A «carbon footprint» of low water demand cements and cement-based concrete

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Abstract. Due to the fact, that the contribution of the global cement industry to CO₂ emissions achieves as 6-7%, the Cement Sustainability Initiative, in collaboration with International Energy Agency, has set up the target value of 370 kg of carbon dioxide emission to 1 t of Portland cement by 2050. Currently, these indicators are at the level of 835 kg (535 kg of CO₂ from decarbonization of limestone, 330 kg for fuel combustion). The well-known and newly developed technologies for CO₂ capture, storage and utilization (CCS, CCU) are being also analyzed for the binders with a low carbon footprint. However, to date, all of them are not ready for commercialization because they are costly and cannot fully achieve the target value of CO₂ emissions by 2050. The most productive and widely used approach, which does not require reconstruction of cement plants, is to reduce the clinker capacity in cement during the grinding of clinker with substitutional hydraulic, pozzolanic, “inert”) additives. Nevertheless, such a dilution affects the performance of cement and reduces the’ strength, especially when using limestone – the most available cement filler; carbon dioxide emissions per standard cement strength are not reduced. The “carbonate” types of cement of low water demand (CLWD-CB) have been developed, which possess low content of clinker (no more than 30%) combined with low energy consumption for grinding, high technological and strength parameters. According to the environment ranking, these types of cement are superior to all standard European types of cement. At all the stages of the life cycle, which includes clinker – cement-concrete – concrete structure – concrete scrap (dismantling of the structure), the replacement of standard types of cement with CLWD-CB will make it possible to reduce the carbon footprint from the binder by two times, and from CLWD-CB-based concrete – by four times.

Keywords: global warming, CO₂ emissions, carbon capture and storage technologies (CCS), carbon capture and utilization (CCU), environmental ranking indicators, cement and concrete, low water demand types of cement, the carbon footprint life cycle.

1 Introduction
Cement-based concrete is considered to be the primary construction material of the XXI century and seems to be such through the 3rd millennium (if only humanity will still exist on the Earth!). The worldwide consumption of cement concrete is growing steadily, and there are no prospects for a substitute for it in the world’s future. According to UN estimates, cement concrete will play an essential role in the construction industry, infrastructure, transport systems caused by further urbanization, industrialization, and high population growth up to 8.2-9.8 billion in 2050 [1, 2]. The reason is that the concrete is the only artificial construction material, which is able to satisfy the ever-growing needs of the world population with limited resources: minimum power consumption of about 4 GJ/n per ton (aluminum – 180, brick – 10). It proposes the most excellent opportunities for recycling secondary materials, including massive scale waste of industry, heat power industry, and construction
as well as the recyclability. Therefore, the production of cement concretes meets the best criteria of the best available technologies, namely energy-saving and minimal negative impact on the environment, including CO₂ emissions [2].

Moreover, the concrete materials are not limited to the improvement and application of innovations. However, the concrete-making industry is considered to be responsible for 2.4 billion tons of annual CO₂ emissions, although the "culprit" of this is Portland cement (PC). Indeed, the PC production is both energy-consuming and environmentally harmful since, besides CO₂ and dust emissions, 1 ton of cement production requires from 1.5 to 2.4 tons of non-renewable non-metallic minerals (limestone and clay), which are extracted mostly from quarries.

The threat of climate change (warming) is considered to be one of the major challenges for substantial world development, and a solution is to change the ways of using energy and decrease emissions of the main greenhouse gas - carbon dioxide, in the manufacturing sector. According to the International Energy Agency (IEA) [3], this sector accounts for roughly one-third of total energy and 40% of global CO₂ emissions. The Intergovernmental Panel on Climate Change (IPCC) reported that by 2050, global CO₂ emissions must be reduced by no less than 50% from 2000 levels to limit the rise in the global average temperature of more than 2.4-2.0 °C. Global climate agreement was reached in Paris in December 2015 [4]. The UN members determined a limit of global warming in the twenty-first century of 2°C. As follows from table 1, the cement-making industry is responsible for a major share of energy consumption (26%) and CO₂ emissions (26%). This impact is mostly due to two factors.

Table 1. The share of energy consumed and CO₂ emitted by the major primary industrial sectors [3].

| Industry                        | Share of energy consumed, % | Share of CO₂ emissions, % |
|---------------------------------|-----------------------------|---------------------------|
| Chemical and petrochemical      | 15                          | 20                        |
| Iron and steel making           | 22                          | 19                        |
| Cement making                   | 26                          | 26                        |
| Pulp and papermaking            | 21                          | 20                        |
| Aluminum                        | 10                          | 12                        |

The first is the large scale of the industry producing more than 4.2 billion tons of cement per year (in 2016, its world consumption amounts to 4.13 billion tons [3]), and the second one is related to technological peculiarities of PC production:
- no less than 535 kg CO₂ per 1 ton of clinker are released during limestone decarbonization;
- about 330 kg CO₂ are emitted from the combustion of fossil fuel for burning 1 ton of clinker.
In total, 835 kg CO₂ are produced per 1 ton of clinker.

The CO₂ emission indicator depends both on the ratio of clinker to cement and grinding techniques [5].

It should be noted that Portland cement is needed to produce concrete. By 2050, global PC production is expected to grow by 12-13% compared to 2014 [6]. Cement Sustainability Initiative (CSI), in conjunction with IEA, set an acceptable target indicator for CO₂ emissions of 370 kg per 1 ton of Portland cement as a goal for 2050 [7], which corresponds to the 2 Degrees Celsius (2DS) scenario by 2100 reported by IEA (Reference Technology Scenario, RTS) according to which average global temperature will rise by 2.7 °C.

Since the PC-clinker is a primary product of concrete construction, it is logical to evaluate the “carbon footprint” at all stages of its life cycle, from annealing process to producing a concrete frame (or the entire concrete-framed building) followed by its utilization after concrete disassembling (or demolishing the building). The steps are as follows: PC-clinker → cement → concrete → concrete frame → concrete waste (secondary raw materials). Both the amounts of clinker and its carbon footprint are reduced from stage to stage.

Over the past two decades, major cement producers worked diligently and successfully to reduce CO₂ emissions using four groups of conventional means [8]:
1. energy efficiency improvement;
2. decrease of the clinker in cement (concrete) ratio;
3. replacing high-carbon fuel with CO\(_2\)-neutral biogenic fuel;
4. decrease of the CaO portion in the PC cement.

Both IEA and CSI agree that the current tools for CO\(_2\) reduction tools are insufficient to achieve future goals. Some ways should be found to capture and remove or utilize CO\(_2\), which will lead to higher additional costs [5]. Table 2 summarizes the CSI target for cement industry development.

### Table 2. CSI target for cement industry development predicted according to the 2DS scenario [7].

| No | Indicator                                      | 2014   | 2030   | 2040   | 2050   |
|----|-----------------------------------------------|--------|--------|--------|--------|
| 1  | Annual world cement production, Mt            | 4171   | 4250   | 4429   | 4682   |
| 2  | Heat use per 1 ton of clinker, GJ             | 3.5    | 3.3    | 3.2    | 3.1    |
| 3  | Electricity use per 1 t of cement production, kWh×h | 91     | 87     | 83     | 79     |
| 4  | Share of biogenic fuel in the fuel overall balance, % | 5.6    | 17.5   | 25.1   | 30     |
| 5  | Percentage of clinker in cement, %            | 65     | 64     | 63     | 60     |
| 6  | CO\(_2\) emission per 1 ton of cement from decarbonization, t | 0.34   | 0.33   | 0.3    | 0.24   |
| 7  | CO\(_2\) emission per 1 ton of cement from energy release and generation, t | 0.20   | 0.19   | 0.16   | 0.13   |

As follows from table 2, the bulk of CO\(_2\) emissions are from clinker production and, to a lesser extent, from a grinding stage (about 55-58% of the former contribution). Therefore, the most principle means of reducing CO\(_2\) emissions is to decrease both the clinker to cement ratio and energy consumption for grinding clinker (including a blend with mineral additives). Meanwhile, according to the reports of world leaders in cement production as LafargeHolcim, HeidelbergCement, and Cemex for 2017, the fraction of the clinker in cement amounted to 73.0, 75.3, and 78.4 %, respectively, and CO\(_2\) emissions per 1 ton of produced cement were 0.581, 0.609, and 0.636 tons. In total, about 60% of CO\(_2\) emissions produced at modern cement plants are from the decarbonization of raw materials upon the production of clinker.

The Information-Technological Handbook of the Best Available Technologies (BAT), ITH 6-2015 Manufacture of cement, which was entered in force in Russia in 2016, presented fifteen BAT aimed at the improvement of three indicators for the efficiency of the cement production process. These indicators are the integrated parameters related, directly or indirectly, with the negative impact on the environment from greenhouse gas emissions and consumption of non-renewable natural resources [9]:

- specific consumption of raw materials for the production of 1 ton of the PC clinker;
- specific heat (fuel) consumption for burning 1 ton of the PC clinker;
- specific energy consumption for the production of 1 ton of PC.

The BAT1 approach is formulated as follows: the decrease in the specific consumption of raw materials for the production of the PC clinker through substituting the natural raw materials with industrial waste products and reducing the fraction of clinker in cement to a minimum acceptable level. It is assumed that the minimum acceptable level of the content of clinker in cement must ensure the preservation of all technical properties of PC without admixtures. For this purpose, the available technological methods should be applied. The decrease in the content of clinker in cement, while maintaining its activity, proportionally reduces the carbon footprint of the construction industry per finished product – concrete, since the cement content is strictly determined by its rank (activity).

However, according to current predictions, even when using all traditional approaches, the cement industry will not be able to achieve the goal to reduce CO\(_2\) emissions per 1 ton of cement by 50% by 2050, if appropriate measures are not taken to capture and store CO\(_2\) (Carbon Capture and Storage, CCS) [10].

The CCS technologies imply compression of captured and purified CO\(_2\), its transportation to a storage location, and subsurface injection (for isolation purpose). Depending on the chosen scenario, all cement manufacturers in the world must capture and storage from 552 to 707 billion tons of CO\(_2\) annually. The geological storage of CO\(_2\) has been used for a long time, especially in the oil and gas
industries [11]. Below are presented four CO₂ capture technologies, which are under development and seem to be feasible from a technical and economic point of view:

1) carbon removal from the fuel before burning;
2) CO₂ capture from combustion products;
3) fuel combustion in oxygen [12];
4) Calix’s Direct Separation technology [13].

The ultimate goal of these processes is to get a stream of clean CO₂ and capture it. An analysis of these four and other technologies revealed that the cost increases by 49-92% for producing the clinker compared to the base route without CO₂ capture since the full CO₂ capture requires additional energy consumption of about 3 MJ/t CO₂ [14].

Further, it is necessary to develop and implement a cost-effective solution to “captured” CO₂ disposal (Carbon Capture and Use, CCU) [12].

During the past 20 years, the following methods of CO₂ disposal have been developed and tested:

- the use of flue gas for the purpose of growing algae in bioreactors to produce biomass. As the experience of LafargeHolcim shows, 1.8 tons of CO₂ produce 1 ton of biomass, which can be converted into fuel (biomethane) [15];
- the biohydrogen production from algae, which is the renewable clean fuels of the future [16];
- the technology of CO₂ conversion into fuel based on the enhancement of reactivity of inert carbon dioxide via changing the pressure or temperature or using catalysts [17]. The catalytic reduction of CO₂ to CO, which is carried out by means of Fischer-Tropsch synthesis, a well-known method, with subsequent production of synthetic fuel from syngas (CO+H₂) and chemicals makes it possible to reduce CO₂ emissions by 40% [18]. However, CO₂ released again during the life cycle of these chemicals and fuel combustion;
- electrochemical reduction of CO₂ to CO via metal catalysts, in particular, nanoporous silver [19];
- CO₂ processing developed to produce binding materials with a low carbon footprint, which has long been employed in cement production.

The review of these works is given in [20], and table 3 summarizes the characteristics of the four primary binders.

**Table 3.** Peculiarities of the main potential binders with low carbon dioxide emission, which are produced with disposal of captured CO₂.

| No. | Technology | Description | Characteristics |
|-----|------------|-------------|-----------------|
| 1   | Synthesis of non-hydraulic silicates (CaO·SiO₂; 3CaO·2SiO₂) according to the Solidia technology | The appearance of binding properties of the Solidia types of cement is associated with carbonization resulting in CaCO₃ and SiO₂ gels | During hardening of concrete based on the Solidia cement and conventional filling matter, the binding of CO₂ occurs |
| 2   | Calera technology (calcium carbonate cement) | Supply of exhaust gases containing CO₂ directly into the flowing solution, where calcium ions are present | Precipitation of CaCO₃ with the required quality indicators under controlled conditions |
| 3   | Soicom concrete technology based on CHP-plant carbon ash (Kajima Corpi) | For carbonization, a specially prepared γ-C₃S additive is used with CHP-plant carbon ash | Molded concrete units are hardened upon processing with carbon dioxide in a special chamber |
| 4   | Production of a MgCO₃-based binder (TecEco/Novocem – Calix technology) | Magnesium silicates are used as a raw material instead of calcium-containing material | Production of MgO, which is reactive towards CO₂ for the synthesis of the MgCO₃-binders |
However, despite the promised benefits, it is premature to talk about the commercialization of their results. The fact is that so far, none of the new binders can compete with PC, although in 10 years, some of them will be applied in many fields and can help to reduce CO$_2$ emissions.

Thus, in order to reduce the intensity of CO$_2$ emissions by about 50%, over the next three decades, the cement industry must develop and implement new technologies along with the promotion of the methods, which are already known as the improvement of energy efficiency, use of biogenic fuel, and substitution of clinker. Since using only these known methods, it is not possible to achieve the intended goals, some of the major international cement manufacturers are working both on a new clinker composition with a lower content of limestone in a raw mixture, which require less heat consumption, and new cement materials, mainly of a non-Portland cement type. However, even after the implementation of these approaches, the CCS/CCU technologies are needed for the additional CO$_2$ emissions reductions.

In general, no technology alone will solve the problem of CO$_2$ emissions reductions in the cement-making industry. Both a combination of appropriate technologies and a coordinated approach to the operation of global cement-making enterprises are needed. Is it possible?

To date, the most effective approach to the CO$_2$ emissions reductions is the decrease of the clinker content and improvement of its efficiency in the cement materials, the same applies to the content and efficiency of cement in concrete while maintaining the available CCS and CCU methods. In this case, firstly, both the “raw” and “fuel” contributions to carbon emissions are decreased, and secondly, the cement-making technologies do not change significantly, ensuring high efficiency of these methods to reduce a clinker capacity. Two other important results of the reduced content of clinker in cement are supposed in the future [22]:

1) the production of the cement volumes, which were projected by CSI will not need to produce more clinker: if by 2050 the target CO$_2$ emission reduction of 37% is achieved by replacing clinker in cement, all the extra cement, which is required to meet the growing demand, will be provided by the substituting additives. The importance of this result is determined by a high correlation between regional cement consumption and the economic development, which is moving from a linear to cyclical model in the 21st century, with the periods of rapid economic growth followed by stabilization, and the cement demand drops. In particular, this is observed in the cement industry of China, whose share accounts for more than half of the world production. Perhaps already in the 21st century, the development of China and India – as the countries with the largest population and fastest population growth, will accelerate approaching the European level: along with the migration of hundreds of millions of people from rural to urban areas, the main infrastructure projects (e.g., transport) will be completed, and human well-being becomes comparable to that of the European countries. It should be noted that Africa and Indonesia are already on the way. Then, the growth rate of the concrete and cement consumption will decrease to the level of developed countries, like the US, which is needed to maintain and improve the macrostructural wealth created by the construction industry.

2) In the cement plants of the future, the investments in a second-cycle milling capacity will play a major role. The high substitution ratio of clinker in cement depends on:

   - The properties of the clinker;
   - The properties of the clinker substitutes;
   - The chemical and physical compatibility of the substitute additives with all other components and both in the cement mixture and concrete as a final product.

Three groups of natural and man-made materials are well known, whose chemical composition and properties are similar to cement:

1) Hydraulically active materials with cementing properties: blast furnace slag (BFS), basic types of flue ash, lime.

2) Pozzolanic materials (pozzolans), which do not react with water, but being active silicones, they react with CaO to form C – S – H. These reactions are slower and lead to an increase in the strength of cement stone at a later date (after 28 days). Pozzolans include acid flue ash, silica fume, volcanic
cinder, calcinated clays. The latter, as pozzolanic additives in cement, provide superior strength and, especially, frost resistance of concrete [23, 24].

3) inert materials, which are used as particulate fillers of cement. These materials include the most common of them – flour limestone. Their role as structuring centers is associated with the packing density of the cement and concrete mixtures, with a limited ability to react with cement. Currently, the substituting additives are mixed with conventional PC during grinding at a cement plant (the European option) or a concrete-making plant (the North American option). Each cement, as a binder, has an optimum grinding fineness in terms of quality, and its mixture with mineral additives is characterized by an optimal particle-particle packing density.

There are two ways to achieve a high packing density of mixed cement. The first method implies the joint grinding of clinker with a mineral additive with close values of grinding capacities (e.g., BFS). The second option is to grind the components separately, and then mix them in optimal proportions. The same principle applies to the packing density of aggregate grains in concrete and fillers – mineral powders mixed with cement with a minimum content of the latter to obtain specified strength of concrete. The authors [22] believe that in achieving a high degree of clinker substitution, it is necessary to grind various components of a cement batch separately and afterward mix them to optimize the packing density of the product particles. However, they left aside the issues of increased water demand of the filled cement, which determines both the mobility (workability) of the concrete mixture and the ultimate strength of concrete (after 28 days). It should be noted that the increased water demand estimated as a water/cement (W/C) ratio is determined not only on the grinding fineness but also on the surface energy of these particles, cement, and mineral additives. The surface energy determines the wettability of their surface with water and the adsorption capacity of molecules of plasticizers – water depleters.

Unlike the above additives, limestone is available for most cement plants in the world in virtually unlimited amounts, and it is easy to grind. When adding limestone to cement, one improves the workability and cohesion of the concrete mixture and reduces water consumption. It is known that limestone reacts with the aluminato phase of cement at a normal temperature of the concrete mixture forming calcium carboaluminates [25, 26]. Its reaction with hydrated lime in a cement paste leads to the formation of calcium hydroxocarbonate (defernite) – \( \text{Ca(OH)}_2 \cdot \text{CaCO}_3 \cdot \text{nH}_2\text{O} \) [27]. The high level of clinker substitution with limestone in cement is possible [28], although the latest version of European cement standard EN 197-1 the limestone content is limited to 20 % by mass [29]. According to EN 197-1, cement type CEM VI is a combination of slag with limestone or fly ash with minimal clinker content of 35%. When reducing clinker in cement, the issue of its practical use is important, i.e., it should be implemented without deterioration of the performance characteristics of the latter, in particular, its durability under various external impact scenarios, for example, freezing and thawing.

The efficiency of the above methods to reduce CO\(_2\) emissions, which include the energy efficiency improvement of the clinker production, fuel switching, reduction of CO\(_2\) content in clinker, and several technologies for CO\(_2\) removal from flue gases in clinker kilns and CO\(_2\) utilization (CCS/CCU), should correspond to 1 ton of clinker produced.

At the second step of the technological cycle of cement production – the grinding of clinker with gypsum, which serves as a grinding intensifier, and various substituting mineral additives, the CO\(_2\) emission reduction efficiency is determined by a mass fraction of clinker in the cement produced – a clinker capacity of cement. However, the main consumer characteristics of cement, as the final product of the cement industry, is the activity of cement, which is evaluated in all world standards by the 28-day mechanical strength. In this case, the cement samples with the same clinker capacity can possess different values of activity, which depend on the grinding fineness of clinker and mineral additives, their chemical nature, packing density of mixed cement. Therefore, the cement CO\(_2\) – intensity relationship should be applied not so much to the share of clinker as to its effectiveness, which is exhibited as the activity (mechanical strength) of cement. In other words, the total CO\(_2\) emissions should be applied to the 28-day compressive strength (\( K_{\text{CO}_2} = \text{kg CO}_2/\text{t Cement MPa} \)).

Evans and Mutter from IAMCEM Consulting Ltd suggested this dimensionality for the environmental ranking of cement [30]. However, this indicator has the following disadvantages:
- it does not account for CO₂ emissions from the production of substitute additives as fly ash, slag, calcined clays, and etc.;
- the values of strength for standard solution are not always reproduced in concrete;
- it does not account for CO₂ formed upon CHP generation of electricity consumed by a cement plant.

For these reasons, a decrease in the clinker content in the cement containing substituting additives, which reduces the specific CO₂ emission per 1 ton of cement does not always improve the environmental ranking since it may reduce the standard strength R28.

This phenomenon is clearly seen in the Kᵣ parameter determined for typical European types of cement, which contain the limestone additives as CEMII/A-LL (6-12%) and CEMII/B-LL (21-35%), compared to CEMIV/A-V with 35% fly ash (table 4).

Table 4. Environmental ranking of types of cement produced by a typical European plant, and specific CO₂ emissions from their production [30].

| Type of cement | Specific emissions, kg-CO₂/t cement | Ranking indicator, kg-CO₂/t·MPa (28-day compressive strength) |
|---------------|-----------------------------------|---------------------------------------------------------------|
| CEM II/A-LL 42.5R | 700                               | 13.4                                                          |
| CEM II/A-LL 32.5R | 649                               | 13.4                                                          |
| CEM II/B-LL 32.5R | 573                               | 15.7                                                          |
| CEM IV/A-V 32.5R | 571                               | 12.2                                                          |

Obviously, the low strength parameters of the types of cement with limestone are caused by imperfect grinding of clinker during its joint grinding with the second softer component. It is beneficial for the cement manufacturer since they can reduce energy costs for grinding while maintaining the specific surface area of mixed cement. Environmentally friendly properties of the cement with fly ash CEM IV/A-V 32.5R are provided by its low clinker capacity and high strength caused by the same grinding of both the clinker and pozzolanic additive.

2 Materials and methods

We developed a technology of the low-water demand carbonate types of cement, CLWD-CB, which is based on the separately-sequenced grinding of Portland cement with a superplasticizer and carbonate rocks (limestone and dolomite). This technology makes it possible to produce the composite types of cement with low content of clinker (no higher than 30%), but with a high standard cement strength (class) and better technological properties (fluidity of cement paste, rate of hardening, etc.) [31].

These new CLWD-CB materials are not only not inferior to standard Portland cement in terms of the complex of all properties, but also surpass them in economic and environmental indicators. The technology of their production meets the criteria for the best available technology for energy conservation, minimized emissions, and discharges. Moreover, when considering the possibility and feasibility of using limestone waste (quarry screenings of a 0-10 mm fraction), one can refer to this technology as low waste and minimum impact technologies. This technology can easily be implemented in existing cement plants and grinding facilities.

3 Results

In this regard, it is of interest to compare the environmental ranking of CNV-KB estimated following the above mentioned method – Kᵣ [kg-CO₂/t·MPa] with that for standard European types of cement. When determining Kᵣ, we relied on the indicators of common CEM I 52.5N reported in [30]: CO₂ emissions = 828 kg/t cement, 28-day compressive strength Rₚ₂₈ = 63 MPa. Hence, its ranking Kᵣ = 13.14 kg-CO₂/t MPa.
As can be seen from the data in Tables 4 and 5, the environmental benefits of carbonate CNV-KB are more significant compared to the European types of cement containing such additives as limestone and fly ash: the value of $K_{\text{CO}_2}^C$ is two times less.

| Table 5. Comparison of the environmental ranking of European types of cement and carbonate CLWD-CB, which contains 30, 50, and 70 % clinker. |
|---------------------------------|-------------|----------------|----------------|----------------|
| No                             | Type of cement | Clinker content, % | Rc28, MPa | Specific emissions Kg CO$_2$/t cement | $K_{\text{CO}_2}^C$ kg CO$_2$/t MPa |
|--------------------------------|-------------|----------------|-------------|----------------|----------------|
| 1                              | CEM I 52.5N (European) | 95–100          | 63          | 828             | 13.14          |
| 2                              | CEM II/A-L 42.5N (European) | 80–94          | 53          | 747             | 14.1           |
| 3                              | CLWD-CB 30 | 30              | 37          | 248             | 6.7            |
| 4                              | CLWD-CB 50 | 50              | 73          | 414             | 5.67           |
| 5                              | CLWD-CB 70 | 70              | 87          | 580             | 6.66           |

The principal application of cement is to produce concrete. Therefore, the decrease in cement consumption in it (and thereby clinker capacity) is the main ecological problem of the concrete industry. At the second stage of the cement life cycle in concrete, it is logical to evaluate the carbon footprint of cement by the share in a cubic meter of concrete. When using the same meaning of $K_{\text{CO}_2}^C$ ranking, one should apply the specific CO$_2$ emissions from the share of cement in concrete to the grade 28-day strength of the concrete itself [28]:

$$K_{\text{CO}_2}^C = \frac{\text{kg CO}_2 \cdot C(t)}{R_{\text{concrete}} \, \text{MPa}}$$

(1)

Here kg CO$_2$ are the CO$_2$ emissions expressed in kg per 1 ton of produced cement; $C(t)$ – cement consumption in tons per 1 m$^3$ of concrete; $R_{\text{concrete}}$ (MPa) is the standard 28-day compressive strength.

| Table 6. Composition and properties of heavy concrete prepared from standard cement and CLWD-50CB (at the same fluidity of concrete mixtures). |
|---------------------------------|-------------|----------------|-------------|----------------|----------------|
| N                              | Type of cement and superplasticizer in brackets | Consumption of materials, kg/m$^3$ | $R_{28}, \text{MPa}$ | Specific consumption of cement per unit of strength, kg/MPa |
|--------------------------------|-------------|----------------|-------------|----------------|----------------|
| 1                              | CEM I 42,5 C CLWD-50CB | 160 0,6 41 | 10.24 |
| 2                              | (Melflux 5581F – 0.6%) CLWD-50CB | 113 - 76 | 5.52 |
| 3                              | (Stachement 2280) CLWD-50CB | 420 750 1100 100 | 85 | 4.94 |

Let us consider how the environmental ranking of a heavy coarse concrete is changing with type of cement used with an equal mass content of superplasticizer as Melflux 5581F and Stachement 2280 – 0.6% (by weight of cement). The superplasticizers were added into the concrete mixture with gauged water or into CLWD-CB during the grinding process (CO$_2$ emissions per 1 t of cement were taken from table 5).
As can be seen from Table 6, the concretes prepared from carbonate CLWD with the same content of mineral components and superplasticizer, and the same fluidity of the ready-made mixture possess a significantly lower water demand compared to that when standard cement is used, two times greater 28-day compressive strength, and lower consumption of a binder per unit of strength (kg/MPa). It is logical that the carbon footprint of the concrete prepared from carbonate CLWD occurs to be much lower (4 times) than that when the standard cement is used, as confirmed by the calculated data from table 7.

Table 7. The environmental ranking indicators of concretes prepared from different types of cement (compositions in table 6).

| Concrete composition | Type of cement | CO₂ emissions, kg per 1 t of cement | CO₂ emissions, kg per 1 m³ of concrete | Ranking $K_{\text{concr}}^{CO_2} = \frac{\text{kg CO}_2}{\text{m}^3\text{MPa}}$ |
|----------------------|----------------|------------------------------------|----------------------------------------|-----------------------------------|
| 1                    | CEM I 42.5     | 828                                | 347.8                                  | $\frac{347.8}{41} = 8.48$ \(\text{kg CO}_2\) \(\text{m}^3\text{MPa}\) |
| 2                    | CLWD-50        | 414                                | 173.9                                  | $\frac{173.9}{76} = 2.28$ \(\text{kg CO}_2\) \(\text{m}^3\text{MPa}\) |
| 3                    | CLWD-50        | 414                                | 173.9                                  | $\frac{173.9}{85} = 2.05$ \(\text{kg CO}_2\) \(\text{m}^3\text{MPa}\) |

### 4 Discussion

The modern trend in global concrete construction is high-strength concrete ($R_{28} = 120–150$ MPa and more) intended for the production of load-bearing structures. Their applications, even at a higher cement consumption in one cubic meter, make it possible to reduce the working section of load-bearing elements, and, as a consequence, their volume, consumption of reinforcement steel, and in total the mass of constructions. This provides a significant environmental effect not only by reducing the consumption of materials for the construction of a building, but also decreases the volume and cost of construction works. It is noteworthy that in India, the second country after China to produce PC, the use of high-strength concretes in structures, which reduces the cement consumption in their production over 25%, is one of the main tasks of the state green building program [32].

Following to Evans-Mutter’s logics of environmental ranking, for a similar assessment of a specific load-bearing structure (and even the whole concrete object) it is necessary to apply the specific CO₂ emissions per 1 m³ of concrete (see Table 7) to the consumption of concrete (m³) in this structure. In this case, the value kg CO₂ per load-bearing structure (volume of concrete) will reasonably characterize its environmental ranking. It should be borne in mind that with an increasing class of concrete the consumption of reinforcement steel, the volumes of CO₂ emissions from which are significant. Indeed, as follows from the data of [32], CO₂ emissions per 1 m³ of unreinforced concrete are 250 kg CO₂-eqv., and that per 1 m³ of reinforced concrete are 312 kg CO₂/m³ (with the calculated content of steel reinforcement in concrete of 100 kg/m³).

Thus, the carbon footprint of cement can be followed and estimated at all four stages of its lifecycle: production of clinker and cement from it at a full-cycle cement plant, production of concrete, and then building construction. At the final stage, which implies the disposal of a failed or dismantled cement concrete structure, the “fate” of cement and the indicator of CO₂ emissions will be determined by a concrete scrap processing technology: conversion into crushed stone or into a hydraulically active filler, which is intended to be added to a new concrete by grinding.

The environmental ranking of concrete being taken into account by consumers, government institutions, and environmental specialists should stimulate concrete manufacturers to use not only the types of cement with low $K_{\text{concr}}^{CO_2}$ but also to decrease its content in concrete per unit of strength. The manufacturers of building structures should apply high-strength concrete.
5 Conclusions
The technical measures considered above for the “control” of carbon dioxide emissions from the global cement-making industry, which causes (supposedly!) warming of the earth’s atmosphere, stimulate research and practical implementation of their results in order to reduce the resource-intensiveness of both cement and concrete, improve their technique and performance parameters, and lower the costs of construction projects. Of course, this is an important task for the further economic development of each country.

However, as follows from the human history of the Earth, as the author [33] suggested), “just one major volcanic eruption releases much more carbon dioxide into the atmosphere than the entire human industry has produced in its history. And if this simple idea reaches the masses, it will be much more difficult for a limited circle of people to line their pockets at the expense of others by trading the «quotas» for CO$_2$ emissions into the atmosphere. And if the governments of developed countries realize that the temperature background depends primarily on the heat flow from the planet's interior during the processes of dehydration and expansion of the Earth (compared with which people’s activities do not even reach a mosquito bite), then they will stop making stupid and populist decisions and wasting money for “the fight against temperament growth on the planet, and, perhaps, they will direct this money to something... at least a little more useful”.

These decisions would lead to a global redistribution of investment flows and fundamental change in the priorities of the global economy. However, it is not an easy task to abandon generally accepted and conventional theories and beliefs. One just has to make the decision to do it…

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