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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 $C0_2$ 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

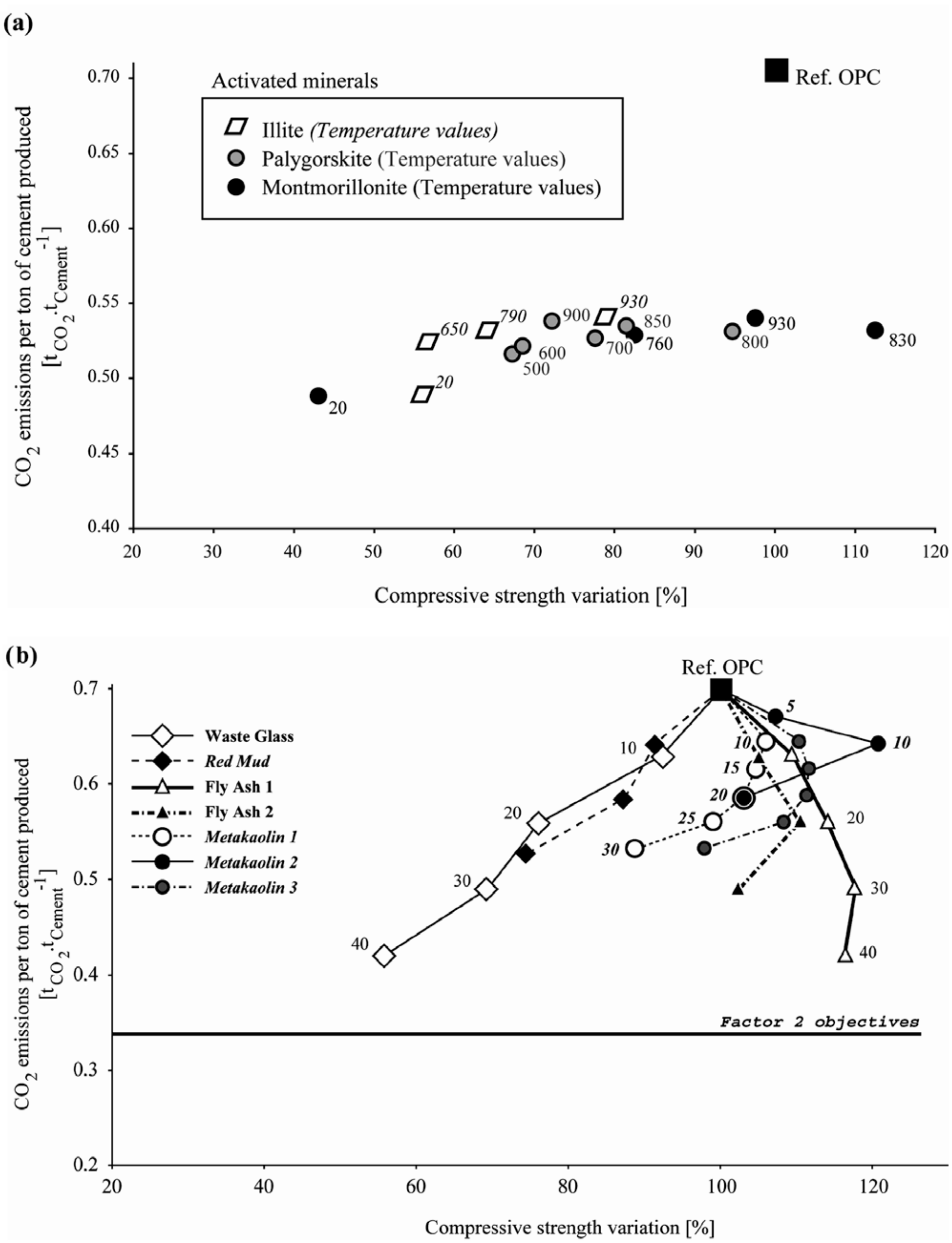

Fig. 1. Relationship between CO_2 emission per ton of cement and the associated strength. (a) Mortars cast with 30 wt.% of clinker substitution with clays thermally activated at different temperatures. Temperatures of thermal treatment are indicated on graph. Data comes from [23–25] and (b) concrete cast with different substitution materials, waste glass, red mud, metakaolin, and fly ash. The substitution percentages are indicated on graph. Values in italic are percentage substitution for materials that have been thermally activated (red mud and metakaolin), and straight values are for waste considered as CO_2-neutral (glass, fly ash). Data comes from [27–31].

phyllosilicates. It is worth noting that CO_2 emissions due to substitutions heating are negligible in comparison with CO_2 emissions reduction.

3.2. Example 2

Fig. 1b is a new presentation of a classical approach of substitution options. Substitution performances are often presented in term of substitution percentage vs compressive strength. In this study, we replace the substitution percentage axis by a CO_2 emission axis by considering that no supplementary CO_2 emissions are released when replacing clinker by other mineral additions. The maximum CO_2 emissions per ton of cement that can be released to meet factor 2 objectives are also ploted (Fig. 1b). In Fig. 1b, substitutions, for which mechanical strength linearly decreases with the substitution content, can be considered as substitution materials with no additional properties, which only takes up some volume in the material for a rather low economical and environmental cost. For such a material, it therefore depends on the concrete mix designer to choose between a strength requirement and a concrete environmental impact as there is no optimal amount.

The type of diagram proposed in Fig. 1 does not bring anything of course on the understanding of the complex underlying physico-chemical phenomena in concrete but could be considered, when further developed, as a handy tool to help engineers to develop a sustainable mix-design that meet factor 2 objectives while maintaining concrete performances.

The cement substitution by alternative mineral additions is a powerful option process to reduce the CO_2 emission from concrete production. The type of presentation we have developed here, where the environmental cost is compared to quality requirements has the potential ability to permit to the mix-design engineers to balance the societal demand in terms of environment with the technical building requirements. With these diagrams, it seems obvious that, according to the type of substitution, there exist optima or maxima (here of the order of a few tens of percent) above which concrete performances may be strongly deteriorated [26]. However, the existence of these limits demonstrates that the cement substitution, with our current level of knowledge, cannot be the exclusive solution to answer the needed reduction of CO_2 emissions to tackle neither the factor 4 scenario nor the factor 2 objectives. Additional knowledge in the concrete design field will therefore be strongly needed in a close future. It can however be estimated that the today level of knowledge should allow for a 40% reduction of CO_2 emission per cube meter of concrete compared to a pure clinker based material. As a final example of this strategy, it can be noted that, in France, it is already rather common to reach at least 25% CO_2 emission reduction by using fly ashes in ordinary concretes.

4. Material performance strategy: reduction of the total CO_2 emissions

Instead of reducing the amount of CO_2 per ton of concrete produced, another option is to reduce the total amount of concrete produced. In this study, we have tried to roughly predict the material volume reduction that could occur by enhancing the concrete mechanical strength. However, increasing the mechanical strength without any of the substitution described above can be most of the time associated with an increase in the CO_2 emission per cube meter of material as it is shown in Fig. 2 where mechanical strengths of various concretes are plotted as a function of their CO_2 emissions per cube meter [32–47]. CO_2 emissions have been calculated here by considering exclusively the cement contribution as detailed in the Section 2. We assumed that each ton of CEM I produces 0.7 tons of CO_2 and that any mineral addition and all aggregates can be considered as CO_2 neutral compared to clinker. Fig. 2 shows that, as a first approximation, the usual way to increase strength resistance is to increase the cement content (and the CO_2 emissions) in concrete up to 70 MPa, where compressive strength becomes strongly dependant on the quality of the granular skeleton [26]. It can be worth noting that, if all other parameters are kept constant (number of granular classes, nature of the cement, etc.), then the Ferret relation [26] which predicts that mechanical strength is proportional to the power 2 of the cement amount per cube meter can also be derived to predict that mechanical strength is proportional to the power 2 of the CO_2 emissions per cube meter.

$$f_c \approx \left(CO_2^{m^3}\right)^2 \tag{1}$$

This relation is plotted in Fig. 2 and proves to be able to describe many results from the literature when only one gravel, one sand, and CEM I cement are used. It can also be noted that increasing the number of granular classes allows for an increase of mechanical strength at a given CO_2 emission level or equivalently a decrease in CO_2 emissions for a given mechanical strength. Finally, as already described in the previous section, substituting pure clinker by an alternative mineral powder allows for a decrease of the CO_2 emissions per cube meter of concrete. This decrease varies a lot according to the nature of the mineral powder and its amount (note the strong dispersion due to the wide variety of mineral powders plotted).

The question we tackle here is the following: by increasing the mechanical strength, we increase on one hand the CO_2 emissions per cube meter of concrete produced but, on the other hand, we could decrease the amount of concrete needed to build a given structural element. There are however many types of structural

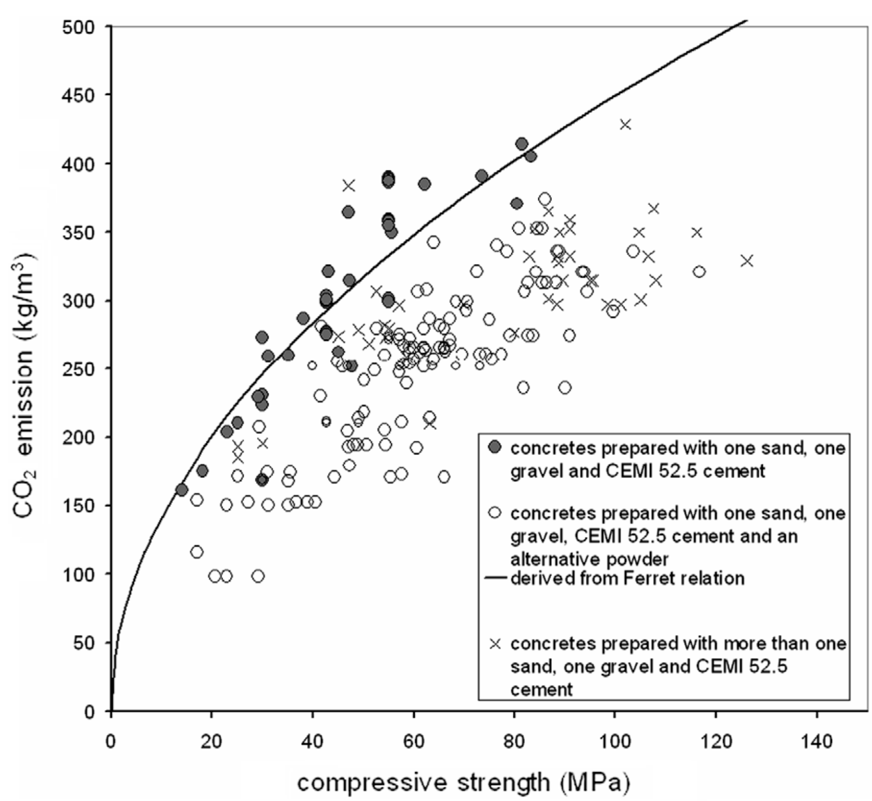

Fig. 2. CO_2 Emissions per cubic meter of concrete as a function of compressive strength resistance after 28 days of curing. Mix and strength data comes from [32–47].

elements in the construction industry and the problem is complex to deal with. We will only develop here a very simple and quasi dimensional approach for standard cases of structural elements. It has moreover to be kept in mind that structural considerations does not always give access to the minimum size of a given element as acoustic, thermal or fire safety aspects may lead to higher minimum sizes. We will however in the following focus on three simplified cases which are representatives of many structural elements in construction industry. We will moreover neglect the presence of steel bars and consider the material as homogeneous.

In the first case, we consider an horizontal element of thickness h which only carries itself. The other dimensions of this element such as width and span are considered as given in this study. This type of element is representative of beams in housing construction, for which external load is small compared to the weight of the element itself. This element is thus only submitted to its own weight and to a flexural torque M proportional to h. The maximum stress in the beam can be written as $\sigma \propto Mh/I$ where I is proportional to h^3. As a consequence, $\sigma \propto 1/h$. In other words, for a given width and span, the maximum stress in the element is inversely proportional to its thickness and thus to its total volume $\sigma \propto 1/V^{total}$. This total volume writes $V^{total} = CO_2^{Total}/CO_2^{m^3}$ where CO_2^{Total} is the total CO_2 emissions involved in the building of this element and $CO_2^{m^3}$ is the CO_2 emission per cube meter of concrete. We have moreover shown above that the compressive strength of a given cementitious materials is more or less proportional to the power 2 of its CO_2 production per cube meter (Eq. (1)). It could of course be objected that tensile strength is playing a stronger role that compressive strength but, in the frame of the simple approach proposed here, it could be answered that only proportionality relations are written and that, at this level of simplification, tensile strength could be considered as roughly proportional to compressive strength. Finally, the above derivations $\left(\sigma \propto 1/V^{total} \propto CO_2^{m^3}/CO_2^{Total} \propto \left(CO_2^{m^3}\right)^2\right)$ lead to:

$$CO_2^{Total} \propto 1/CO_2^{m^3} \tag{2}$$

This means that, because of the strength increase of the cementitious material and of the element volume reduction, the total CO_2 production CO_2^{Total} decreases when the CO_2 production per cube meter $CO_2^{m^3}$ increases in the case of horizontal elements in housing construction. As a consequence and if, as an other approximation, considerations other than structural aspects are neglected, high mechanical performances concretes are the most environmental friendly materials for this type of structural element.

In the second case, we consider an horizontal element of thickness h which carries an external load. This type of element is representative of beams in bridges, for which external load is large compared to the weight of the element itself. If we carry the same analysis as above, we obtain that total CO_2 production CO_2^{Total} does not depend on mechanical strength of the concrete. This means that the strength increase of the cementitious material and the element volume reduction more or less compensates the increase in CO_2 production per cube meter. As a consequence, and if, as above, considerations other than structural aspects are neglected, high mechanical performances concretes do not bring anything from an environmental point of view for this type of structural element.

In the third case, we consider a vertical element of characteristic size (radius) r which carries an external load F. Vertical elements only carrying themselves are indeed rare in the construction industry. This element is thus submitted to a compressive stress $\sigma \propto 1/r^2$. As a consequence, for a given element height, the maximum stress in the element is inversely proportional to its total volume and total CO_2 production CO_2^{Total} follows Eq. (1). High mechanical performances concretes are therefore the most environmental friendly materials for this type of structural element. However, it could be objected that these conclusions in the case of vertical elements are limited by the fact that, when a structural element is submitted to a compressive stress, it has first to resist to structural instability or buckling. This means that, for a given external load F, the inertia of the element I which is proportional to r^4 cannot be lower than a critical value proportional to L^2F/E, where E is the elastic modulus and L the height of the element. If we assume, as another rough assumption, that elastic modulus is proportional to compressive strength and therefore to the power 2 of $CO_2^{m^3}$, it can then be concluded that, although the use of high mechanical performance concretes does not bring anything to the buckling resistance, it does not either increase the total CO_2 emission of the structural element.

It should therefore be kept in mind that higher mechanical performances, on the whole, could reduce total CO_2 emissions following roughly Eq. (1). In France, it is rather common to use concretes displaying 25/30 MPa compressive strength for housing while using concretes displaying 50/60 MPa compressive strength for bridges. By doubling these values and of course making the needed structural design changes, it can thus be estimated using the very simplified rough approach developed that CO_2 emissions could be reduced by 30%. Doubling the strength will indeed increase the CO2 emissions per cube meter of concrete by a factor $\sqrt{2} \cong 1.4$. Using Eq. (2), it can then be estimated that the total CO2 emissions will be reduced by factor 0.7 (i.e. 30% reduction). Following the same spirit, it can also be extrapolated that using ultra high performance concretes (mechanical strength of the order of 120 MPa) [48] could lead in housing constructions to reductions of the order of 50%. Other materials than clinker based concrete should then be used to fulfil the other requirements such as fire resistance, acoustic or thermal behaviour as all these other materials (plaster, bricks, wood, etc.) have all lower CO_2 emissions than concrete and can be easily dedicated to these functionalities. Strongly composite walls and slabs could therefore fulfil all the technical requirements with a reduced total environmental impact.

5. Conclusion

In this study, two different environmental options for sustainable concrete mix-design were considered and evaluated. 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 concrete produced. The second one is the reduction of the concrete volume needed for a given construction process by enhancing the concrete performances. It has been estimated that, in France, the CO_2 emissions could be reduced by 15% by increasing the level of substitution in concrete. It has also been estimated that the second option could lead to reduction of the order of 30%. But it has to be kept in mind that, as it can be seen in Fig. 2, it is possible to combine cement substitution and mechanical strength increase. From the present results and the observation of the nowadays French practice, this could lead to CO_2 emissions reduction of the order of 40% (15% for substitution and 30% for mechanical strength increase). This represents what could be achieved in a medium term perspective with the actual level of knowledge in concrete industry. It is therefore not far from the factor 2 objectives to be reached in 2020. However, this would not be sufficient to reach the "*factor* 4" objectives as edited in the French climate action plan. In the long term perspective of 2050, other options will have to be considered. For example, new types of clinker with very low CO_2 emissions could be developed, especially Sulfoaluminate clinker [49,50], or even belite activated sulfoaluminate clinkers [50]. Finally, it has to be kept in mind that, as most readers will acknowledge, concrete is very complex material, and that, in order to reach orders of magnitude within the frame of this paper, strong simplifying assumptions have been made, and more work has to be done to confirm these results.

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