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Why development of technologies (alone) will not save us. The example of alternative binders in the concrete sector.

Author	M. Sc. Richard Caron
University	Karlsruher Institut für Technologie (KIT)
Institute	Institut für Massivbau und Baustofftechnologie (IMB)
Address	Gotthard-Franz-Str. 3, Geb. 50.31, Raum 507
	76131 Karlsruhe, Deutschland
Field of Study	Concrete technologies
Email address	richard.caron@kit.edu
Phone number	00 49 721 608-47781
	00 33 6 66 82 30 41

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Abstract

Human societies are confronted with two huge challenges: resource depletion and climate change. Technology carries promises that both issues can be handled without affecting our current standard of living. In this paper, the concrete industry is used as an example: alternative binders are a potential technological solution to reduce both material and carbon footprints of structures. The creep and shrinkage performances of these materials are evaluated in the laboratory to determine for which applications they can be suitable. However, this sole solution fails to reduce CO_2 emissions from a global vision, just as the development of technologies has failed to tackle the increase of CO_2 emissions for the past fifty years. Thus, technological improvements must be accompanied by a profound reconsideration of the functioning of society.

1 Introduction

Preserving an inhabitable environment is directly linked to the notion of inter-generational equity. Mitigating both greenhouse gas (GHG) emissions and extraction of non-renewable resources is necessary to ensure that the next generations will have the same technical, social and democratic possibilities as the current generations in the privileged regions of the world.

Issues about climate change and resource scarcity have been known and published by climate scientists for the past fifty years. The Intergovernmental Panel on Climate Change (IPCC) compiles and sums up the contemporary knowledge on sciences related to climate change on a regular basis. It informs the public and the politicians on the most recent consensus and findings of the scientific community by releasing reports of different levels of complexity. One of the main conclusions is that net zero CO_2 emissions must be reached before 2050 to mitigate global warming to 2 °C, level above which point of no return is reached. Another important publication is the pioneer work of the Club of Rome of 1972: *The Limits to Growth* [1]. Manufacturers and researchers in domains as diverse as science, economy or politics warned of dangers from unlimited and uncontrolled economic and demographic growth on our societies. Many of their scenarios predicted a collapse, i.e. a rapid decrease of the population and level of comfort of the society, which can be due to the scarcity of resources or to pollution. To avoid it, birth rate, consumption and pollution must be necessarily limited in their models.

Accordingly, international political meetings have been organized for the past fifty years to face those issues. Few examples are the 1972 United Nations Conference on the Environment in Stockholm, the 1979 Conference in Genève and the yearly Conferences of the Parties (COP) leading notably to the Kyoto protocol in 1997 and the Paris agreement in 2015. Nevertheless, none of these meetings contributed to stop the growth of global CO_2 emissions as shown in Figure 1. This seems quite paradoxical given the tendency in the past years to finance "green" technologies, such as more efficient engines, electric cars, renewable energies or even recyclable plastic bags. In the concrete industry, a focus has been made on one technology: alternative binders.

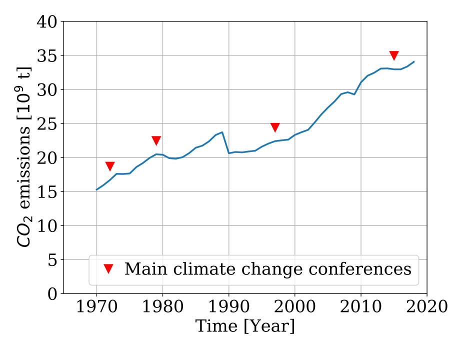

Figure 1: Evolution of CO_2 emissions for the past fifty years and influence of political meetings on the curve. Data from [2].

2 Alternative binders, a solution for the concrete industry?

The production of concrete is responsible for 8 % of the CO_2 emissions in the world. Concrete is the second most used material after water with around 25 billion tonnes of concrete manufactured each year worldwide [3]. Its composition can vary depending on the usage and on the desired mechanical and durability properties. Concrete is a composite of aggregates, sand, water and a binder, the reactive component. The main binder in the concrete industry is cement. It is a rich-calcium (Ca) binder with a particle size of 1-100 µm. Upon contact with water, it partially dissolves into ions, which react further to form the hardening paste sticking aggregates together. To generate cement, calcite ($CaCO_3$) is extracted and must be heated at around 1450 °C. At this temperature, the molecule is split in order to get the main oxide of cement, calcium oxide (CaO). This oxide is associated with silicon, aluminium, iron and sulphur to form the classical reactive phases of cement: alite, belite, aluminate and ferrite. Grossly, the production of 1 ton of concrete equals to the release of 0.8 tons of CO_2 in the atmosphere. Around half of the emissions comes from the chemical separation of calcite:

$$CaCO_3 \rightarrow CaO + CO_2$$

The other half is due to the heating process, usually realized with fuel. This energy consumption must also be taken into account in the ecological costs: in 2006, 110 kWh per ton of cement were needed and only small efficiency improvements are expected in the next thirty years [4]. For these reasons, alternative binders with comparable properties are sought to reduce the carbon footprint and the energy need of the concrete industry. The most common ones are slag, fly ash and clay [5]. In comparison to cement, they contain less or even no CaO but more silicon and aluminium oxides [Figure 2]. Slag is a by-product of the steel industry produced during the melting process and allowing to remove impurities. Fly-ash is a waste product of coal combustion which is filtered during the process. Finally, clays are natural soil minerals available in nature.

These alternatives can be used in two different ways. Firstly, they can partly replace cement: the latter must still be produced, but in smaller quantities. As a second option, an alkali solution with one of these alternative binders is used. The alkali solution helps the dissolution and the hardening of the material. In that case, the formed concrete is named alkali-activated concrete. This last solution reduces the CO_2 emissions at the production by the nature itself of the component since no $CaCO_3$ molecule must be broken and no or less heating of the binder is needed. In that respect, several projects have been supported by political and industrial investments and are regularly promoted in public events and in outreach journals [6].

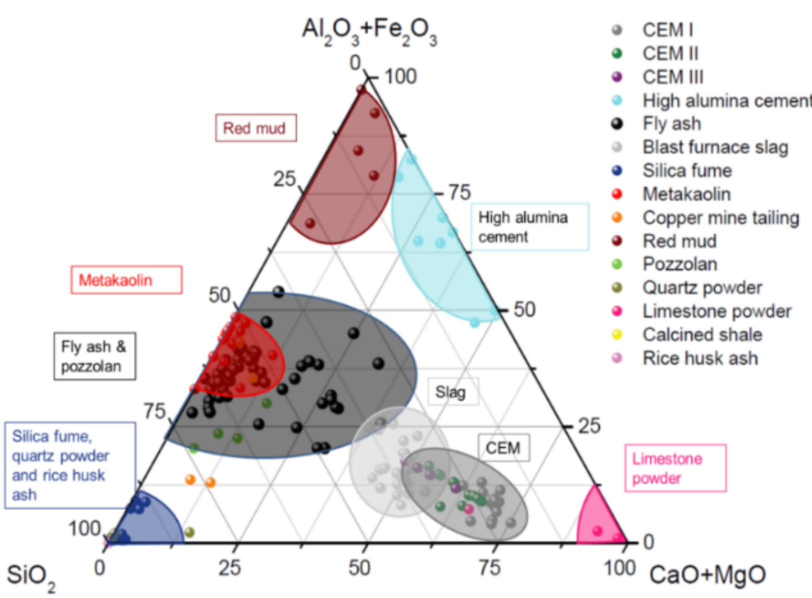

Figure 2: Ternary diagram of composition of classical binders. Metakaolin is the anhydrous form of the clay mineral kaolinite. In comparison to cement, silicon oxide (SiO_2) and aluminium oxide (Al_2O_3) replace calcium oxide (CaO) in the compositions of slag, fly ash and metakaolin. [5]

However, fly ash and slag cannot be viable at long-term. As explained, fly ash comes from combustion of coal to produce electricity. If the goal is to reduce the global CO_2 emissions, there is no place for coal power plants. As a matter of fact, a coal power plant emits around 1 000 g CO_2eq / kWh, to be compared for instance with 10 g CO_2eq / kWh for hydroelectric generators or 32 g CO_2eq / kWh for solar photovoltaic [7]. For slag, the production is dependent on the production of steel, which emits 2.2 tons of CO_2 per ton. Finally, the available resources of slag and fly ash are not large enough: less than one billion tons of each are produced each year, while more than four billion tons of cement per year are required to meet demand today. Clay reserves are much larger but the use of this binder still involves a calcination at around 700-800 °C with fuel to obtain a reactive binder [8].

Another limitation is that current norms and models are adapted for cement-based concrete and not for alternative binder concretes. Yet, a specific standardization for these materials is necessary to promote their use and to apply them in the right conditions. Though, research on these innovative materials have only started in the 2000s. Thus, they are still regarded as "niche" materials which must be understood scientifically [5]. Alkali-activated materials present three main problems. The first one is a quicker setting time, not letting time to apply and use the material properly [9]. The two other are creep and shrinkage, i.e. the temporal progressive volumetric contraction with and without load applied on the material. Investigating them is of huge importance to assess durability properties of concrete. If the strain is too large, cracks can be created and the structure is weakened.

To evaluate these two last properties, concrete specimens were cast and tested in the laboratory, following the norms DIN EN 12390-16 [10] and DIN EN 12390-17 [11]. Various environmental conditions were tested, notably covered specimens. This allows preventing any moisture loss from the material and facilitates the modelling of the material behaviour. Results of creep and shrinkage are presented in [Figure 3]. The creep coefficient is defined as the strain after loading normalized by the elastic strain. For alkali-activated slag, it is around two times higher after three months than the prediction done by the current *fib* MC 2010 (model code drafted by the *fédération internationale du béton*) [12]. This suggests that the viscoelastic properties of alkali-activated slag concrete is quite different from the ones of cement concrete. The shrinkage obtained after three months is around eight times higher than the prediction done by the same model code. This can be understood from the fact that the chemical reaction of alkali-activated slag consumes more available water and induces a higher drop of relative humidity. In the poro-viscoelastic theory, this drop of relative humidity leads to a greater capillary pressure applied on the meniscus covering the particles and as a consequence to a greater shrinkage [13]. Nevertheless, it was shown that this theory is valid until a certain relative humidity [14]. If the drop is too high, other physical mechanisms occur and must be modelled. For cementitious systems, the drop of relative humidity is low enough and the sole capillary pressure mechanism can be taken into account to predict shrinkage. The results for alkali-activated slag show that the existing models codes are not adapted to predict neither shrinkage nor creep. It means that extensions or even new models must be developed to take into account further physical mechanisms. In the context of global environment and energy issues, a final limitation to this problem is that the release of a model code requires time; for instance, the time lapse between two releases from the *fib* is around ten years. In addition, so far, they have only released regulations for concrete based on cement, which has been used for many decades.

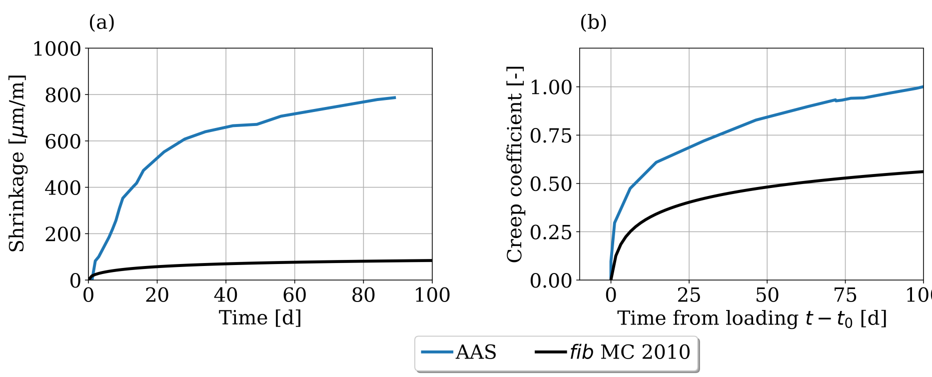

Figure 3: Creep (a) and shrinkage (b) results of alkali-activated slag (AAS) and comparison with existing standards (*fib* model code 2010). High strains lead to the formation of cracks and to reduced mechanical and durability properties of the concrete (Experimental results from the author).

A further question is the quantity of binder needed each year. Forecasts show that the world cement demand will continuously grow from around 4.1 billion tons in 2020 to around 6.0 billion tons per year in 2050, corresponding respectively to around 3.3 and 4.8 billion tons of CO_2 emitted per year [15]. At the same time, implementation of technologies mitigating CO_2 emissions at the production of concrete could reduce the CO_2 emissions of 1.3 billion tons per year. In other words, the enhancement of the technology will hardly compensate the rise of CO_2 emissions due to the growing demand. With this perspective, projects like "Save CO_2" launched by the *Bundesministerium für Bildung und Forschung* to promote research on slag are unfortunately largely insufficient.

Additionally, the CO_2 allocated to the concrete industry can not be limited to the concrete production, but also to its use. Considering it, the part of responsibility of the concrete industry for the CO_2 emissions is no longer 8 %. Indeed, even if the production of concrete did not emit any CO_2, the concrete industry should be allocated a part of the CO_2 emissions associated to its use. Looking at the distribution of CO_2 emissions per sector [see Figure 4], the concrete industry has a – partial – responsibility of at least 46 % of the global CO_2 emissions: without concrete, there is neither industry (32 % of the CO_2 emissions) nor transport (14 %). In that regard, the construction of the Brisbane Airport that is called "the greenest airport in the world" (sic) [17] because it was built with alkali-activated slag can only be regarded as a campaign of green washing. To mitigate climate change and prevent resource depletion, the question is unfortunately not only reducing CO_2 emissions occasionally, but reaching global climate neutrality, and this before 2050.

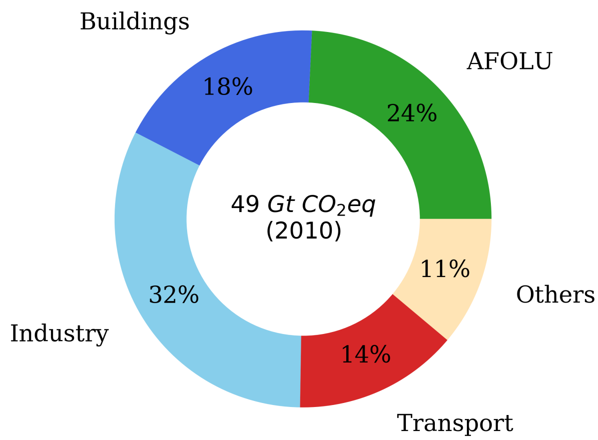

Figure 4: Total anthropogenic GHG emissions ($GtCO_2eq/yr$) by economic sectors. AFOLU stands for Agriculture, Forestry and Other Land Use. [16]

In conclusion, alternative binders are a solution to reduce the CO_2 emissions of the concrete production. Nevertheless, understanding their properties is still a challenge, and adequate norms and engineering models are not available for the moment. Even ignoring these problems, using such binders does not solve the problem of reducing the global CO_2 emissions. The needed quantities and the practical use of concrete should be put at the core of any debate regarding the ecological impact of the concrete industry.

3 The place of technology in a holistic vision

With the growth of the population and the relative increase of wealth all over the world, both world GDP and world CO_2 emissions have raised continuously since 1970 [see Figure 5] [2]. The interesting thing is that the path of worldwide CO_2 emissions and worldwide gross domestic product (GDP) are linearly correlated. Macroscopically, for each new \$ 1000 generated in the economy, 200 kg CO_2 are emitted in the atmosphere. This linear relation of CO_2 with GDP relativizes the impact of technology and research with regards to the objective of reducing the CO_2 emissions. Given the reduced equation from Kaya [18]:

$$CO_2 = POP \cdot \frac{GDP}{POP} \cdot \frac{CO_2}{GDP}$$

with CO_2 the world CO_2 emissions, POP the world population and GDP the world growth domestic product, technology and research can only influence the last ratio of the equation $\frac{CO_2}{GDP}$. Note that the original equation of Kaya replaces this term by $\frac{E}{GDP} \cdot \frac{CO_2}{E}$, where E is the world primary energy consumption. For the sake of simplicity and because the linearity of CO_2 versus GDP comes from both linearity of E with GDP and linearity of CO_2 with E [19], the sole term $\frac{CO_2}{GDP}$ is considered. If technology was effective to reconcile the objective of less CO_2 emissions with the development of the society, the second derivative of the model should be negative. Indeed, every new point of GDP would be associated with reduced CO_2 emissions. Yet, the historical trajectory of these last fifty years invalidates this possibility.

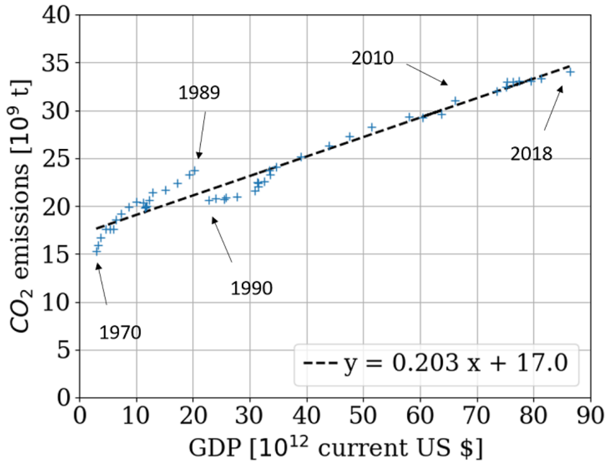

Figure 5: Correlation between CO_2 emissions and gross domestic product (GDP) from 1970 to 2018. Data from [2].

Mechanisms should be enquired to explain the relation between CO_2 and GDP. To do so, rebound effects must be introduced to understand the shape of the curve. For each technology, given potential emissions savings PES and actual emissions savings AES, the rebound effect R is defined as [20]:

$$R = 1 - \frac{AES}{PES}$$

If $R = 0$, technology keeps its promises and reduces the CO_2 emissions. If $R > 0$, the rebound effect occurs: economic or psychological mechanisms induce more emissions than expected and mitigate the positive effect of technology. If $R = 1$, the potential emissions saving is completely compensated by other mechanisms. The perfect linearity between the world CO_2 emissions and the world GDP suggests that the global rebound effect must be close to 1. For the past fifty years, every potentiality to reduce CO_2 emissions per new point of GDP with the enhancement of technologies has been compensated. The demonstrated mechanisms for the concrete industry can be generalized. Indeed, development of technologies can be improved locally in the production chain and not thought globally. In that case, the environmental impact is moved to another part of the system. For instance, digitization decreases the CO_2 emissions allocated to the production of paper; however, it entails an increase in the CO_2 emissions allocated to the production of electronic devices. Practical applications of technology participate also to the rebound effect. Using ecological-friendly materials does not allow to build more airports or roads. About indirect rebound effects, cheaper "green" technologies are not an excuse to invest more in polluting industries. For example, financing the energy transition and subsidizing coal power plants is paradoxical [21]. Finally, quantities in general should be questioned. In the period 2008-2017, around 5.6 GtC (Giga ton of Carbon) per year were absorbed by nature, while 10.9 GtC were emitted by human activity [22]. Aiming at a net zero carbon flux means that the human species must restrict its emissions to 5.6 GtC per year. Eventually, it means dividing our economic activity by two.

4 Conclusion

In this paper, it was shown that despite warnings from scientists on climate change and resource depletion, despite improvements in technologies and despite good will from decision-makers to finance these developments, technology alone brings no holistic answer to the main challenges of the twenty-first century. The example of alternative binders in the concrete industries illustrates problems of taking into account the whole supply chain and the time needed for validating new technologies. Furthermore, development of alternative binders seems to allow postponing two further crucial aspects: manufactured quantities and use of concrete. Technology is necessary but not sufficient. If our goal is truly to pass a stable society on to our children, the core idea of limiting ourselves in our quest of wealth must be put seriously on the table, in echo to *The Limits to Growth*.

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Energy and environment – My idea for tomorrow

Why development of technologies (alone) will not save us
The example of alternative binders in the concrete sector

M.Sc. Richard Caron

IMB KARLSRUHE MPA KARLSRUHE

Institute of Concrete Structures and Building Materials, Department Building Materials and Concrete Construction
Materials Testing and Research Institute, MPA Karlsruhe

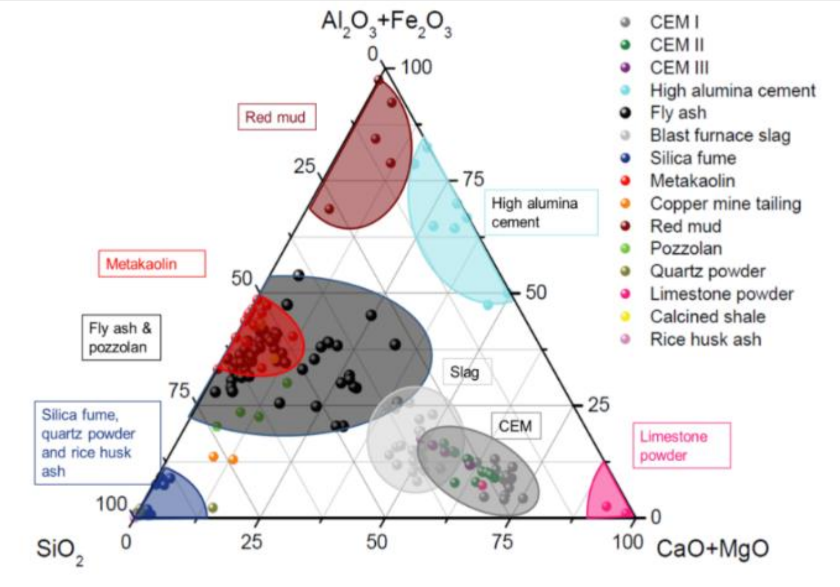
Alternative binders, the solution for concrete?

- Concrete production = 8 % CO_2 emissions worldwide

- 4 Gt cement / year
- 1 t cement ~ 0.8 t CO_2

$$CaCO_3 \xrightarrow[1500°C]{} CaO + CO_2$$

- Alternative binders
  - e.g. slag: waste product from industry



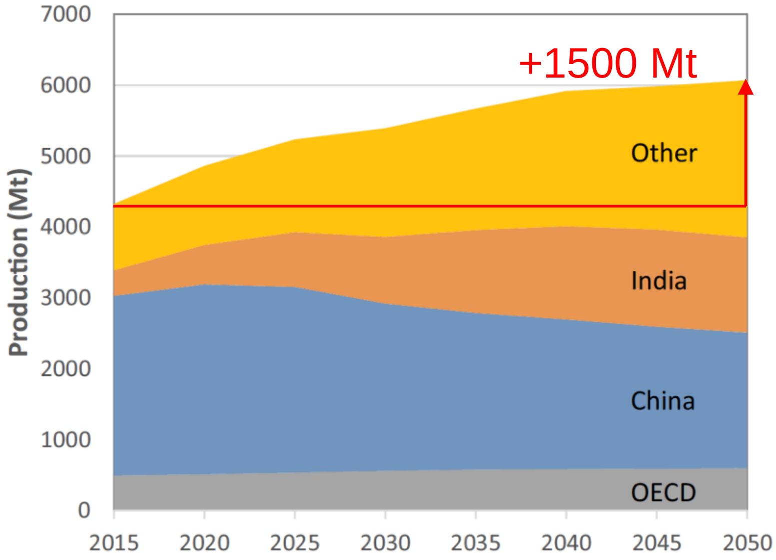
Binders used for making concrete

Reference: Barthel, M.; Rübner, K.; Kühne, H.; Rogge, A.; Dehn, F. (2016) From waste materials to products for use in the concrete industry, Advances in Cement Research, Volume 28, Issue 7, pp.458-468

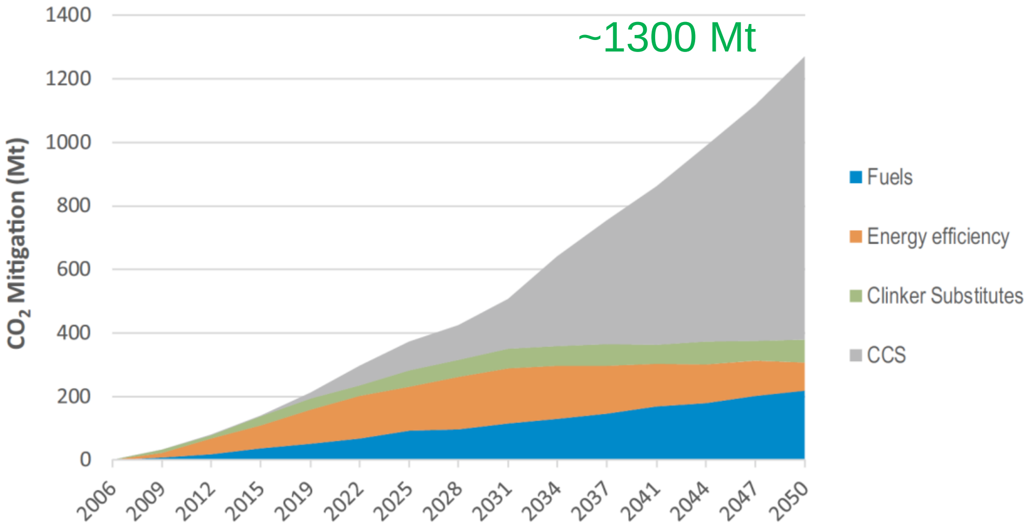
Forecasts on CO_2 emissions from concrete

Karlsruhe Institute of Technology

- Improvements of technology only compensate increase of demand



IEA scenario for yearly cement consumption



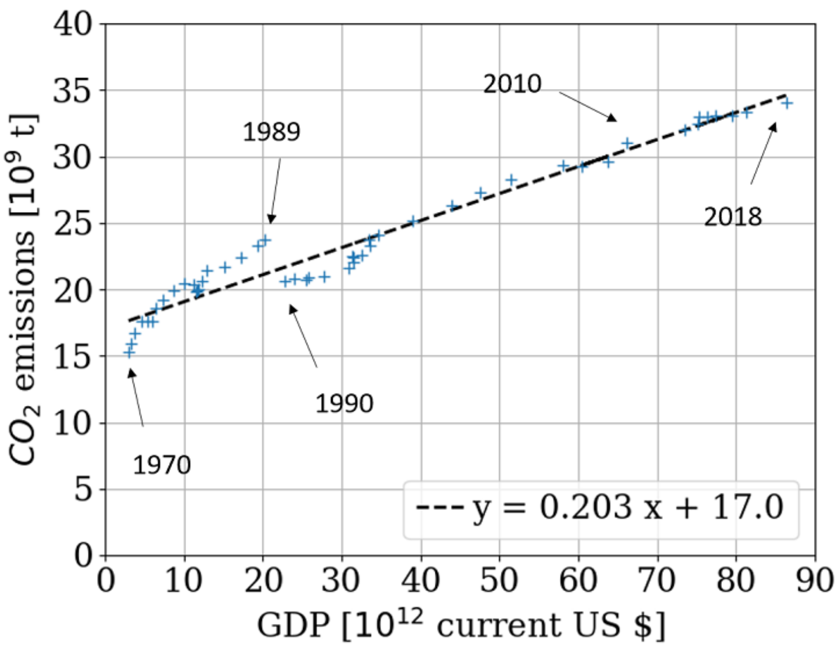
Cement sector CO_2 emissions reductions (baseline: 2006)

Reference: Scrivener, K.L., John V.M., Gartner E.M., Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry, Cement and Concrete Research,Volume 114, 2018, pp. 2-26,

Technology to solve climate change issue?

- Linear relation between CO_2 and Gross Domestic Product (GDP)

- + \$1000 → +200 kg CO_2 regardless of the used technology



World CO_2 emissions versus world GDP

Reference: The World Bank, "World Bank Open Data", 2021 https://data.worldbank.org/ accessed 01.10.2021

Research: between promises and green washing

- Rebound effect: augmentation of CO_2 emissions after a technological improvement that was supposed to reduce them

- Example:
  Eco-friendly materials…
  to build airports?

Brisbane airport, built with alternative binders: "the <u>greenest</u> airport in the world"

Reference: Wagner, "Toowoomba Wellcamp Airport", *Earth Friendly Concrete* https://www.wagner.com.au/main/our-projects/toowoomba-wellcamp-airport/?division=5655 accessed 02.11.2021

It’s time to conclude… My idea for tomorrow?

- CO_2 emissions and GDP are linearly correlated
- Development of technology does not reduce CO_2 emissions
- What remains: economic degrowth and acceptation of the physical limitations of our environment

Thank you for your attention…

M.Sc. Richard Caron
richard.caron@kit.edu