-1) z mieszanki odpadów tworzyw sztucznych, papieru i drewna. Dostępne dane wskazują, że węgle kamienne ze złóż ukraińskich posiadają podwyższoną zawartość zanieczyszczeń chemicznych (S = 3,1% wag., As = 135 ppm, Hg = 0,7 ppm). Wysoka zawartość cynku (do 4100 ppm) w zużytych oponach ogranicza ich wykorzystanie jako paliwa alternatywnego w piecach cementowych. Paliwo alternatywne stałe TP-1 zostało przygotowane zgodnie z wymaganiami EURITS i Grupy Lafarge Cement. W porównaniu z wykorzystaniem wyłącznie ukraińskiego węgla kamiennego stosowanie paliwa kompozytowego, w którym ilość zużytych opon nie przekracza 10% energii cieplnej, wywołuje większy o 8% wpływ na ekotoksyczność dla wód oraz o 5% większy wpływ na ekotoksyczność lądową. Jednak zmniejszał się negatywny wpływ na globalne ocieplenie, eutrofizację i zakwaszenie

wód, zakwaszenie i eutrofizację gleby, efekt dla układu oddechowego i toksyczność dla ludzi. Częściowe zastąpienie węgla stałym paliwem alternatywnym TP-1 w równych proporcjach z zużytymi oponami zmniejsza negatywny wpływ spalania paliwa w piecu cementowym na środowisko w porównaniu z wykorzystywaniem samego węgla i w przypadku współspalania węgla z zużytymi oponami. Zastąpienie węgla paliwem alternatywnym według proponowanych scenariuszy (receptur mieszanki paliwowej) powodowało mniejsze szkody dla zdrowia człowieka, jakości ekosystemu i zmian klimatu w porównaniu do wykorzystania wyłącznie węgla kamiennego. Zwiększenie udziału współspalanych paliw alternatywnych doprowadziło do zmniejszenia szkód dla środowiska naturalnego.

Słowa kluczowe: **ocena oddziaływania na środowisko, poziom środkowy oddziaływania na środowisko, poziom szkód, obrotowy piec cementowy, paliwo alternatywne, zużyte opony, paliwo alternatywne stałe (TP-1), węgiel, spalanie, współspalanie, zanieczyszczenia**