UDC 691.32
DOI: 10.15587/2706-5448.2023.281246

**Anastasiia Bielohrad**

# CONCRETE MANUFACTURING WITH A LOW $CO_2$ FOOTPRINT

*The object of the research is the current state of the climate action strategy for cement and concrete production, including possible levers for reducing $CO_2$ emissions.*

*It has been determined that the main source of carbon dioxide emissions per tonne of Portland cement, and subsequently per cubic metre of concrete, is the decarbonization of calcium carbonate, the main raw material component of Portland cement clinker. It also involves the combustion of fossil fuels, which are necessary for the decarbonization and firing of raw materials. Therefore, Portland cement with a reduced content of Portland cement clinker is considered as a solution for concrete manufacturing with a low $CO_2$ footprint. Additionally, the potential of Ukraine in the development of a sustainable Portland cement clinker production approach based on using alternative fuels and alternative raw materials, which will positively affect the total amount of $CO_2$ per ton of clinker, was evaluated. Improved quality performance of cement has been identified as a key direction in product portfolio management to promote cements with a lower clinker factor by increasing the content of active mineral additives. It is shown that the production of concrete with increased strength and durability requirements based on cements saturated with active mineral additives is an important task. Since active mineral additives have different origins, not all of them available for use in cement production exhibit hydraulic properties inherent in Portland cement clinker.*

*Was investigated that «Complex Performance Testing System» (CPTS) as the main test method for evaluating the quality parameters of Portland cement with a reduced clinker factor in accordance with specific applications. This customer-oriented approach opens up the possibility of producing low-$CO_2$ concrete. It has been shown that using the CPTS method, a reduction in the total amount of cement per cubic meter of concrete can be achieved, given the specified parameters of the concrete mix, which has a direct impact on the total amount of $CO_2/m^3$.*

**Keywords:** *cement production, carbon dioxide emissions, alternative raw materials, building materials, Net Zero $CO_2$, clinker-factor.*

*Received date: 19.04.2023*
*Accepted date: 03.06.2023*
*Published date: 08.06.2023*



***How to cite***
*Bielohrad, A. (2023). Concrete manufacturing with a low $CO_2$ footprint. Technology Audit and Production Reserves, 3 (3 (71)), 6–10. doi: https://doi.org/10.15587/2706-5448.2023.281246*

## 1. Introduction

Nowadays sustainability one of the main strategic pillars for businesses and building materials production are not an exception. From seventeen global goals for sustainable development – climate actions is pillar to drive circular economy and carbon reduction targets in cement and concrete production, which is embarking on an ambitious journey to enact changes to the value chain to ensure that concrete is also a sustainable solution for the smart cities of the future, because compared to the other building materials, concrete has a lowest carbon footprint and it emits only AVG 0.13 kg·$CO_2$/kg, where cement representing only 10 to 15 percent of the concrete mix, industry should looking for the $CO_2$ reduction solutions on the cement production level [1].

Based on McKinsey analysis made in 2022, about 6 to 7 % of worldwide $CO_2$ emissions caused by cement production [2]. Clinker – the key component of cement – that emits the largest amount of $CO_2$ in cement-making: 40 % thermal emissions (fossil fuels combustion), the rest process emissions by decarbonization reaction calcium carbonate – main raw materials component. Greenhouse gas protocol organization establishes global standardized frameworks to measure and manage greenhouse gas (GHG) emissions. Operational boundaries was defined as scope of direct and indirect emissions (Fig. 1), that relate to a company's activities.

Globally, building materials industry is looking for the opportunities to reach carbon neutrality target before 2050. The levers which helping to reduce emissions were investigated, moreover considering the market of Ukraine. Alternative fuels and alternative raw materials, green energy, clinker factor reduction in cements portfolio are key focus areas which should applied into cement production process, bringing the value in the way to Net Zero $CO_2$ future.

Topic, regarding climate actions already has clear direction that received official status on $12^{th}$ of December 2015, when the Paris Agreement was signed and sets long-term goals to guide all nations in reaching Net Zero $CO_2$ emissions [3].

The ambition of carbon neutrality generates changes in all product supply chain, and speed of these changes depends of how fast price of carbon emissions grows as a means of encouraging emissions reduction and incentivizing investments to the low-carbon solutions.

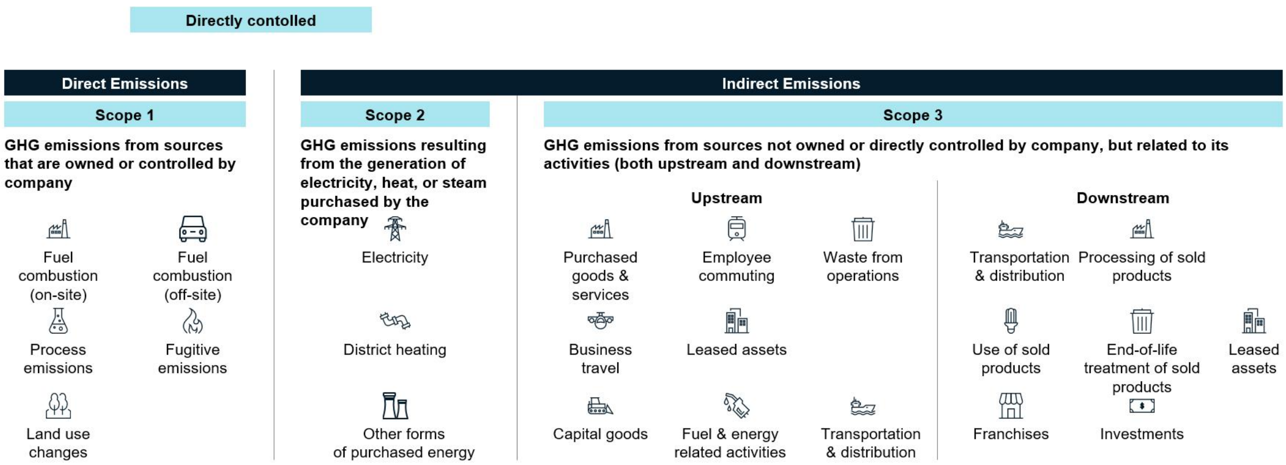


**Fig. 1.** Overview of scopes and emissions across a value chain

Ukraine shares the EU's goals in climate policy by signing the Agreement on 22nd of April 2016 in New York and was one of the first countries to ratify it on 14th of March [4].

On November 5, 2021, the Verkhovna Rada of Ukraine adopted the Resolution «On the appeal of the Verkhovna Rada of Ukraine to the United Nations Conference on Climate Change, which will include the 26th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change» and declare support for global climate change goals to make clean technologies and sustainable development solutions more accessible, affordable and attractive in every greenhouse gas-emitting sector by 2030 [5].

Moreover, Nationally Determined Contribution to the Paris Agreement, the creation of a corresponding plan and the implementation of measures for its implementation were updated.

In general, taking into account the commitments as a result of the 26th climate summit in Glasgow, the national climate policy will need to be adjusted in the following areas [6]:

- to update legislation in the field of waste management and emissions of greenhouse gases reduction;
- to reduce the consumption of coal and other fossil fuels for «green» transformation of industry;
- to create a national system for trading emissions quotas, accordingly to EU regulations;
- to initiate Ukrainian Climate Fund;
- to reform the system of environmental control and to approve relevant legislation;
- to reform of the field of forestry in the direction of increasing the area of forests;
- to implement of measures to protect steppe ecosystems;
- to develop of measures to combat land degradation, and increase natural absorption of greenhouse gases.

If the climate policy will take a fundamental place in the chain from government initiatives to the average citizens, Ukraine will move to developed high-tech production, growing of demand for goods and services related to clean technologies, to ensure the transformation of industrial production and the structure of exports. These actions will have an ambition impact to the cement industry as one of the main emission makers.

Let's investigate low $CO_2$ concrete topic based on $CO_2$ lifecycle, this is. Cement itself is commodity product, which can be not treated separately. The methods to reduce cardon dioxide emissions are developing all over the world, but all of them will influence on the final cement application – concrete. Therefore, *the aim of this research* is to find the solution for the end users.

## 2. Materials and Methods

*The object of the research* is the current state of the climate action strategy for cement and concrete production, including possible levers for reducing $CO_2$ emissions.

Cement production generates ~80 % of Scope 1 and 2 emissions from Fig. 1, it requires clear strategy on reduction levers and projects to execute.

Looking though the direct emissions from the Scope 1 and indirect emissions from Scope 2 cement plant operation can be optimized for $CO_2$ reduction in four main directions:

1. Fuels: gradual decreasing of fossil fuels and switching to alternative fuels.
2. Raw materials: partially replacing raw materials to decarbonated ones.
3. Renewables: shifting to clean and renewable electricity sources.
4. Clinker substitution: increasing of secondary cementitious materials dosage which directly related to the product portfolio management.

In Ukrainian context, first three directions are limited for the implementation. Talking about alternative fuels, it is facing the problem of low level of waste management, which is not motivated from the legislation and tax policies. Collecting, sorting and preparing of waste are much more expensive than storage at landfills. Moreover, as it was investigated, from laws perspective any producer who potentially has waste which later on goes to landfill has a low level of responsibility and is not legally obliged to dispose of waste from its production.

Taking in account issues of waste management in Ukraine, there is a high potential area for development for the local market, or big opportunity for import from European Union. For clinker production is most relevant alternative fuels could be [7]: SRF (solid recovered fuel), tires and agricultural waste.

Almost with the same issues, it is facing in alternative raw materials usage. Cost of natural raw materials is lower than of alternative. For example, air cooled slag from blast furnaces is possible to for clinker production from the chemical composition point of view, but the material cost and logistic cost are higher, compared to the price of $CO_2$ emitted.

Summarizing highlighted $CO_2$ reduction levers overviewed above, Ukraine has a great opportunity to maintain the mechanisms of waste management, which will encourage municipality and business for developing the low $CO_2$ strategy, protecting the natural reserve fund of Ukraine and making a great contribution to the global reduction of emissions.

But, before alternative fuels and alternative raw materials will be widely used for clinker production in Ukraine, first call solution which it is possible to see is clinker substitution with secondary cementitious materials.

Driving clinker factor reduction in cement production the emission paradox was observed: low $CO_2$ cement isn't equal to low $CO_2$ concrete. This is conclusion was made though the test results, which were received in the laboratory, based on cement which were produced in Ukraine which shown in Tables 1, 2.

For the testing, were chosen four cement types: CEM I, CEM II/A, CEM II/B, CEM III/A. Let's create the concrete recipe based on market requirements, to see the results from concrete producer's angle. The main idea was to calculate $CO_2$ per $m^3$ of concrete mixture calculated by $CO_2$ input pet ton of each component, switching only cement types in the recipe to reach the same strength and workability performance.

From Table 2 it is possible to make a conclusion that cement which has lower clinker factor and lower $CO_2$ kg per ton respectively, didn't reflect in concrete due to increase in cement consumption per $m^3$ of concrete.

Moreover, calculated $CO_2$ emissions per $m^3$ of concrete included only $CO_2$, which goes from clinker production counted as nominal, means without indirect emissions. From this perspective with increasing cement dosage per $m^3$ of concrete the $CO_2$ will grow even more.

General approach to avoid increasing of cement dosage per cubic meter should include cement performance. To check this solution was additionally investigated cement from one of European cement plants, Table 3, with the same approach like in Table 2.

The main point to highlight in Table 3 is improved performance decreases cement volume in concrete, during switching between cement grades compared to the same test results, which have been made, based on cement from local producer in Ukraine. For switching from CEM II/A 42.5 to CEM III/A 32.5 Ukrainian customer should increase cement dosage in 38 % when with EN cement this number decreasing to 10 %. This is one more step to low $CO_2$ concrete, which can be directly influenced on a cement plant level.

From the process point of view, cement with advance performance can be overgrind, which can be estimated by measuring sieve residues or specific surface areas by Blane, if residue is low or/and specific surface high respectively. Overgrinding can cause a high water demand, which in the end of the day will influence on the increasing of water to cement ratio in concrete mixture and as result – lowering the concrete strength.

The task is to work on product performance through the benchmark in concrete, especially targeting on initial rheology and kinetics of strength development. For this benchmark is essential to use the customer-oriented approach, grounded on applicational mapping on the market and using new testing method were proposed by Prof. Dr. Jürgen Oecknick which named «Complex Performance Testing System» (CPTS).

The CPTS methodology based on rheologically controlled mixing process. The quality factor of water demand is the main performance indicator of the mix design requirements in workability and strength context. This means that two important performance characteristics for the evaluation of the production process are already being recorded in the laboratory [8].

Water demand determination based on standard method described in EN 196, and has individual values for each cement type. CPTS closely related to the standard method but for testing should be used the «Niehoff/Oecknick Consistency» Mixer which has been applied since 1996 in the competency center of Dornburger [9].

**Table 1**

$CO_2$ kg per ton of cement gross

| CEM I | CEM II/A | CEM II/B | CEM III/A |
|---|---|---|---|
| 765 | 645 | 525 | 460 |

**Table 2**

$CO_2$ kg emitted per $m^3$ of concrete

| B25 P4 | CEM II/A 42.5 | CEM II/A 32.5 R | CEM II/B 32.5 | CEM III/A 32.5 |
|---|---|---|---|---|
| | per $m^3$, kg | per $m^3$, kg | per $m^3$, kg | per $m^3$, kg |
| Cement | 300 | 330 | 370 | 415 |
| Water | 180 | 180 | 180 | 180 |
| Aggregates | 1910 | 1885 | 1850 | 1815 |
| Admixture | 2 | 2 | 3 | 3 |
| $CO_2$ emissions | 199 | 218 | 200 | 198 |

**Table 3**

$CO_2$ kg emitted per $m^3$ of concrete based on EU cement

| No. | Cement type | Cement per $m^3$ | $CO_2$ per $m^3$ | 28 Day, MPa EN 197-1 |
|---|---|---|---|---|
| Mix 1 | CEM II/A-S 42.5 N | 300 | 217 | 55 |
| Mix 2 | CEM III/A 32.5 N | 320 | 173 | 48 |
| Mix 3 | CEM III/B 32.5 N | 330 | 117 | 47 |

In the first step of the process, the constituent materials are mixed with a constant amount of water, i. e. the reference water content. In the next step, the viscosity of the mix is adjusted to the design value through the addition of extra water, which is controlled with the target torque of the mixer [8].

Methodology has a various modifications according to the cement applications in concrete depending on prioritized paraments. Let's apply this procedure for determination of cement performance in precast application. Targeted paraments were strength development in early age to optimize forms rotation time and savings for curing by reaching the highest hydration heat.

## 3. Results and Discussion

CPTS methodology was used to determine the dependence of product performance with concrete in precast application. For testing was chosen 3 cement samples from different producers.

Results in Table 4 shows that analyzed samples require different amount of water to form a working consistency. Moreover, first and third samples have almost the same number for the specific surface according to the Blane method, which indicates degree of dispersity.

Cement water demand has direct impact on water to cement ratio in concrete mixture. This relation can be caused by increased degree of dispersity [10]. As finer particles is contained into cement as higher surface area for water adsorption. CPTS method shows that with the same dispersity samples has different adsorption of water. The first sample has lower energy potential in the hydration heat, and increased water demand, which has direct impact on strength development in the early stages due to excessive porosity caused by increased water/cement ratio.

So, from the performance point of view the third sample can enable decreasing of cement consumption in the recipe and respectively $CO_2$ per cubic meter, reducing curing time and forms rotation time.

CPTS method can be used in parallel with cement quality control methods regulated by standards in the production laboratory. Ukrainian national standard (DSTU) [11] has some differences in mortar preparing process for strength determination compared with European norm (EN) [12]. CPTS method is based on EN standard mortar, which should be taking into account during CPTS method implementation.

Russian invasion in Ukraine has caused irreversible losses for the Ukrainian people, and infrastructure is no exception. For the cement and concrete producers it is a huge challenge to renovate damaged and destroyed buildings and transport infrastructure, as most necessary for life activities of the country. Estimated total infrastructure damages based on 2022 official calculations as 95 billion USD [13] loss (Fig. 2), and this number increasing every day when the war still in Ukraine.

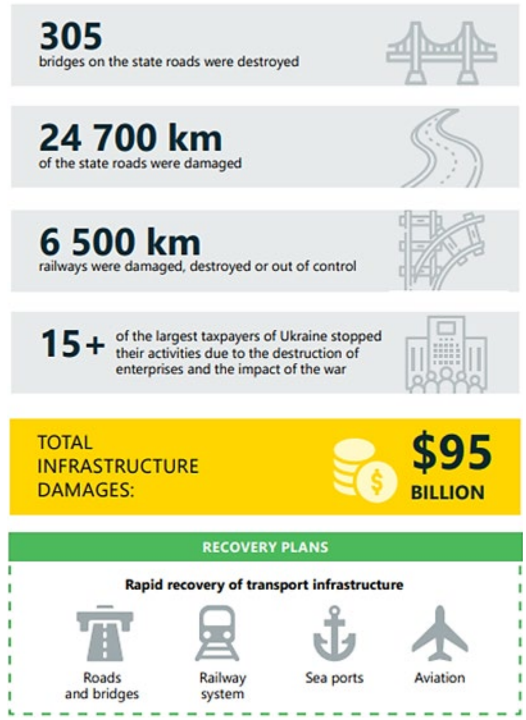


**Fig. 2.** Damages in Ukraine caused by russian invasion

This calculation has direct influence on the cement and concrete market volumes, which predictably will be higher compared to the peace time in 2021. That means cement producers should think about clinker factor not only in climate actions prospective, but for meeting the need for cement for the local market.

So, cements with active mineral additives will be the solution in the same time for two main challenges that Ukraine have: climate actions and growing demand. With cement performance sale approach this challenges could be eliminated.

From the concrete perspective Complex performance testing system can be used for fine aggregates and admixtures and additives (fly ash, GGBS, ultrafine limestone etc.) testing. This will bring to the concrete mixture full strength potential avoiding excessive water.

However, it is important to mention that the discussed laboratory approach (CPTS) must be considered as a tool for operational raw material management and does not allow any evaluation of the potential durability of the final product [8].

Durability of concrete products must correspond to the exposure classes specified in the project documentation for a specific building or structure. Binders, fillers, water and additives for concrete of various types, which are used for development of production on the basis of project documentation for them, subsequent verification of the requirements of regulatory documents for these materials (DSTU or/and EN).

**Table 4**

Early strength kinetics determination based on CPTS

| Sample labelling | Blaine | R45 | Total water | Max. Hydration $T$ | Time to $T_{max.}$ | 1D Strength | 2D Strength |
|---|---|---|---|---|---|---|---|
| | $m^2$/kg | % | ml | °C | min. | MPa | MPa |
| CEM I 42.5 Producer 1 | 385 | 4.7 | 224.6 | 41.6 | 1279 | 11.4 | 21.9 |
| CEM I 42.5 Producer 2 | 440 | 3.4 | 217.3 | 48 | 772 | 20.3 | 32.6 |
| CEM I 42.5 Producer 3 | 385 | 5 | 211.2 | 46.6 | 758 | 21.2 | 33.7 |

ISSN 2664-9969

The rheology-controlled mixer [9] and CPTS technology can be future solution and tool for testing of cement types and secondary cementitious materials according to the new European cement norms: 197-5 [14] and 197-6 [15], in parallel with standard methods.

## 4. Conclusions

Lowering clinker-factor by replacing clinker with secondary cementitious materials shows $CO_2$ reduction effect on the cement production level. To duplicate $CO_2$ reduction from cement to concrete it is possible to use complex approach to avoid increasing of cement dosage in concrete.

Dependence of $CO_2$ in cement to the $CO_2$ was determined. During the substitution of high clinker factor cement to the low clinker factor cement, concrete producer should increase cement dosage to reach the same concrete performance, but the amount of cement addition is depend of cement performance. This conclusion was taken after comparison cements from local Ukrainian producer and cements from one on the European cement plants, when the last ones shows higher strength potential in concrete mixture with lower cement overdosage per cubic meter.

CPTS procedure can show the real cement performance in targeted applications, according to the test results cement performance potential brings up to 50 % strength development more.

Working on cement performance it is possible to reduce product overdosing per cubic meter up to 28 %.

For the Ukrainian market «low $CO_2$» concrete is the great opportunity to reduce emissions at the national level within the limits of compliance with obligations as a signatory country of the Paris Agreement, stimulate the development of mechanisms and motivations in the field of waste management, which can be used as alternative fuels and raw materials for the cement industry, as well as by reducing the clinker factor, to get an opportunity to ensure the cement demand for the post-war reconstruction of Ukraine.

## Conflict of interest

The author declares that she has no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

## Financing

The research was performed without financial support.

## Data availability

The manuscript has no associated data.

### References

1. Stashwick, S. (2022). *Cut Carbon and Toxic Pollution, Make Cement Clean and Green*. NRDC. Available at: https://www.nrdc.org/bio/veena-singla/cut-carbon-and-toxic-pollution-make-cement-clean-and-green
2. Reiter, S. (2022). *Transition to NET ZERO*. McKinsey Sustainability. Available at: https://www.mckinsey.com/capabilities/sustainability/our-insights/spotting-green-business-opportunities-in-a-surging-net-zero-world/transition-to-net-zero/cement
3. *The Paris Agreement. United Nations*. Available at: https://www.un.org/en/climatechange/paris-agreement
4. *Pro ratyfikatsiiu Paryzkoi uhody* (2016). Zakon Ukrainy No. 1469-VIII 14.07.2016. Available at: https://zakon.rada.gov.ua/laws/show/1469-19#Text
5. *Pro Zvernennia Verkhovnoi Rady Ukrainy do Konferentsii Orhanizatsii Obiednanykh Natsii zi zminy klimatu* (2021). Available at: https://zakon.rada.gov.ua/laws/show/1870-20#n14
6. Ivaniuta, S. P., Yakushenko, L. M.; Smenkovskyi, A. Yu. (Ed.) (2022). *Evropeiskyi zelenyi kurs i klimatychna polityka Ukrainy*. Kyiv: NISD, 95.
7. Bielohrad, A., Tokarchuk, V. (2019). Alternative fuels for cement production. *Innovative Solutions in Modern Science, 8 (35)*, 31–37.
8. Oecknick, J. (2020). *Cements for use in Precast Concrete Industries – evaluation of their application potential in customer oriented way*. Concrete Plant International.
9. Oecknick, J., Niehoff, D. (1997). *The compressive strength of cement – a new laboratory mixer with an integrated consistency test installation*. Betonwerk und Fertigteiltechnik, 78–83.
10. Cement PSD and Water Demand (2021). *GCP Applied Technologies*. Available at: https://gcpat.vn/en-gb/about/news/blog/cement-psd-and-water-demand
11. DSTU B V.2.7-46:2010. *Tsementy zahalnobudivelnoho pryznachennia*.
12. DSTU B EN 197-1:2015. *Tsement. Chastyna 1. Sklad, tekhnichni umovy ta kryterii vidpovidnosti dlia zvychainykh tsementiv* (EN 197-1:2011, IDT)
13. *KSE institute. Zvit pro priami zbytky infrastruktury vid ruinuvan vnaslidok viiskoi ahresii rosii proty Ukrainy*. Kyiv, 2022.
14. CEN EN 197-6:2023. *Cement – Part 6: Cement with recycled building materials*.
15. CEN EN 197-5:2021. *Cement Portland-composite cement CEM II/C-M and Composite cement CEM VI*.

***Anastasiia Bielohrad,*** *Department of Chemical Technology of Composite Materials, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Kyiv, Ukraine, ORCID: https://orcid.org/0009-0005-8954-7823, e-mail: anastasiya.belograd@gmail.com*