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Low-Carbon Cement: Technological and Production Impacts of Clinker Factor Reduction

Natalia Junakova[1*], *Magdalena* Balintova[1], *Jozef* Junak[1], *Pavol* Kočiš[2], and *David* Pacak[1]

[1]Technical University of Kosice, Faculty of Civil Engineering, Vysokoškolska 4, 042 00 Košice, Slovakia
[2]Danucem Slovensko a.s., Cementáreň Turňa, 906 38 Rohožník, Slovakia

Abstract. The impact of the cement industry on the environment is undeniable, and therefore it is necessary to look for options and ways to minimize this impact as much as possible. A promising solution is the use of alternative fuels as a replacement for fossil fuels and the greatest possible degree of recycling and use of secondary raw materials. The paper focuses on the proposal of an alternative recipe for a specific cement produced in a cement plant in Slovakia with the aim of preparing low-carbon cement by optimizing the clinker factor. The proposed recipes were compared primarily in terms of technological and production parameters. The environmental impact was assessed only from the perspective of reducing the proportion of clinker. The results of the work show that reducing the clinker factor has a positive impact on the resulting environmental impact of the product, but the negative side of this approach is an increase in electricity consumption and a decrease in the amount of produced cement, that negatively affect the production process and reduce the competitiveness of the cement plant. However, the use of alternative grinding additives may offer a promising solution to improve grinding efficiency, allowing for increased production rates and lower energy demand despite reduced clinker content.

1 Introduction

The cement industry constitutes a fundamental component of the global economy due to its indispensable role in the construction of infrastructure and building projects. Simultaneously, it ranks among the largest emitters of carbon dioxide (CO_2) and other greenhouse gases. Cement production releases substantial amounts of CO_2, primarily as a result of high-temperature calcination of raw materials such as limestone and clay, as well as the use of energy- and resource-inefficient production technologies [1]. It is estimated that the production of one tonne of Portland cement releases approximately 0.65 – 0.95 tonnes of carbon dioxide into the atmosphere [2, 3] depending on the energy efficiency of the process, the fuels used, and the specific type of cement, making the cement sector responsible for approximately 5% to 7% of global CO_2 emissions [4]. Moreover, the manufacturing of Portland cement is highly energy-intensive [5], typically requiring between 3.2 and 6.3 GJ of

* Corresponding author: natalia.junakova@tuke.sk

energy per tonne of cement produced [6]. It is estimated that approximately 50% of CO_2 emissions associated with cement production originate from the calcination of limestone during clinker formation. Around 40% of CO_2 emissions result from the combustion of fossil fuels used to generate the high temperatures required for this process. An additional 5% of emissions are indirect, stemming from electricity consumption necessary to operate the plant. The remaining 5% are attributed to activities related to raw material extraction and transportation, including quarrying and logistics operations [7]. These factors substantially contribute to environmental burdens and intensify global climate change. Despite these challenges, the cement sector continues to expand, primarily driven by the increasing demand for infrastructure development in emerging economies and ongoing urbanization in developed countries. According to the World Cement Association, global cement production is projected to reach 8.2 billion tonnes by 2030 [8, 9].

The Slovak cement industry is likewise currently facing challenges related to technological processes and innovation, with the primary aim of increasing energy efficiency and reducing the environmental footprint of cement production. The modernization of production systems realised in many cement plants involves investments in advanced technologies such as dry-process production lines that contribute to reducing CO_2 emissions. These initiatives are essential for complying with European directives and achieving the targets set in the field of sustainable development [10, 11]. Additional important factors include product quality and market competitiveness, which necessitate continuous innovation and close monitoring of the latest trends in the construction sector. In response to the current increase in demand for construction materials driven by building and infrastructure projects, the cement industry is working to optimize production capacities and ensure a reliable supply of raw materials. Simultaneously, there is an active discussion on the prospects of integrating renewable energy sources into the cement production process, with efforts focused on identifying strategies to minimize environmental impacts [10, 11].

One of the solutions to reduce the carbon footprint in the cement industry is lowering the clinker factor by replacing clinker with alternative materials [12]. These materials such as steel slag, fly ash from power plants, natural pozzolans, or limestone can chemically or physically substitute the main component of cement - clinker. Since they are CO_2-neutral, their addition not only improves the properties of the final product but also significantly reduces CO_2 emissions. Depending on the product and its application, the use of these materials can save up to 60% of the CO_2 emissions that would otherwise be generated during clinker production [12].

The aim of this study is to propose an alternative composition for a specific type of cement produced in a Slovak cement plant, with the objective of reducing clinker proportion by optimizing the clinker factor.

2 Material and methods

2.1 Characterization of cement plant

The cement plant in Turňa nad Bodvou, operated by Danucem Slovensko a.s., is one of the key cement production facilities in the Košice region. Currently, the plant is equipped with modern technology and has a daily production capacity of up to 2,700 tons of grey cement [13].

Since 2004, thanks to advancements in modern technologies, the plant has been able to produce cement using solid alternative fuels, utilizing them as energy in the rotary kiln. The volume of waste used for co-processing currently reaches approximately 65,000 tons per year. Around 100 kilograms of coal can be replaced by approximately 170 kilograms of solid alternative fuels (TAP). When using alternative raw materials, no CO_2 is emitted, as these materials are already decarbonized.

Additionally, 30% of natural limestone is replaced by blast furnace slag, making the cement production among the most efficient in the EU in terms of CO_2 emissions. In recent years, several significant investments have been made in this cement plant to improve its environmental performance as well as the quality and efficiency of production.

2.2 Current types of cement products

The plant in Turňa nad Bodvou focuses exclusively on the production of three cement types: CEM I – Portland cement, CEM II – Composite Portland cement, CEM III – Blast furnace cement. It utilizes specific raw materials such as limestone, demetalized steel slag, clay, and sorted artificial metallurgical aggregates. Additionally, granulated blast furnace slag is used. Gypsum is also added to regulate the setting time of the cement. The clinker factor of the cement plant is below 65%, which places it among the leading producers on the domestic market.

The mentioned cements are classified according to a ECO$_2$CLASS emissions classification system developed by Danucem, which categorizes them into groups A to C. Category A products are considered the most environmentally acceptable, with CO_2 emissions from production less than 300 kg CO_2 per ton of cement. Category B includes emissions ranging from 300 to 450 kg CO_2 per ton, while Category C covers emissions from 450 to 600 kg CO_2 per ton of cement.

2.3 Proposal of a new approach to cement mix design aimed at optimizing the clinker factor

In order to reduce the clinker factor (clinker-to-cement ratio) and thereby reduce cement emission load, a new cement recipe was designed in cooperation with the company Danucem. The reduction was achieved by replacing clinker in the cement type CEM II/A-LL 42.5 R with an alternative material - limestone. This type of cement was chosen because clinker itself makes up a significant majority of its composition, and its carbon footprint is rated as category "C" according to Danucem's internal assessment. The currently used cement recipe is composed of clinker (82%), limestone (10%), anhydrite (5%), and bypass dust (3%). In addition, a grinding additive (0.03%) is added in order to reduce the electrostatic resistance of the cement during grinding, maintain the final strength of the product, and increase the performance of the cement mill.

One of the goals in designing new cement recipes was to maintain the final strength of the original recipe despite the reduction in the amount of clinker. The strength was identified as a key parameter representing the quality of the final product. As part of the clinker factor optimization, four new recipes were proposed (Table 1). In the first three recipes, the clinker factor was gradually reduced. The last recipe was prepared with the same clinker factor as recipe no. 3, but with the use of a different grinding additive.

In the designed recipes, cement technological parameters such as flexural strength, compressive strength, grinding fineness of cement samples, setting time of cement samples, and production parameters such as amount of produced cement and electricity consumption were monitored. Testing of mentioned parameters were carried out in laboratories directly at the cement plant, which has its own laboratory for testing the properties of the resulting cement formulas.

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Table 1. Current recipe and proposal of new cement mix design.

	Recipe	Clinker (%)	Limestone (%)	Anhydrite (%)	Bypass dust (%)	Grinding additive (%)
Current produced type of cement	CEM II/A-LL 42.5 R	82	10	5	3	0.03
Clinker factor optimization	No. 1	80	12	5	3	0.03
	No. 2	78	14	5	3	0.03
	No. 3	75	17	5	3	0.03
	No. 4	75	17	5	3	0.03* (different type)

* Note: Properties are subject to trade secret

3 Results and discussion

3.1 Evaluation of technological parameters of prepared recipes

In order to evaluate the technological parameters of the prepared recipes, the flexural and compressive strength of the currently produced recipe compared with the proposed recipes were performed and are shown in Table 2.

Due to the maintaining the strength of the final product as a key parameter representing its quality (presented in Table 2) and in order to compensate the reduced content of reactive clinker in the mixture, it was necessary to grind the designed/optimized cement more finely (Table 3), which subsequently affected cement produced quantity and also the electricity consumption. Samples 3 and 4 had the same grinding fineness set due to the same replacement of the clinker amount, but using a different grinding additive, which had better properties and enabled more efficient grinding of the sample with a lower clinker factor.

However, finer grinding led to an acceleration of the setting time of prepared cement samples due to the increased specific surface area that directly affects the workability of the mixture and the process of hydration. Similar results were published in the study [14], where it was emphasized that a further reduction of the clinker factor can only be achieved when compensated by optimizing the particle size distribution and the efficiency of grinding or dispersing additives. It was also highlighted that such measures are essential to maintain mechanical performance and workability while ensuring the eco-efficiency of low-clinker cements. Both the initial setting time and the final setting time were recorded (Table 4).

Table 2. Flexural and compressive strengths of prepared new cement mix design compared to initial material.

	Recipe	Flexural strength (MPa)		Compressive strength (MPa)	
		1 day	2 days	1 day	2 days
Current produced type of cement	CEM II/A-LL 42.5 R	4.6	6.6	17.6	27.5
Clinker factor optimization	No. 1	4.6	6.6	17.6	27.5
	No. 2	4.6	6.6	17.6	27.5
	No. 3	4.6	6.6	17.6	27.5
	No. 4	4.6	6.6	17.6	27.5

Table 3. Fineness of grinding of cement samples.

	Recipe	Grinding fineness (μm)
Current produced type of cement	CEM II/A-LL 42.5 R	16.5
Clinker factor optimization	No. 1	16.2
	No. 2	16.0
	No. 3	15.6
	No. 4	15.6

Table 4. Setting time of prepared cement samples.

	Recipe	Setting time (min)	
		initial	final
Current produced type of cement	CEM II/A-LL 42.5 R	140	165
Clinker factor optimization	No. 1	145	172
	No. 2	150	179
	No. 3	157	190
	No. 4	157	190

As the results given in Table 4 show, with increasing degree of clinker replacement and simultaneously increasing fineness of grinding, the setting time gradually increased. While the current recipe showed an initial setting time of 140 minutes, for samples with optimized composition the value increased up to 157 minutes. A similar trend was observed for the final setting time, which increased to 190 minutes for the last two samples. This increase can be attributed to the reduced content of reactive clinker, which although was compensated by finer grinding, nevertheless manifested itself in the form of a slower onset of hydration.

3.2 Evaluation of production parameters of prepared recipes

When designing optimized cement recipes with a reduced clinker factor, in addition to the aforementioned technological properties, parameters related to production were also monitored, namely the cement produced quantity and electricity consumption (Table 5). Monitoring the amount of produced cement allows to evaluate whether new recipes lead to a decrease in productivity or whether their impact can be considered negligible.

Table 5. Cement produced quantity and electricity consumption of prepared cement samples.

	Recipe	Cement produced quantity (t/h)	Electricity consumption (kWh/t)
Current produced type of cement	CEM II/A-LL 42.5 R	125	47.6
Clinker factor optimization	No. 1	120	48.2
	No. 2	118	49.0
	No. 3	110	52.0
	No. 4	118	49.0

Table 5 summarizes the hourly production rates and specific electricity consumption for each cement type. As expected, cement output decreases with finer grinding, which is accompanied by higher electricity consumption per tonne of cement (Fig. 1). The standard CEM II/A-LL 42.5 R recipe achieves the highest productivity (125 t/h) and the lowest specific electricity consumption (47.6 kWh/t). On the contrary, the most unfavorable situation was observed with sample no. 3 with the finest grinding, when the cement production dropped by approx. 13%. The use of a different grinding additive (sample no. 4) can also positively affect the amount of produced cement (compared to sample no. 3).

Since finer grinding is directly related to higher electricity consumption, it was important to monitor to what extent fineness adjustment affects the energy efficiency of the process. This data is also key from the point of view of economic, environmental impacts and carbon footprint assessment. The least amount of electricity is consumed by a cement plant when producing one ton of the currently used recipe. With increasing fineness of grinding, electricity consumption increases. The highest consumption was observed for sample no. 3. (Table 5), which was 9% more compared to the reference sample.

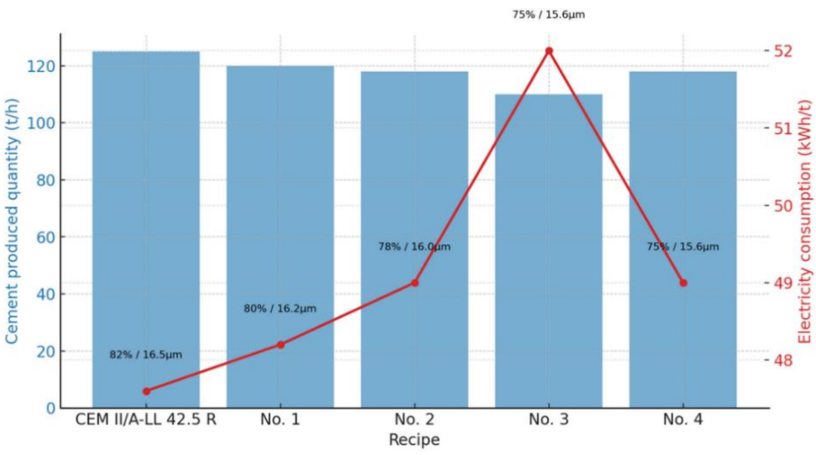

Fig. 1. Effect of clinker factor reduction and grinding fineness on cement production efficiency and energy consumption.

The relationship between clinker factor reduction and increased grinding energy demand is a crucial factor for assessing sustainability. Although lowering the clinker content helps reduce CO_2 emissions from the calcination process, finer grinding increases electricity demand, partially offsetting these savings. When assessing the impact of optimizing cement recipes on the carbon balance, it was necessary to quantify how the reduction in clinker content and changes in electricity consumption affect the total CO_2 emissions per ton of cement produced. The assessment focused on comparing the reference cement type CEM II/A-LL 42.5 R with four optimized recipes, which differ in the amount of clinker replacement and grinding fineness and subsequent electricity consumption. The approximate estimation was based on the assumptions that the clinker emission factor according to Commission Implementing Regulation (EU) 2021/447 is 0.693 t CO_2/t clinker (i.e. 693 kg CO_2/t) and the electricity emission factor for Slovakia (according to tco2e.net) is 0.123 kg CO_2/kWh, which corresponds to the average value of electricity production in the Slovak Republic. Total CO_2 emissions per tonne of cement consisted of process emissions from clinker (calcination $CaCO_3 \rightarrow CaO + CO_2$) and energy emissions associated with cement grinding. The results of the carbon balance calculation are presented in the Table 6.

Table 6. Approximate estimation of the carbon footprint of proposed cement formulations and comparison with the reference type.

Recipe	Clinker (%)	Electricity consumption (kWh/t)	Clinker emissions (kg CO_2/t)	Electricity emissions (kg CO_2/t)	Total emissions (kg CO_2/t)	Difference vs. ref. (kg CO_2/t)	Difference (%)
CEM II/A-LL 42.5 R	82	47.6	568.26	5.85	574.11	-	-
No. 1	80	48.2	554.40	5.93	560.33	-12.78	-2.4
No. 2	78	49.0	540.54	6.03	546.57	-27.54	-4.8
No. 3	75	52.0	519.75	6.40	526.15	-47.96	-8.3
No. 4	75	49.0	519.75	6.03	525.78	-48.33	-8.4

The results confirm that the dominant source of CO_2 emissions in cement production remains clinker production, on the contrary, the share of emissions from electricity is very low in Slovak conditions. Each reduction in the clinker factor by 2% means a saving of approximately 14–15 kg CO_2/t cement. The largest emission reduction was observed in recipes No. 3 and No. 4, where the clinker share was reduced to 75%. These variants achieved an emission reduction of 8.3–8.4% compared to the reference type, which represents approximately 48 kg CO_2/t cement. However, it should be added that recipe No. 3 showed lower mill performance (a decrease in production of approximately 13%), which may negatively affect the overall operating efficiency and economic balance. On the contrary, sample No. 4 achieved a similar emission reduction while maintaining higher productivity, which indicates a more advantageous combination of clinker replacement and the additive used.

In conclusion, clinker factor optimization contributes significantly to CO_2 reduction, but the associated rise in energy consumption and lower mill output must be balanced. The optimal recipe is therefore not the one with the finest grinding, but the one achieving the best compromise between clinker substitution, grinding efficiency, and production performance to ensure both environmental and economic sustainability.

4 Conclusion

The results of this study indicate that reducing the clinker factor in cement formulations is an effective way to reduce the environmental impact of cement. However, it has also been shown that increasing the grinding fineness leads to an increase in electricity consumption and a decrease in the amount of cement produced. These two facts negatively affect the entire production process, as they reduce the competitiveness of the cement plant. However, a positive step here may be the use of a different grinding additive, which will make the grinding process more efficient, resulting in higher output and lower electricity consumption at a lower clinker factor.

These findings point to the need for a comprehensive optimization approach that takes into account not only the chemical and technological properties of cement, but also its production and energy efficiency. When designing low-clinker formulations, it is therefore necessary to seek a balance between environmental benefits, the workability of the mixture and the sustainability of production in real operating conditions, which could be the subject of further research.

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References

1. G. Habert, S.A. Miller, V.M. John, J.L. Provis, A. Favier, A. Horvath, and K.L. Scrivener, Environmental impacts and decarbonization strategies in the cement and concrete industries. Nat. Rev. Earth. Environ. **1**, 559–573 (2020). https://doi.org/10.1038/s43017-020-0093-3
2. T.R. Naik, Sustainability of cement and concrete industries, in Proceedings of the international conference global construction: Ultimate concrete opportunities, Dundee, Scotland, July 5-7 (2005), p. 141-50. https://doi.org/10.1680/asic.34044.0017
3. RMC Research & Education Foundation, Sustainable concrete plant guidelines (2011). https://irp.cdn-website.com/1fa14e81/files/uploaded/SCP-Guidelines-Version-1.1.pdf
4. E.F. Felix, E. Possan, Balance emissions and CO_2 uptake in concrete structures: simulation based on the cement content and type, Ibracon structures and materials journal **11**, 135-162 (2018). https://doi.org/10.1590/S1983-41952018000100008
5. C. Meyer, Concrete as a Green Building Material, (Department of Civil Engineering and Engineering Mechanics, Columbia University, New York, 2005).
6. H.G. Van Oss, A.C. Padovani, Cement Manufacture and the Environment. Part II. Environmental Challenges and Opportunities, Journal of Industrial Ecology **7**(1), 93-126 (2003). https://doi.org/10.1162/108819803766729212
7. European Commission, Cement, waste and carbon markets. Problems related to waste incineration in cement kilns under the EU ETS. Report, 2016. https://climate.ec.europa.eu/system/files/2016-11/global_3_en.pdf
8. R.M. Andrew, Global CO_2 emissions from cement production, Earth Syst. Sci. Data, **10**, 195–217 (2018). https://doi.org/10.5194/essd-10-195-2018
9. B. Schäppi, S. Kaufmann, L. Kessler and J. Füssler, Development of the cement clinker production under the EU ETS: Overview and country level analysis from 2005 to 2017. Report. German Environment Agency, 2025. https://www.umweltbundesamt.de/sites/default/files/medien/11850/publikationen/04_2025_cc.pdf
10. CEMBUREAU – European Cement Association, Cementing the European Green Deal: Executive Summary of the 2050 Roadmap, 2020. https://cembureau.eu/media/w0lbouva/cembureau-2050-roadmap_executive-summary_final-version_web.pdf
11. Ministry of Environment of the Slovak Republic, Low-Carbon Development Strategy of the Slovak Republic until 2030 with a View to 2050 (in Slovak). Výskumný a informačný geologický ústav, 2020. https://ec.europa.eu/clima/sites/lts/lts_sk_sk.pdf
12. P. S. Fennell, S. J. Davis, and M. Aseel, Decarbonizing cement production, Joule **5**(6), 1305–1311 (2021). https://doi.org/10.1016/j.joule.2021.04.011
13. Danucem, a CRH company: Turňa nad Bodvou cement plant (in Slovak). https://www.danucem.com/sk/site/2/turna-nad-bodvou-cement-plant
14. UN Environment, K.L. Scrivener, V.M. John, E.M. Gartner, Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry. Cement and concrete Research, **114**, 2-26 (2018). https://doi.org/10.1016/j.cemconres.2018.03.015