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ON THE SELECTION OF A SUITABLE CONCRETE

Abstract

This paper aims to analyze the carbon footprint which the construction industry leaves on the global GHG emissions. It focuses on understanding the sources of the embodied carbon in each stage of the structure's lifecycle. It also explores the ways of reducing the CO_2 costs, focusing primarily on the RC structures. A comparative analysis of different types of cement as well as their corresponding carbon signature is performed and explored. Finally, the ecological benefits of the appropriate concrete and cement selection are presented though real-life examples.

Keywords: Construction industry, carbon footprint, CO_2 *emission, concrete, cement*

О ОДАБИРУ АДЕКВАТНОГ БЕТОНА

Сажетак

Циљ овог рада је анализа количине угљен-диоксида који грађевинска индустрија ослобађа у оквиру глобалне емисије штетних гасова. Рад се фокусира на разумевање извора поменутог угљеника у свакој фази животног циклуса конструкције. Такође истражује начине смањења CO_2, концентришући се првенствено на бетонске конструкције. Врши се и компаративна анализа различитих типова цемента и поређење њиховог утицај на животну средину. Еколошке предности одређених врста бетона и цемента су представљене кроз примере из стварног живота.

Кључне ријечи: Грађевинска индустрија, штетни гасови, угљен-диоксид, бетон, цемент

1. INTRODUCTION

During the United Nations Climate Change Conference held in Paris in 2015, 196 countries agreed to undertake an ambitious goal to keep the average rise of the global temperature below 2°C, in order to reduce the negative effects of the climate change. In 2021 the world witnessed massive floods in Germany and Belgium, as well as the spreading of major wildfires in Turkey and Greece; both disasters serving as reminders of what our future might look like unless immediate action is taken.

The Joined Research Center, part of the European Commission, has published in 2021 an extensive rapport on the Greenhouse gases (GHG) emissions involving 213 world's countries [5]. Based on this report we see an overall reduction in CO_2 since 2019, but further efforts need to take place so that the ambitious goal of "Net Zero carbon by 2050" can be archived (refer to Fig.1).

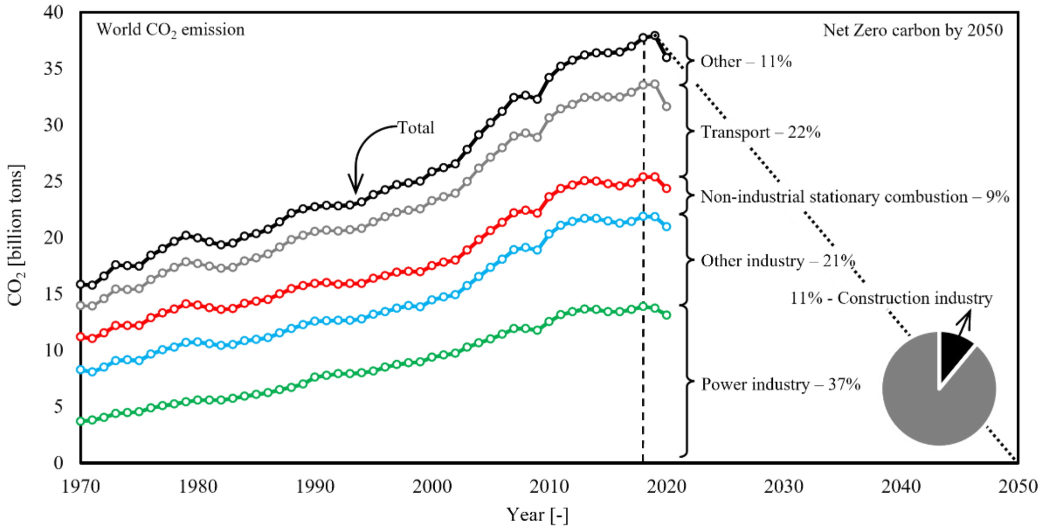


Figure 1. *Annual CO_2 emissions over the past 50 years per sector*

Looking at the Fig.1, one can observe that the first major contributor to the CO_2 emission is the industry sector which makes up for 58%, power industry being the leader of the sector with the participation of 37%. The second major contributor is the transport sector that accounting for 22% of the global carbon emission, followed by the non-industrial stationary combustion units often found in residential buildings that contribute with 9% of annual CO_2. Remaining 11 % are added by the other industrial processing emissions involving non-metallic minerals, non-ferrous metals, solvents and chemicals, agricultural soils and waste.

Focusing on the construction sector, according to the UN environment program [6], it represents11% of the total CO_2 emission (in Fig.1 it is accounted for under the "other industry" category). This sector is defined as an estimate of the overall production of the building materials such as cement, steel, bricks and glass. Thus, the construction sector becomes the 3rd world's major pollutants; bringing a great responsibility to the engineers and the architects alike, to take a more proactive role in this great challenge of our generation.

Transport of the raw components (steel, aggregates and cement), as well as the building materials (re-bars and fresh concrete), translates into additional CO_2 that is directly related to the construction industry. Providing the structures with heating, ventilation, suage and electricity broadens the carbon footprint even further,-the initial 11% of the annual CO_2 caused directly by the construction sector, is bumped to 39% according to the UN environment program [6].

Putting the emphasis on the carbon footprint of the construction industry is one of the objectives of this paper. It also aims to analyze the structure's emissions from the perspective of its lifecycle, as well as to offer recommendations on how these emissions can be reduced through a critical material selection, focusing primarily on the concrete structures.

2. LIFECYCLE AND CO_2

As a response to the Net Zero 2050 policy, organizations such as The Institution of Structural Engineers (UK) and London Energy Transformation Initiative (UK) have published design guidelines [7,11], which provide the engineers and the architects with a better overall understanding of how much embedded carbon is induced throughout each of the following stages of structure's lifecycle (refer to Fig.2):

- Products/materials phase (indicated in black in Fig.2)
- Constructing phase (indicated in gray in Fig.2)
- Exploitation/usage phase (indicated in red in Fig.2)
- End of life (indicated in white in Fig.2).

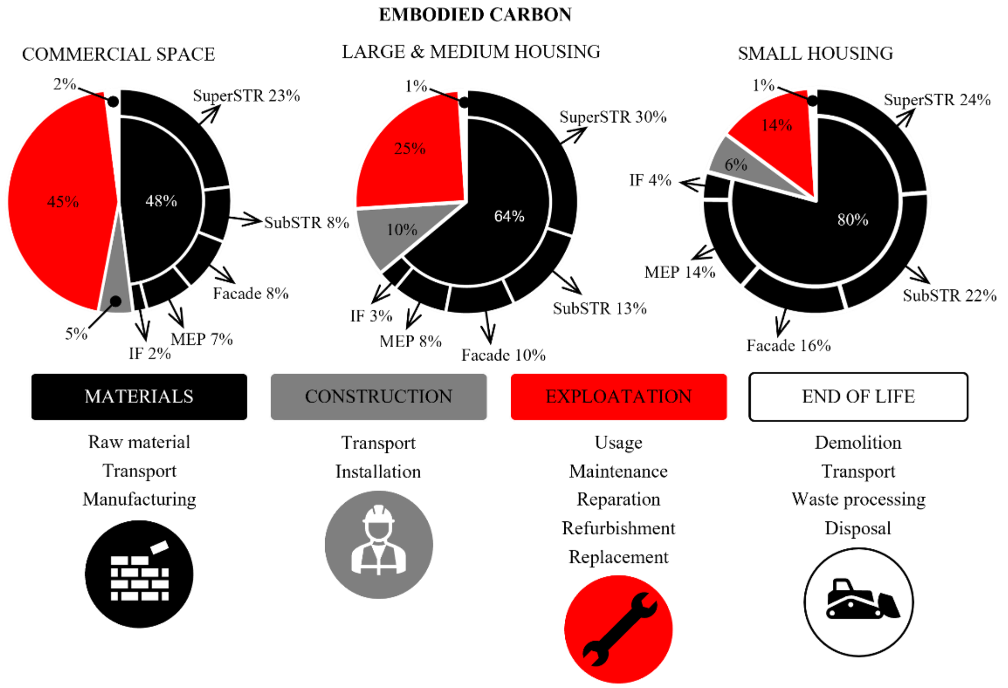


Figure 2. *Amount of embodied carbon in commercial and residential buildings induced in different stages of the structure's lifecycle*

As seen in Fig.2 the carbon footprint of each stage depends on the type of the project. It is therefore more important to focus on the optimization of the exploitation stage of commercial buildings (where it contributes with 45% of the total CO_2) than it is on the small residential buildings (where it represents–only14%). Material optimization on the other hand is something which should constantly be underlined, as it participates with 80%, 64% and 48% for the small, large & medium housing units and the commercial spaces respectively. Building more with less has historically always been a challenge of the construction industry, principally governed by the economic reasons. Today it is even more relevant due to the added ecological criteria.

Looking closer at the material/product phase, one can distinguish between the CO_2 emissions related to the:

- Superstructure (SuperSTR) – the load carrying part of the building
- Substructure (SubSTR) – the non-load carrying part of the building
- Façade
- Mechanical, electrical and plumbing (MEP)
- Internal finishes (IF)

Design of the superstructure is the main responsibility of civil engineers, and it alone uses up to 30% of the total embodied carbon over the entire lifespan of a building (refer to Fig. 2). Combining this with the data from Fig.1, means that at least 2.5 % of the entire worlds CO_2 emission is directly dependent on the work of civil engineers and architects. Therefore, if the objective of the construction sector is to set a benchmark for the other industries in reducing its carbon footprint, then reducing the spans whenever possible, avoiding the structural misalignments, and designing foundations based on non-conservative geotechnical rapports should be the way for the future building [14,15]. Engineers should be included from the beginning in the decision-making process, in order to find a good compromise between the architectural expression and the environmentally responsible structure.

3. SELECTING THE ECOLOGICALLY RESPONSIBLE CEMENT

Let’s focus-on the material whose application in construction industry can hardly be overlooked: the Reinforced Concrete (RC). Almost every modern structure created in the 20th century, uses RC for its foundations, if not for the entire superstructure, substructure, and facade. Combining high compressive resistance with workability, durability, unique aesthetics, and an affordable price, has helped reinforced concrete remain the most produced man-made material in the world, being second in use to water [3,7].

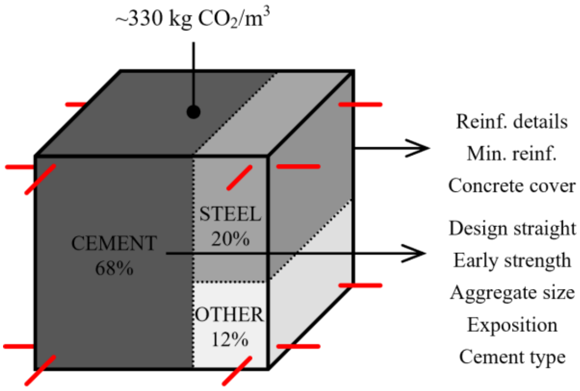


Figure 3. *Amount of embodied CO_2 in $1m^3$ of reinforced concrete (type NPKC) with CEM I cement and 100 kg/m^3 of reinforcement*

Fig.3 shows a breakdown of the embodied carbon in $1m^3$ of RC type C30/37 that uses 300 kg of CEM I cement and 100 kg of reinforcement. The vast majority (68%) of emitted CO_2 is associated with the cement, additional 20% are related to the reinforcement and the remaining 12% are divided between the aggregate, water consumption and the energy required to mix the components.

If one’s goal is to reduce the amount of emitted carbon of RC, their efforts should focus on:

- Choosing the type of the cement that is being used
- Choosing the minimal necessary design and early concrete strength,
- Choosing concrete based on its exposure,
- Putting the minimal reinforcement that corresponds to the exploitation of the element in question,
- Minimizing the amount of reinforcement through accurate calculation,
- Minimizing the concrete cover in order to increase the lever arm,
- Maximizing the aggregate size in order to gain maximal shear resistance.

Even though all the points mentioned above can be discussed in detail, this article will focus solely on the two points: the selection of the concrete based on its exposure and the impact of the cement type on the overall amount of the embodied carbon in RC.

These two parameters, which are perhaps the most overlooked by the structural engineers in practice, are some of the most important ones when it comes to the Net Zero carbon policy. The carbon emissions of cement mainly come from the production of Portland Cement (PC) clinker. The total amount of the carbon embodied in PC clinker comprises approximately of [8]:

- 10% of CO_2 related to the kiln operations,
- 40% of CO_2 related that are thermal energy,
- 50% associated with the chemical decomposition of limestone ($CaCO_3$) into lime (CaO), the process that chemically releases the CO_2.

Even though it is possible to reduce the carbon associated with kiln operations and substitute fuel in the thermal energy to favor more green options; the release of CO_2 cannot be avoided in the production of the clinker.

Tab.1 summarizes the types of cement that are being used for the construction of residential and non-residential buildings.

Tab.1: Types of cement used in buildings according to SN EN 197-1

Type	Notation	PC clinker [%]	Primary constituents* [%]	Secondary constituents** [%]
CEM I	CEM I	95-100	-	0-5
CEM II	CEM II/A	80-94	6-20	0-5
	CEM II/B	65-79	21-35	0-5
Special	CEM ZN/D***	50-64	36-50	0-5

* Silica fume / natural pozzolan / calcified natural pozzolan / silica fly ash / calcium fly ash / calcined shale / limestone
** Secondary constituents of cement
*** Developed by HOLCIM

There are 2 basic types of cement (CEM I and CEM II), whose type and composition of the primary as well as the secondary constituents are directly given by the norm SN EN 197-1 [10]. The main difference between the CEM I and the CEM II cement is that the first one consists almost entirely of PC clinker, whereas the second one employs a specific percentage of the primary constituents, thus lowering the amount of PC clinker in the mix. Depending on the quantity of these constituents, CEM II can be categorized as CEM II/A or CEM II/B. CEM ZN/D, is a special (non-standard) cement whose type of primary and secondary constituents is governed by the norm SN EN 197-1 [10], but their composition is not. Compared to the previous two types, CEM ZN/D has even a lower content of PC clinker and has been developed with the Net Zero carbon policy in mind.

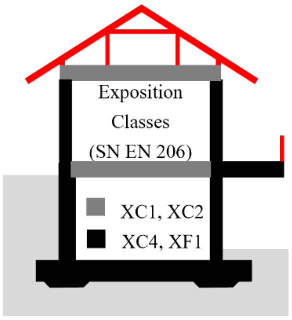
There is a number of products that can be used to substitute the PC clinker, some of them being silica fume, silica fly ash and calcium fly ash. These products are classified as industrial waste, and as such their carbon footprint has already been made. Therefore, replacing the PC clinker with the industrial waste lowers the amount of the emitted CO_2.

Regarding the strength of cement types indicated in Tab.1, both CEM I and CEM II exist in all three strength classes (32.5, 42.5 and 52.5). CEM ZN/D however can only be ordered with the strength of 32.5 and 42.5 [10].

This article focuses primarily on concrete used for the construction of residential and non-residential buildings, which does not require the application of the highest cement strength class. In order to have a direct comparison of the emitted CO_2 related to different types of concrete, all the recipes considered in the following chapter assume 42.5 cement strength class.

4. SELECTING THE ECOLOGICALLY RESPONSIBLE CONCRETE

Tab.2 shows 3 most used types of concrete in the building industry: NPKA, NPKB and NPKC [12]. These mixtures have different design strength, various exposure classes and cement quantities. According to SN EN 206 [9], NPKA and NPKB types of concrete can be used for all internal RC elements. NPKC however should be used for the elements that are exposed to atmospheric influence as well as the elements that are in direct contact with the soil. Choosing the correct concrete for a specific element directly influences the amount of used cement and choosing the right cement directly influences the amount of embodied carbon. There is however a matter of price which varies very little between NPKA, NPKB and NPKC concrete. If the costs are almost the same, then why choose a less resistant material? Why complicate the execution of the project by having to change concrete type for each element? The answer to these questions is simple: in order to help the climate.



Tab 2: Type of concrete SN EN 206

Type	NPK A	NPK B	NPK C
Design strength	C20/25	C25/30	C30/37
Exposition class	XC1, XC2	XC3	XC4,XF1

The aggregates that can be used in the concrete production are made from natural or recycled construction materials (refer to Fig.4). The natural aggregates (shown in Fig. 4a) have a dense microstructure which can be seen under the microscope (the image on the right). Recycled aggregates (RA) on the other hand are much more porous by comparison (refer to Fig. 4b).

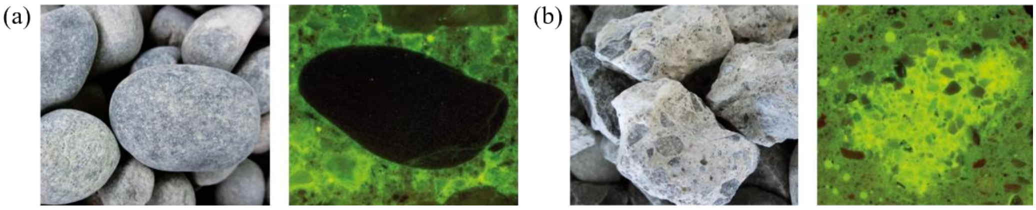


Figure 4. *Aggregates used in concrete mixture: (a) natural aggregate; (b) recycled aggregate*.
Source: https://www.holcimpartner.ch/fr/betonpraxis/beton-de-recyclage

Both concrete and clay-based materials (various types of bricks and building blocks for example) can be crushed, turned into aggregates and revalorized as recycled concrete, thus saving natural resources. In order for concrete to be recognized as recycled (RAC), it needs to contain at least 20% or 25% of recycled aggregates depending on the standard considered (EC2 or SIA2030 [16] respectively). Going further, the reference to RAC in the paper implies only mixtures containing 25% of concrete based RA.

As stated previously, such aggregates are more absorbing due to their increased porosity. Therefore, it is to be expected that RAC needs more water compared to conventional concrete. Simply adding more water into the mixture might reduce the final compressive strength. To prevent this from happening suppliers often increase the amount of cement, therefore directly enhancing the carbon footprint.

Tab.3 summarizes the amount of cement used in different types of concrete (NPKA, NPKB and NPKC) made entirely with natural aggregates (conventional concrete) or containing 25% of recycled concrete aggregates (recycled concrete).

Tab.3: Quantity of cement in various concrete types [kg/m^3]

Type	Conventional concrete		Recycled concrete	
	According to SN EN 206	According to NFIC* experience	According to SN EN 206	According to NFIC* experience
NPK A	280	315	280	328
NPK B	280	315	280	328
NPK C	300	330	300	340

* NFIC - Nicolas Fehlmann Ingénieurs Conseils SA

The table shows a difference between the minimum quantity of cement recommended by the SN EN 206 standards and the average quantities that Nicolas Fehlmann engineering office (NFIC) finds on the Swiss market. Furthermore, suppliers systematically use more cement in recycled concrete mixtures compared to conventional ones.

Fig. 5 shows the amount of embodied CO_2 in 1m^3 of multiple types of concrete (NPKA, NPKB and NPKC) made with cements indicated in Tab.1 and quantities from Tab.3. In other words, Fig. 5a shows the minimum theoretical carbon footprint while Fig. 5b and Fig 5c present realistic carbon emission of conventional and recycled concrete on the Swiss market. The amount of CO_2 was estimated using the Data from the lifecycle assessments in construction developed in 2016 for the Swiss market [1,2,4,13].

Looking at each individual graph, there is no major difference between the amount of embodied CO_2 in NPKA and NPKB concrete, which is to be expected given the same amount of cement used in both mixtures. The slight difference comes from the emitted carbon linked to aggregate, water and energy consumption (indicated as "other" in Fig.3). NPKC however has constantly higher values of CO_2 due to the additional amount of cement compared to the other two types. The main difference nonetheless does not come from the amount of cement but from its type, and a direct impact of reduced amount of PC clinker in the mixtures can be seen. In the most extreme case (NPKC with CEM I vs NPKA with CEM ZN/D) this can add up to 76 kg/m^3 of CO_2 saved in conventional concrete, and 77 kg/m^3 of CO_2 saved in recycled concrete.

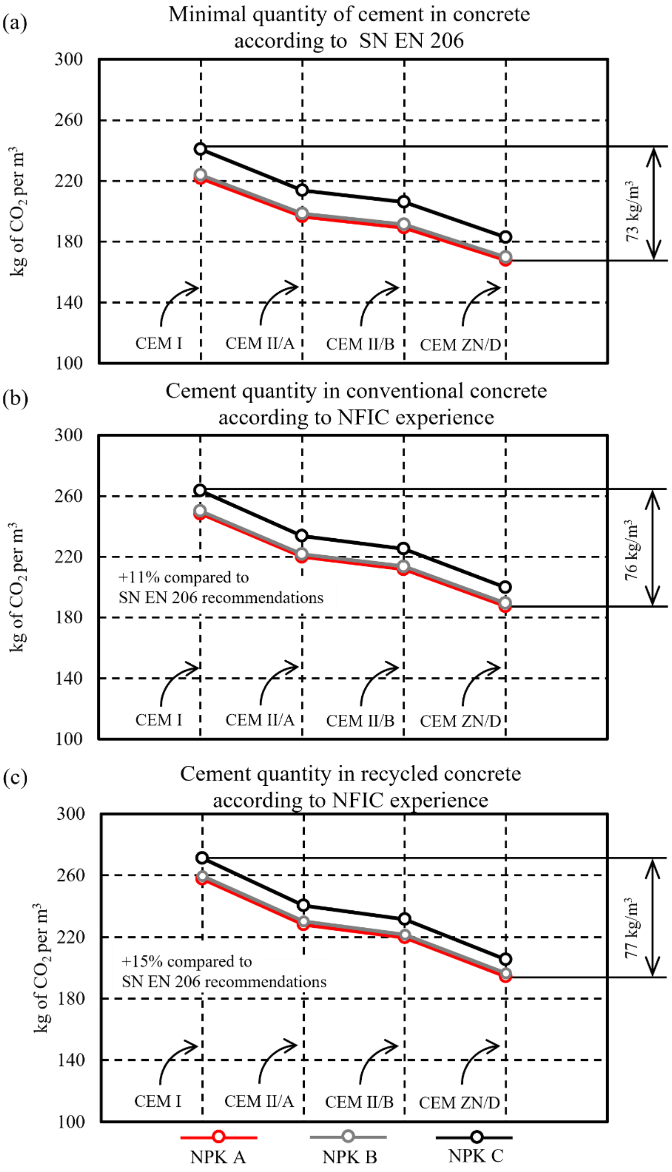


Figure 5. *Amount of embodied CO_2 in $1m^3$ of multiple types of concrete using CEM I, CEM II A & B and CEM ZN/D: (a) assuming the minimum theoretical amount of cement; (b) assuming a realistic amount of cement used in the Swiss market for conventional concrete; (c) assuming a realistic amount of cement used in the Swiss market for recycled concrete*

Keeping in mind that the data is taken from Swiss market, it is important to underline that on average additional 11% of CO_2 are emitted in reality compared to what it could be emitted respecting the SN EN 206 standard. This comes from the fact that the concrete suppliers often add more cement in order to achieve higher concrete compressive strength than the ones requested by the designers. This leaves some room for the recipe optimization that most actors are reluctant to, due to increased risks of having unacceptably weak concrete. Same thing applies to the recycled concrete where this difference reaches 15% of CO_2 emitted due to increased porosity of RA.

5. PUTTING THINGS INTO PERSPECTIVE

In order to have a clear idea on how big of an impact the rigorous choice of concrete and cement actually have on the carbon footprint, it is best to express it through some real-life examples.-For this purpose, two very different projects, both developed by Nicolas Fehlmann Ingénieurs Conseils SA (NFIC), are considered.

Project Sauges 30 (see Fig.6) is a residential medium sized building located in Lausanne (CH). The load carrying structure is made from RC walls which are supported by a series of columns located in the underground parking. All slabs are made from RC, and all the façade walls are precast sandwich RC panels. The residential building has one ground floor with 5 stories and an attic, with a total area of 5’120 m^2 of living space. Underground parking has 1’060m^2 of surface and consists of a single floor. The overall theoretical volume of concrete used in Project Sauges 30 is 2’525 m^3. A portion of that concrete is used for the interior elements of type NPKB. The remaining part is the NPKC type and it’s being used for the construction of exterior elements exposed to the atmospheric influence and/or direct contact with soil. In other words, Project Sauges 30 is a typical medium housing project which most structural engineers and architect have constructed multiple times in their professional careers.

Project SAUGES 30, Lausanne, Switzerland	
Parking area	1’060 m^2 **
Residential area	5’120 m^2 **
Number of stories	-01 + GF + 6
Volume of concrete	2’525 m^3 **

* DOLCI architectes, Atelier d'architecture et d'urbanisme Sàrl
** Theoretical values

Figure 6. *Residential building in Lausanne (CH) developed by DOLCI architecture and NFIC civil engineering office*

Substituting the CEM I with CEM ZN/D type of cement for the entire volume of concrete used for the Sauges 30 project saves approximately 140 t of CO_2. If we compare this to the pollution of an average new passenger car produced in 2018 (see Fig.7a), this represents an equivalent of the CO_2 released from circling the globe along the equator 29 times (see Fig.7b).

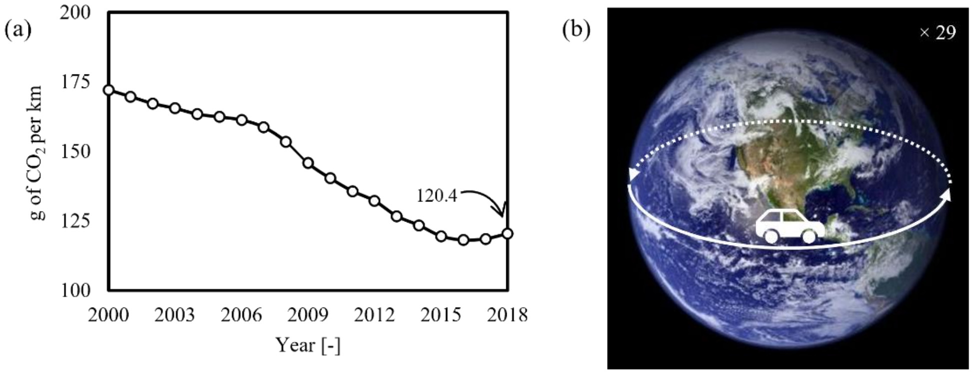


Figure 7. *Amount of embodied CO_2 saving potential through a responsible cement selection on a mid-sized housing project:(a) Average CO_2 emission from new passenger cars; (b) CO_2 savings of a responsible cement selection in the SAUGES 30 Project*

Another project, which is currently being developed by the NFIC office, in presented in Fig.8. It is a residential and commercial complex which is currently under construction in Lausanne. The entire superstructure is made from concrete and it consists of RC slabs that are supported with pillars and escalator/staircase cores. The complex consists of 5 buildings which are placed on 2 separate underground parking lots.

Central Malley, Lausanne, Switzerland	
Parking area	18’685 m^{2**}
Residential area	59’656 m^{2**}
Number of stories	-03 + GF + 26
Volume of concrete	32’646m^{3**}

* Pont12 architectes sa
** Theoretical values

Figure 8. *Commercial/Residential building complex in Lausanne (CH) developed by Implenia general contractor, Pont 12 architecture and NFIC civil engineering office*

The total theoretical amount of residential surface is 59’656 m^2 with a total of 18’685m^2 of parking area. The highest building has 26 floors and with the height of 79.7 m, it will be one of the highest in the city of Lausanne. Total estimated amount of concrete used for this complex is 32’646m^3.
Once again by substituting the CEM I with CEM ZN/D type of cement in the concrete mixtures, approximately 2.3 million tons of CO_2 can be saved.

Amsterdam, Nederland	
Population	1’158’000
City area	219.3 km^2
CO_2 traffic emission*	840’000 t
Cement choice benefit	~ 1 day of traffic induced CO_2 saved

* Total CO_2 traffic emission in 2021

Figure 9. *Amount of embodied CO_2 saving potential through a responsible cement selection on a Central Malley project in Lausanne (CH)comparing with traffic in Amsterdam*

Comparing that saving to the total amount of CO_2 emitted by traffic in the city of Amsterdam (refer to Fig.9), one can realize that the saved amount of carbon represents an equivalent of 1 day worth of traffic.
This only demonstrates that even though the reduction of CO_2 through a critical selection of concrete and cement is significant, it is by far not the only consideration that will lead us to Net Zero carbon by 2050. However, when taking into consideration the amount of effort required by the engineers and architects to obtain these savings, this reflection is a paramount one.

6. CONCLUSIONS

Based on the facts presented in this paper, following conclusion can be drawn:

- Choosing the concrete type based on the exposure of the element has a direct impact on the carbon footprint reduction
- The difference in the carbon footprint between the concrete with the lower exposition class (XC1/XC2) and medium exposition class (XC3) is minor
- Choosing the cement type with the lowest content of PC clinker leads to a significant reduction of the carbon footprint, while being very time efficient from the engineering point of view
- Concrete suppliers often increase the amount of cement in their recipes in order to minimize the risks of delivering material with insufficient resistance to construction sites
- Using recycled concrete saves natural resources and revalorizes materials obtained from demolishing existing structures

- Concrete with recycled aggregates currently has an increased amount of cement compared to conventional concrete due to higher water absorption
- Usage of simple load-carrying mechanisms (superposed beams and pillars with little to no eccentricity) has the biggest potential to minimize the ecological impact on the environment and therefore they should be favorized
- The correct choice of material represents only one step towards achieving the Net Zero carbon policy.

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