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Study of two concrete mix-design strategies to reach carbon mitigation objectives

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ABSTRACT

The building and construction sector is a major CO_2 producer and climate change perspectives urged to reduce CO_2 emissions. The impact of concrete buildings on environment is mainly due to clinker, which is the main material used all over the world to produce cement and which releases a bit less than 1 ton of CO_2 per ton of clinker produced.

In this study, we first evaluate if the medium term CO_2 emission reduction objectives for the cement industry are realistic according to our current scientific and technologic knowledge. We consider two environmental strategies. The first one is the substitution of clinker by mineral additions in cement in order to reduce the environmental cost of the material for a given volume of material; the second one is the reduction of the concrete volume needed for a given construction process by enhancing the concrete performances. The impact on CO_2 emissions of a combination of these options is also roughly evaluated. We show that medium term objectives can be reached although long term objectives will need further research developments. We moreover present here a first step towards mix-design methods associating environmental costs and performance requirements which could allow for a better balance between societal demand in terms of environment and technical building requirements.

1. Introduction

The industrial sector is responsible for approximately 25% of global carbon dioxide (CO_2) emissions among which CO_2 emissions from cement plants represent no less than 5% of total anthropogenic emissions [1,2] despite the efforts of the cement industry to reduce emissions. Recent studies on the Life Cycle Assessment (LCA) for concrete structures show that 85% of the CO_2 emissions are related to cement production [3]. Moreover, LCA for cement shows that 95% of the CO_2 is produced during the fabrication of the cement, compared to emissions during the transport of raw materials and finished products [4]. It seems therefore obvious that the necessary effort in the building and construction sector in term of CO_2 reduction has to be made on the type and amount of cement used in concrete, at least as a first step.

The cement industry has been encouraged to keep on improving its production processes to reduce its CO_2 emissions due to the Kyoto protocol goals. The so-called Kyoto protocol was signed in 1997 with the aim of reducing the developed country's greenhouse gas emissions by 5.2% from the 1990 level by 2008–2012. To enforce the implementation of the Kyoto targets, the European Union launched the Emissions Trading Directive in 2003, in which plant-specific CO_2 caps were introduced into the largest energy production and energy-intensive industry sectors (*e.g.* cement, oil refining, steel, pulp, and paper) [5]. It can be noted that these industries are strongly encouraged to respect this protocol as there is a cost impact for not meeting the quotas. Cost estimations show that, for energy-intensive industries such as the cement industry, the CO_2 cost could be as high as 50% of production value [6] if no technologic or scientific changes occur. This value could be compared to the case of paper for which the CO_2 cost would reach only 1% of production value [6].

It has to be noted that, in this study, we limit our observations to the French context, but the conclusions drawn here could be easily extrapolated to other concrete industries from developed countries. In France, a climate action plan was edited in 2005 [7]. It is based on the "*factor* 4" concept [8] which aims to reduce by a factor 4, the carbon emissions in the developed countries in 2050, in order to reach a global world reduction of 50% of the 1990 level. This "*factor* 4" concept is in concordance with the Intergovernmental Panel on Climate Change (IPCC) recommendations, which state that, in order to constrain the global warming between 1.4 °C and 3.1 °C, a reduction of current annual greenhouse gas emissions by 52–90% by 2100 would be needed [9].

Furthermore, in this study, we do not take into account the Clean Development Mechanisms of the Kyoto protocol, which can substantially modify the emission quotas from developed country industries [10]. We deal with a factor 4 reduction as a quantitative reduction of CO_2 emissions. Within the frame of this hypothesis, if a linear reduction is considered, this leads to a reduction by half of the 1990 emissions in 2020. A medium term objective is therefore a "*factor* 2" reduction by 2020.

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In this study, we evaluate if this French reduction objective is realistic in a medium term perspective according to our current scientific and technologic knowledge. In order to carry out this evaluation, we consider that, in France, as in many other developed countries, the cement demand will not increase much from now on to 2050. We will briefly discuss the strategy of improving the cement production process by decreasing energy losses or by fuel substitution [11], but we will not include this CO_2 reduction potential in our main strategies as the major improvements in kiln technology have already been done in French cement plants and as further benefits would induce large investments costs [12]. We will however focus here on two other environmental strategies, which are of great interest in the French context. The first one is the substitution of clinker by mineral additions in cement in order to reduce the environmental cost of the material for a given volume of material whereas the second one is the reduction of the concrete volume needed for a given construction process by enhancing the concrete performances. In the last section of this paper, we evaluate the long term perspective (2050) and discuss the opportunity of further technologic development such as alternative binders in the concrete building sector.

The second objective of this paper is to present a first step towards associating environmental costs and performance requirements. Instead of traditionally plotting concrete performances as a function of mix-design parameters such as cement amount or water to cement ratio, we will plot them as a function of estimated CO_2 emissions. We hope that this simple method could allow for a better balance between societal demand in terms of environment and technical building requirements.

2. Environmental impact of concrete

Limestone (80%) and clay (20%) are the major raw materials used in the production of cement. These materials are burnt at 1450 °C to produce clinker and are then blended with additives. The finished product is finely grounded to manufacture different types of cement.

Through the cement production process, around 0.706 ton of CO_2 is released per ton of clinker produced. This emission is mainly due to the decarbonation of limestone (0.521 ton), and the use of coal and fossil fuels for heating (0.185 ton) [11,13–15]. These estimations come from the European cement industry where important investments have already been done to enhance the combustion efficiency of the cement kilns. In the United States of America, the production of 1 ton of clinker still releases 0.935 ton of CO_2. In China, the IPCC group estimates that 0.9 ton of CO_2 is released per ton of clinker [2]. In this study, we will not develop these technologic improvement options (dry vs wet combustion processes) as we are focusing on the European context where improvements have already been pushed to a far extent (the European commission estimated that only a 2.2% improvement could still be gained [12]). It has however to be kept in mind that massive investment to enhance the efficiency of cement kilns all around the world could lead to 25% of CO_2 emissions reduction per ton of clinker produced.

The development of substitution fuel used in cement kiln can also reduce CO_2 emissions [16]. In France, the cement industry has already replaced 30% of the fossil fuels by CO_2-neutral materials coming from biomass, such as animal meal or wood, and, in northern Europe countries, 60% substitution levels have already been reached [17]. In this context, a value of 0.6 ton of CO_2 per ton of clinker produced could be achieved in a medium term perspective. However, in this study, we will not include this additional CO_2 reduction option and keep a conservative value of 0.706 ton of CO_2 per ton of clinker.

Another way to reduce the greenhouse gas emissions from cement production is to partially replace clinker. The main substitutions to clinker are fly ashes from coal-fired thermal power plants (although these are not easily available within the French context as discussed below), slag from blast furnaces in the iron and steel industry, natural pozzolans, limestone fillers, and various other wastes. These additives contain large quantities of reactive SiO_2 and Al_2O_3, which produce cementitious materials in the presence of lime. In France, electricity is produced by nuclear power generation which has a very low impact in term of CO_2 emissions. As the addition of alternative material to clinker in the cement is essentially consuming electricity for grinding, we assume that no supplementary CO_2 emissions are released when replacing clinker by other mineral additions. We consider here fly ashes and blast furnace slags as industrial wastes, which therefore do not release CO_2 to be produced. It is an approximation, especially for granulated blast furnace slags as the granulation and the vitrification are additional industrial processes used exclusively for the slag valorisation, which are not CO_2-neutral. However, these emissions are negligible in comparison to clinker production emissions [18,19]. Finally, the additional CO_2 emissions of most other additives in the mixture can be neglected compared to the above figures.

3. Material substitution strategy: reduction of the CO_2 emissions per unit of volume

One of the two strategies to reduce CO_2 emissions studied in this paper is to substitute a large part of the clinker by the mineral additions described above. The scientific background needed to use these mineral additions has already been developed, and this option has been extensively used since decades (more for economic reasons than environmental ones at that time). Depending on their physical properties (grading curve, average size, etc.) or their chemical nature and properties, mineral additions will have either a filler function (i.e. they will fill the porosity of the material and thus enhance its elastic modulus and its mechanical strength) and/or a binding capacity (i.e. they will react with water or with clinker hydration products in order to form stable hydrates). The main objective of this section is not to describe the extensively studied clinker substitution processes, but to propose a first step towards associating environmental costs and performance requirements in concrete mix-design. Actually, there exist a few softwares to help engineers to mix-design concrete while taking into account sustainability [18], but mix-design options are not well extended and implications on other concrete requirements such as durability or mechanical strength are not presented. The association between a cost and a quality requirement had however been proposed from an economical point of view by Aïtcin [20], who envisioned the evaluation of concrete volumetric economic cost in comparison with its mechanical strength (i.e. in $\$ \, m^{-3} \, MPa^{-1}$). Fig. 1 presents two examples where results are presented from an environmental point of view.

3.1. Example 1

It is known that there exist temperature optima for each clay type, which allows for an activation of clay materials into a pozzolanic substitution to clinker [21–25]. In Fig. 1a, we present these results from an environmental perspective. The energy consumption for clay heating at 500 °C or 900 °C has been calculated from Gartner [11] and induces, respectively CO_2 emissions from 0.088 to 0.159 ton of CO_2 per ton of clay. This indicates that it is possible to reduce the environmental impacts while maintaining quality requirement up to an optimum for most thermally activated