Cement and Concrete Research 40 (2010) 820–826

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Cement production technology improvement compared to factor 4 objectives

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ARTICLE INFO

Article history:
Received 12 May 2009
Accepted 17 September 2010

Keywords:
Carbon dioxide
Cement manufacture (A)

ABSTRACT

In this study, the effects of potential technological improvements in cement industry are compared to global goals of sustainability such as those from the Intergovernmental Panel Group for Climate Change. In other words, does the current and standard technological knowledge in the cement and concrete industry make it possible to achieve the “factor 4” concept? This concept aims at reducing the CO_2 emissions in developed countries in 2050 by a factor of four from their 1990 levels, after they have first been reduced by a factor of 2 by 2020. The present study shows that it seems technically possible to design concretes to meet “factor 2” objectives whatever the evolution of cement production, but a technological turnaround is needed to reach factor 4 objectives. This technological shift will require not only changes in concrete raw materials and mix designs, but also new building techniques, using less materials for the same final structure.

1. Introduction

The building materials sector is the third-largest CO_2 emitting industrial sector worldwide and in the European Union. This sector represents 10% of the total anthropogenic CO_2 emissions, most of which are related to concrete manufacture [1]: about 85% of these CO_2 emissions come from the provision of cement [2]. A Life Cycle Assessment of cement shows that 95% of this CO_2 is released during the production and only 5% in the transport of raw materials and finished products [3]. Because of the importance of the cement industry, many studies have dealt with its future prospects [4–7], mainly focussing on CO_2 reduction potential and to comparing the energy efficiency improvement options to expected variations in cement production. In this paper we will compare the effects of potential technological improvements to global sustainability goals. It has to be noted that the technological improvements that will be studied here are the ones for which the scientific and technical backgrounds are accepted but which are not yet industrialised on a large scale. Neither “clean development mechanisms” nor new binders will be considered. This study aims to evaluate whether, with the current technological knowledge of the cement and concrete industries, it is possible to achieve the global sustainable objectives such as the ones from the Intergovernmental Panel Group for Climate Change (IPCC). In term of CO_2 reduction, these objectives have been introduced into French law by a climate action plan edited in 2005 [8] and transcribed as “the *factor 4* concept” [9], which aims to reduce the emissions of the developed countries by a factor of four by 2050 in order to reach a global world reduction of 50% (relative to 1990 levels) [8]. Industries are strongly encouraged to respect this protocol as there will be a cost impact for exceeding the quotas. This impact will evidently be more important for CO_2-intensive industries such as the cement industry, where it could be as high as 50% of production costs [10].

In the first part of this paper, a detailed description of cement production is given, in order to identify the primary technological parameters that can be modified to reduce CO_2 emissions. The evolution of these parameters is then addressed over the last 30 years (1975–2005), and the CO_2 reduction perspectives per ton of cement are then estimated for each parameter individually. Finally the global CO_2 emissions are calculated over the historic period and perspectives compared to factor 4 objectives. The present study is restricted to the French context, for which an important set of data on different technologies is available. It can however be noted that the main results and trends obtained here should also apply to western European countries in general.

2. Construction system description

Greenhouse gas (GHG) emissions impact from concrete production can be reduced to GHG emissions from cement production as more than 80% of the CO_2 emissions from construction come from cement production. Fig. 1 describes schematically the cement production process.

In cement production, limestone is the major raw material used. It is burnt at 1450 °C to produce clinker and is then blended with additives. The finished product is finely grounded to produce different types of cement. During cement production process, around 0.92 t of CO_2 is released for each ton of clinker produced. This emission is mainly shared between decarbonation of limestone (0.53 t), and the

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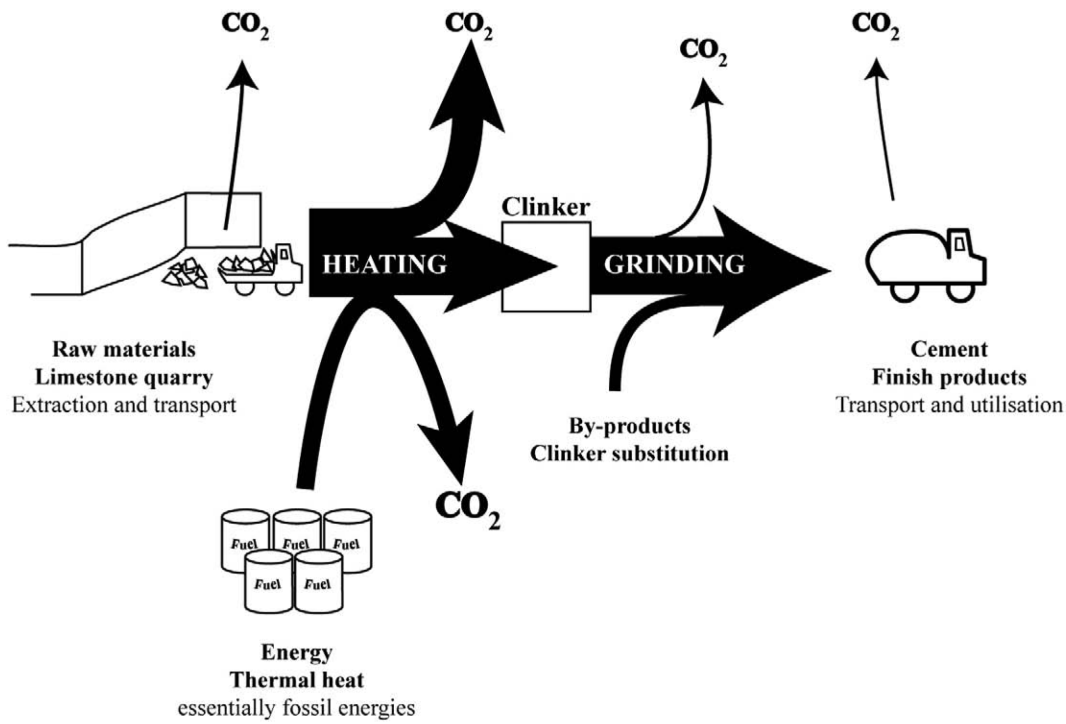

Fig. 1. Simplified cement fabrication process, with a specific interest in the CO_2 emissions. The thickness of the arrows is proportional to the amount of material. See text for details.

use of carbon-based fuels for heating (0.39 t) [11,12]. Average CO_2 emissions associated with grinding processes are of the order of 0.1 t of CO_2 per ton of cement [11] and are mostly associated with electricity production. These are far lower than the contribution of decarbonation and heating and will thus be neglected in this paper. This simplification is certainly justifiable in France where most electricity is produced in nuclear power plants and thus has a very low impact in term of CO_2 emissions. Thus, the two main approaches to reducing the CO_2 emissions associated with the cement supplied for concrete manufacture are considered to be (1) reducing the CO_2 emissions of clinker production and (2) reducing the clinker content in cement.

There are three main factors involved in determining the CO_2 emissions of clinker production: the nature of the fuels used, the thermal efficiency of the kiln and cooler systems, and the nature of raw materials used. CO_2 emissions from cement industry can then be expressed by Eq. (1).

$$t_{CO_2}/\text{year} = [(\text{Fuel}_{emis} \cdot \text{Energy}_{kiln} + \text{Raw—mat}_{emis}) \times \text{Clinker}_{content}] \cdot \text{Production}_{cement}/\text{year} \quad (1)$$

Where Fuel_{emis} represents the CO_2 released from fuel burning and is expressed in t_{CO2}/MJ; Energy_{kiln} is associated with the kiln technology and is expressed in MJ/$t_{clinker}$, Raw-mat_{emis} refers to the CO_2 released from the raw materials and is then expressed in $t_{CO2}/t_{clinker}$; $\text{Clinker}_{content}$ is the percentage of clinker in the cement ($t_{clinker}/t_{cement}$) and finally the production of cement per year ($\text{Production}_{cement}$/year) is expressed in t_{cement}/year. A comparison between the description of the cement system presented here and the one of Gartner [11] shows a difference in the emissions associated with raw materials use. Gartner made a distinction between Fuel-Derived CO_2 (FD-CO_2) and Raw-Materials derived CO_2 (RM-CO_2) [11], which is equivalent to group Fuel_{emis} and Energy_{kiln} parameters from equation in the FD-CO_2 parameter and Raw-mat_{emis} and $\text{Clinker}_{content}$ in the RM-CO_2. Compared to RM-CO_2, Eq. (1) takes into account the difference that exists between substituting materials before or after burning. This difference will be discussed in this paper, where the two main parameter groups for technology efficiency are a clinker production derived CO_2 parameter (that includes Fuel_{emis}, Energy_{kiln} and Raw-mat_{emis}) and a cement production derived CO_2 parameter described as the $\text{Clinker}_{content}$. Finally, in order to predict the global evolution of the CO_2 emissions of cement industry, it is necessary to introduce the production of cement. In other industrial sectors and in country-specific impact evaluations studies, a classic way to assess the balance between an increase in product demand and technology improvement is to use the Holdren/Erlich framework that is known as $I = PAT$ equation [13], where I represents environmental impact, P is the population size, A is the affluence per capita and T is the effect of technology. This model illustrates that CO_2 emissions can continue to grow if the effect of increased efficiency (reduced T) is outweighed by increased population size (P) and/or affluence per capita (A) (for a recent review on IPAT equation see [14]). In the frame of *IPAT* equation, t_{CO2}/t_{cement} reflects the cement technology and cement production reflects the *AP* product. In this study only the variations of the *T* parameter will be studied. *AP* product evolution will be considered as an exogenous parameter.

3. Data from 1975 to 2005 and perspective assessment

In this section, the historical evolution of each of the main parameters influencing CO_2 emissions from the cement industry is examined, and a potential future evolution of each parameter is proposed. Furthermore, the extreme technology for each parameter (according to the current literature) is also presented and justified.

3.1. Cement plants efficiency (MJ/$t_{clinker}$)

The cement plant efficiency mainly depends on the type of cement kiln. Four different process technologies are currently used in Europe. Their energy efficiencies have already been described [15–17]. They are gathered in Table 1. The less energy efficient is the long rotary kiln burning wet raw materials (5000–6000 MJ/$t_{clinker}$), then the semi-dry process, the dry process with preheater, or precalciner kilns and the most efficient is rotary kiln with preheater, precalciner and heat

Table 1
Energy use of different cement kilns. Source: [15]; [16]; and [17].

Process type	Specific energy consumption ($MJ/t_{clinker}$)
Wet process long kiln	5000–6000
Semi-dry process	3300–4500
Dry process kiln with preheater	3100–4200
precalciner kiln and dry process rotary kiln equipped with multistage cyclone preheater	3000
Optimal entropy related virtual kiln	1800

recovery system, that burns dry materials (3000 $MJ/t_{clinker}$) . Gartner [11] notes that the theoretical enthalpy requirement is around 1800 $MJ/t_{clinker}$. One approach to getting closer to this theoretical maximum energy efficiency is to use pure oxygen instead of air, in order to reduce the volume of kiln exhaust gases and the associated heat loss. A further justification for such an investment could be that it should produce an exhaust gas that is essentially a simple mixture of CO_2 and water vapour, which could then be easily liquefied for injection into underground aquifers for CO_2 sequestration [17]. However, on the negative side, there is a very significant energy cost associated with the production of pure oxygen, which might well counterbalance most of the apparent gains in efficiency of the clinker-manufacturing process.

The historical evolution of French kiln thermal efficiency has been calculated with data from [18], where the percentages of plants using the different technologies are reported, and using the energy efficiencies of cement kilns taken from [15–17] (Table 1). Results are presented in Fig. 2. They show a major improvement over the period 1973–2000.

Gartner noted that the 1973 OEPC oil embargo that forced the cement industry to reduce its dependence on oil and, more generally, to improve its overall energy efficiency [11]. The shock provided by the OPEC oil embargo led western countries to become more virtuous in term of energy savings and provided short-term economic incentive necessary to force industry to adopt new process technologies. These new technologies turned out to have long term benefits for the overall efficiency of the industry, reducing the average specific fuel energy requirement for clinker manufacture by about 10% during the decade starting in 1973, but a decrease in the improvement rate is observed over the last two decades (Fig. 2) [5]. This recent trend shows that large investments for kiln transformation are no longer current policy in the European cement industry. This is because the construction of a new cement plant costs the equivalent of the income of 3 years of activity of the plant [12], which gives a pay-back period of 30–50 years. As the long term trends in cement use in European Union countries are uncertain, such big investments are no longer priority investments

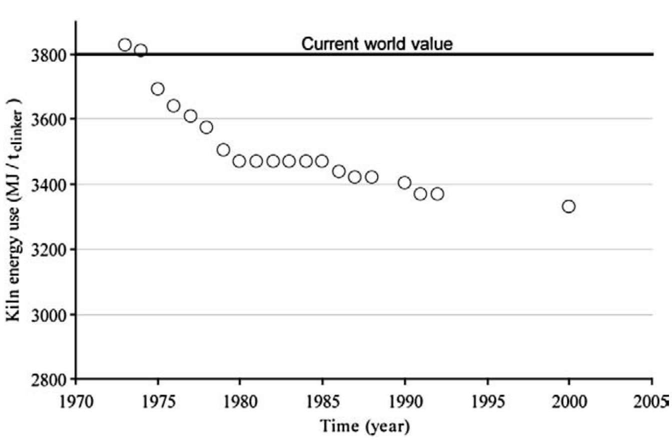

Fig. 2. Evolution of cement kiln energy use from 1973 to 2000 (data from [18]).

[12]. In term of perspectives, the transformation of all cement plant to use dry process with preheater and precalciner can then be considered as an ambitious objective but, within the frame of this study, as a potentially accessible value. The theoretical enthalpy requirement has been considered as the extreme solution (Table 2). This solution will never be reached even in a system using pure oxygen instead of air as there will still be still significant volumes of kiln exhaust gas, at least because there is always some need to evaporate water from raw materials. Therefore the value in Table 2 is an extreme one and it is unlikely that it would be possible to go much below 2500 $MJ/t_{clinker}$, even if energy required to produce the oxygen is neglected (which they should not be!).

3.2. Use of waste as alternative fuels (g_{CO2}/MJ)

Heating raw materials (mainly limestone) up to 1450 °C needs fuel combustion which induces CO_2 release. To reduce the cost production and lower CO_2 emissions, alternative fuels are used. However, most alternative fuels are not approved as carbon-neutral by IPCC [19]. CO_2 emission values for the different fuels used in cement plant are presented in Table 3. Carbon-neutral fuels, as defined by the European commission, are essentially biomass which include agricultural and forestry biomass, biodegradable municipal waste, animal waste, paper waste [20] (Table 3). Certain authors argue that, in fact, burning these carbon-neutral waste can be even regarded as a GHG sink because they would otherwise decay to form methane which is much a more powerful GHG than CO_2 [17,21]. Waste materials derived from fossil fuels such as solvent, plastics, used tyres are not regarded as carbon-neutral. However, it is important to note that transferring waste fuels from incineration plants to cement kiln results in a significant net CO_2 reduction because cement kilns are more efficient. Another advantage is that no residues are generated since the ashes are completely incorporated in clinker [21]. Finally, fossil fuels can be more or less CO_2 intensive for the same energy production [22]. Natural gas releases less CO_2 than coal for the same energy produced (Table 3). Over the last 30 years, the ongoing pressure to reduce energy costs has led the cement industry in most countries to use more coal than oil, and, when using oil-based products, to choose inexpensive by-products such as petroleum coke.

To assess potential and extreme variation of this parameter, fuel composition from the French cement association report is used here [18]. The percentage of carbon-neutral fuels within substitution fuels was assumed to be constant and equal to 40%, which is the present European value [20]. Results are presented in Fig. 3. After a peak of substitution around the year 2001(34%), the amount of alternative fuel has decreased to reach a stable value (28%). This increase around 2001 could be related to the Bovine Spongiform Encephalopathy crisis (Mad cow disease) as the cement industry has been largely put in contribution to safely destroy all the contaminated meat and bone meals. The potential accessible value of fuel efficiency has then been assumed to be 65 g CO_2/MJ (Table 2). The extreme fuel efficiency is defined in this paper as the one reached in Netherlands cement plants that use low-CO_2 fossil fuels and 70% of substitution fuels [22,23]. This leads to a CO_2 emission of 54 g CO_2/MJ (Table 2).

Table 2
Medium and long term perspective in cement production efficiency. For the different parameters studied, potential accessible value and extreme value are reported. See text for details.

Studied parameter	Potential accessible value	Extreme value
$Energy_{kiln}$ ($MJ/t_{clinker}$)	3000	1800
$Fuel_{emis}$(g_{CO_2}/MJ)	65	54
$Raw\text{-}mat_{emjs}$($t_{CO_2}/t_{cljflker}$)	0.478	0.398
$Clinker_{content}$ ($t_{clinker}/t_{cement}$)	70%	50%

Table 3
Energy efficiency of cement fuels. Source: [19]; [20].

Fuel	Net CO_2 emission factor (9_{CO_2}/MJ)
Petcoke	101
Coal	96
Natural gas	54.2
Used tyres	85
Waste oil	74
Plastic	75
Refused derived fuels	8.7
Animal meal	0
Waste wood	0

3.3. Alternative raw materials for the replacement of limestone in kiln feed ($t_{CO2}/t_{clinker}$)

Decarbonation of standard raw materials (mainly limestone) generates the emission of approximately 0.53 $t_{CO2}/t_{clinker}$ produced. Limestone could in principal be replaced by materials with a lower carbon content but a similar calcium content; however, such materials are not abundant and essentially consist of slags (e.g. blast furnace slags (BFS) and steel slags), and cement waste. Few data are available concerning current levels of replacement of raw materials in cement kilns; 10% replacement is reported for some "best practice" cement plants [17]. There is no reason to assume that replacement has been much higher in the past or has changed much since then. As the content of CaO in BFS is of the order of 40%, the maximum level of limestone replacement lies between 20 and 30% [17]. This replacement possibility is also limited by the effective availability of these products as the worldwide production of BFS was around 150 million tons in 2005 compared to the 2500 million tons of clinker production. Furthermore, it should be noted that slags are also used as a cementitious additive which will reduce even more the effective availability of these products for their use as alternative raw materials in kiln feed. Therefore it can be assumed that the current level of replacement is close to zero, that a potential improvement could lead to 10% of replacement, and that the extreme replacement could be fixed at 25% (Table 2).

3.4. Use of Industrial by-products as constituents of cement ($t_{clinker}/t_{cement}$)

Moreover, clinker itself may be partly substituted by industrial by-products like coal fly ash or granulated blast-furnace slag. In addition, limestone and natural pozzolans may also be used. These cements and their constituents are standardised in the European standards and are commonly used [24].

Fig. 4 presents the evolution of mineral additions in cement from 1973 to 2007. It shows that the percentage has remained roughly constant at about 20% over the last 30 years, but its nature has changed, with a diminution of BFS and an increase in limestone addition. This can be associated with the decline in the French steel industry that began in the late 1970s, coupled with changes in standards that permitted higher level of limestone addition. It has to be noted that such substitutions are not made exclusively during cement production; they can also be made during concrete production. Under EN 206-1, concrete producers are permitted to mix CEM I cements (composed exclusively of clinker and gypsum) with limited amounts of cementitious additions such as pozzolans or fly ash [25]. Comparison between SNBPE data [26], which gathers data of ready mix concrete production in cubic meter per year and data from SFIC [18], which gathers data of cement production in tons per year and its percentage used in Ready mix, allows for an estimate of the average cement amount per cubic meter of concrete and therefore an evaluation of the substitution level.

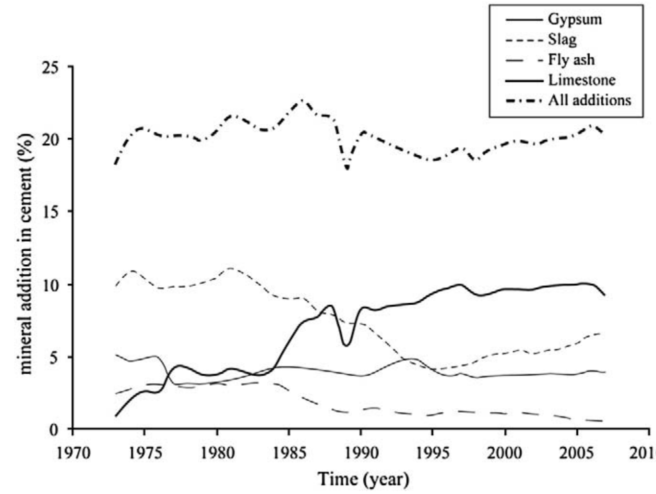

Fig. 4. Evolution of clinker substitution from 1973 to 2007 (data from [18]).

Data from 1988 to 2006 are presented in Fig. 5. They show no significant evolution of cement content, which evolved from 290 kg/m^3 to 280 kg/m^3. The current average level of clinker replacement is thus of the order of 20% and is made essentially within the cement. However, it can be noted that current concrete typical of the Paris area contains on average 240 kg/m^3 of CEM I and 80 kg/m^3 of fly ash [27] that are added at the ready mix plant. If a calculation is made to evaluate the equivalent binding of this ready mix concrete, with an equivalent binding capacity for fly ash between 0.4 to 0.6 [25], the total content of binder of the average Parisian ready mix is around 280 kg/m^3, but contains 25% of cement substituted by fly ash. It is then equivalent to 30% of clinker substitution (25% fly ash and 5% gypsum). This current practice in Paris is not repeated over the whole country. A

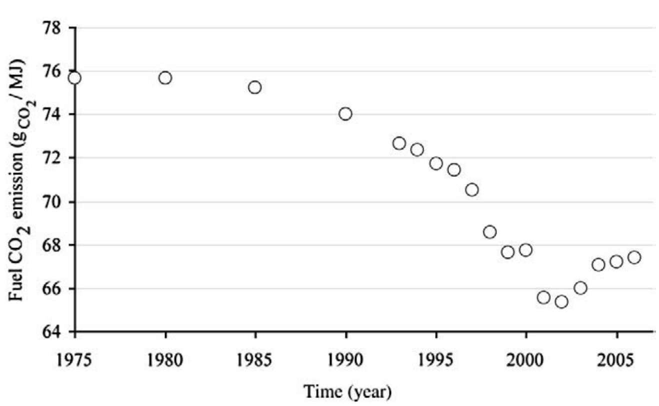

Fig. 3. Evolution of fuel CO_2 emissions from 1980 to 2006 (data from [18]).

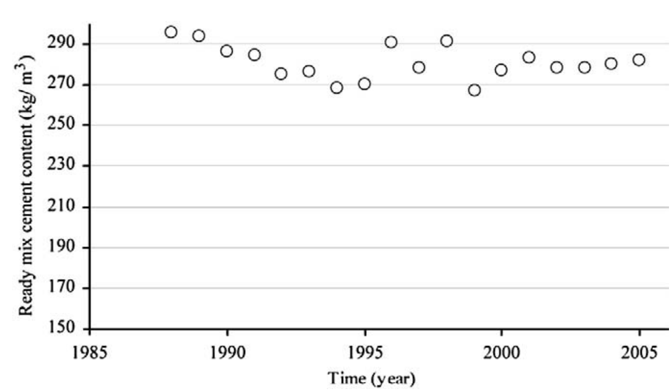

Fig. 5. Evolution of cement content in concrete from 1988 to 2006 (data from [18]; [26]).

potential level of clinker replacement can then be estimated at 30% either in cement or in concrete (Table 2). Numerous studies have been done to evaluate the maximum substitution level as it is a known feature that over a certain amount of clinker substitution, cement and concrete performance will be reduced. Habert and Roussel assume that 40 to 50% of substitution either at the cement stage or at the concrete stage seems to be a maximum when substitution have a pozzolanic activity [27]. The extreme substitution level can then be fixed at 50% as it is assumed that, at higher substitution level, important technological and practical changes have to be envisioned to avoid drops in strength and durability (Table 2).

4. Sensitivity of parameters and perspective scenarios

To evaluate the efficiency of the different parameters to reduce CO_2 emissions, simulations where parameters evolve independently have been done. For each parameter, emissions have been calculated when the parameter is set to its extreme value while other parameters are maintained constant and equal to their 2005 values. Results are presented in Table 4.

Not all parameters give the same degree of improvement. Kiln and fuel improvements have a 30% efficiency in CO_2 emissions reduction whereas clinker substitutions can be 100% efficient. For instance, a reduction by 60% of $Energy_{kiln}$ will only induce a 20% reduction of CO_2 emissions, while the same reduction in $Clinker_{content}$ will achieve a 60% reduction in CO_2 emissions. Furthermore, the different parameters do not have the same associated costs for cement industries. Options that lead to a kiln modification or replacement are the most cost-intensive. In France, cement production costs are distributed between energy (31%), raw materials (28%), production and maintenance (30%) and paying-off debt (11%) [28]. As a consequence, using waste as clinker substitution product induces a cost reduction associated with raw materials and a highly efficient CO_2 emission reduction (Table 4). It has no kiln modification costs and allows for recycling waste from coal power stations and iron furnace. The use of waste as alternative fuels can reduce energy costs; however this option has a higher cost than the previous one as waste combustion induces kiln modifications due to an increase in water vapour and dioxin levels in the exhaust gases [22], and the environmental efficiency is lower (Table 4). The amount of waste used as alternative fuels is very different between countries. The world level is around 10%, the current French level is close to 30% and northern European countries can locally reach 70%. It is interesting to note that these variations are essentially linked with the ability of countries to organise recycling supply chain which allow for a regular provisioning of cement plants. Finally from an economic point of view, clinker substitution allows for an increase in cement plant production capacity and then for a reduction of the costs per ton of cement produced. This option is, for example, the one chosen by Lafarge as its long term development strategy [28]. It is now just limited by standardisation and availability of alternative materials. Another evaluation method is to consider the previous technologic ameliorations (Figs. 2 and 3). It is possible to evaluate the improvement already achieved in comparison to a baseline technology referred as the 1970 situation. Looking at that trend of improvement (Figs. 2 and 3) gives an evaluation of the further possibilities. It is then possible to assume that kiln efficiency improvement and fuel substitution integration have already been largely done in French cement kilns, and that these technology improvements seem therefore to reach a limit. From this analysis different scenarios have been envisioned, from the easiest to reach to the most improbable.

- Scenario 0: All parameters are kept constant to their 2005 values
- Scenario 1: Materials substitution are done up to their potential accessible values (30% for clinker substitution and 10% for the raw material substitution). Other higher cost improvements are not done and parameters are kept to their 2005 values.
- Scenario 2: Clinker substitution is fixed to its extreme value (50%) and raw materials substitution is fixed at 10% (potential accessible value). Actually it is assumed that it is easier to massively substitute clinker leading to change in the concrete mix-design (which is just a knowledge and knowhow improvement), rather than to substitute raw materials that needs technologic improvement of cement kiln to adjust the percentage of substitution to chemical variation of materials (which is at the end a cost-needed improvement).
- Scenario 3: Clinker substitution is fixed to its extreme value (50%) and all other parameters are fixed to their potential accessible values: 10% for raw material replacement, 45% for alternative fuel substitution and Dry process for cement kiln.
- Scenario 4: All technologies are set to their extreme values.

5. Results: Goals and perspectives

5.1. Historic evolution from 1990

The detailed calculation of all parameters throughout the last 30 years permits to calculate the CO_2 emissions per tons of cement produced. To calculate the total CO_2 emissions it is necessary to multiply these emissions per ton by the yearly cement production. Results are presented in Table 5 from 1985 to 2005. The calculation of the variations of both parameters (technology and production) for the different five year periods between 1985 and 2005, and their comparison with the variation of the CO_2 emissions for the same periods, show that it is mainly the production evolution that finally controls the emissions. The technologic improvements are not able on that period to overweight production variations. It is also possible to compare these emissions to the factor 4 perspectives. Results in Table 5 show that, in 2005, due to an increase in cement production over the last 5 years, CO_2 emissions increased but are however still in accordance with the objectives from the French climate action plan [8].

Table 4
Potential evolution of CO_2 emissions due to independent technology parameter variations. (*) Cement production is constant and equal to its 2005 value. Variations of technology parameter and emissions are presented in relation to the 2005 value. Efficiency is defined as the factor between CO_2 emissions and technology parameter variations.

Parameters	Current technology	Optimal values			
		$Fuel_{emission}$	$Energy_{Kiln}$	$Raw\text{-}mat_{emission}$	$Clinker_{content}$
t_{CO_2}/t_{cement}	0.601	0.574	0.519	0.496	0.377
CO_2 emissions (t_{CO_2})*	12.80	12.24	11.06	10.58	8.03
Technology variations (%)		−14.92	−45.94	−24.67	−37.26
Emission variations (%)		−4.41	−13.59	−17.37	−37.26
Efficiency (%)		30	30	70	100

Table 5
Historic evolution of French cement sector characteristics (technology, production and related CO_2 emissions). Variations of technology, production and emissions are calculated for the last five years time period.

	1985	1990	1995	2000	2005
Technology efficiency (t_{CO_2}/t_{cement}	0.619	0.619	0.628	0.606	0.601
Cement production (10^6 t)	22.2	25.4	19.9	19.7	21.3
CO_2 emissions (t_{CO_2})	13.7	15.7	12.5	11.9	12.8
Factor 4 perspectives (t_{CO_2})		15.7	14.7	13.8	12.8
Technology variations (%)		0.01	1.43	−3.41	−0.87
Production variations (%)		14.31	−21.65	−1.01	8.12
Emission variations (%)		14.32	−20.53	−4.38	7.18

5.2. Different scenarios for medium and long term perspectives

To evaluate the CO_2 emissions perspectives, the different technology improvement possibilities have to be multiplied by the future cement production. CO_2 emissions can then be compared to factor 2 ($7.85 \cdot 10^6$ t/year) and factor 4 ($3.93 \cdot 10^6$ t/year) objectives.

In this study, cement production is considered as exogenous variable, therefore different production growths have been envisioned. Cement production evolution is linked with economic activity and the levels of industrialisation and infrastructures development of the country. These parameters can be expressed as an intensity of cement use that refers to the amount of cement used per unit of GDP (kg/unit of GDP). Note that a Unit of GDP is here adjusted to 1000 constant dollars (base year: 2000) and expressed in term of Purchasing Power Parities (PPP) which are the rates of currency conversion that eliminate the differences in price levels between countries. Cement intensities differ between countries according to economic growth (GDP) and economic structure. Different studies attended to demonstrate that this intensity follows an inverted U-shape curve [29–32]. Intensity of cement demand will then decline in developed countries and increase in many developing countries [7].

In Western Europe OECD countries, the intensity of cement use is currently estimated at 21 kg of cement per unit of GDP (1000 USD, PPP 2000) and will be around 17 kg of cement per unit of GDP at the 2050 horizon [7]. To give a comparison, the intensity of cement demand in China is today around 131 kg of cement by unit of GDP (1000 USD, PPP 2000) and is expected to be reduced up to the intensity of Western European countries by the 2050 horizon [7].

Then, with assumptions on GDP evolution and on cement demand intensity, it is possible to evaluate the cement production evolution. A model described as VLEEM 2 (Very Long Term Energy Model) has been used to make assumption on future cement production [33]. It expects a strong increase of cement production in developing countries [32] and a limited increase in developed OECD countries in 2050 [33]. Others evaluations, following a Business As Usual scenario (BAU scenario) expect an increase in cement production in Western European countries until 2020 and stagnation afterward [32].

We have not so far addressed the effects of our assumptions on cement intensity or on expected production growth; therefore different scenarios for cement production will now been considered. We have tested seven possible scenarios for cement production. Four of them consider a decrease in cement production; one scenario shows a stagnation; and the last two envisage positive growth in cement production. If a constant cement intensity in Western Europe is assumed, as VLEEM2 [33] does, an increase of 5% in cement production appears to be a realistic scenario (as it induces a low increase of GDP). A value of + 10% appears to be an upper boundary [32]. Table 6 resumes the results.

It is evident that, with low clinker substitution (scenario 1: 30% of clinker), factor 2 objectives cannot be achieved without a reduction in cement production. However, with an important effort made on clinker substitution (scenario 2: 50% of clinker and 10% of raw materials) factor 2 can be achieved whatever the evolution in cement production may be. Finally, factor 4 objectives can only be achieved with the highest technology improvements (scenario 4) and an important decrease in cement production (−30%).

Table 6
CO_2 emission perspectives due to variations in cement technology efficiency and/or cement production growth. Emissions are expressed in percentage compared to their value in 1990.

	Gross production (%)	−30	−20	−10	−5	0	5	10
	t_{CO_2}/t_{cement}	Cement production						
		14.91	17.04	19.17	20.24	21.30	22.37	23.43
Scenario 0	0.601	57	65	73	77	81	86	90
Scenario 1	0.485	46	53	59	62	66	69	72
Scenario 2	0.347	33	38	42	45	47	49	52
Scenario 3	0.322	31	35	39	41	44	46	48
Scenario 4	0.251	24	27	31	32	34	36	37

6. Discussion

This study suggests that technological improvements in cement technology are not sufficient to reach factor 4 objectives and that the $Production_{cement}$/year parameter in Eq. (1) must also be modified. A detailed study will be necessary to develop this parameter. It is important to note that the first assumption in our study was that no alternative cement products, such as, for example, alkali-activated cements [34], calcium-sulfoaluminate-based cements [35–37] or MgO-based cement [38] will penetrate the market. These low-CO_2 cements could partially replace standard Portland clinker-based cements and therefore indirectly permit reductions in Portland-based cement production without affecting construction industry activity. Secondly, construction practices have not been studied in this paper, but they are another key source of improvement possibilities. The intensity of cement consumption depends of course on the practices of the building industry, and it could be possible to build differently and use less cementitious material to build the same final structure. It has been shown, for instance, that improving concrete strength in a structure such as a beam could permit reductions in final cement use [17,27] while maintaining concrete performance, thus permitting to reductions in cement production without modifying standards of living. This approach can be strongly influenced by public policy decisions such as particular fiscal incentives to build in such a way as to reduce CO_2 emissions. However, it is important to avoid any policies that would incite the construction industries to increase their cement imports so as to reduce the production of cement in Europe as a means of meeting European CO_2 emissions quotas. Clearly, this would mean increasing the production of cement in developing countries, which are less tightly bound in term of environmental constraints; and it would, as a consequence (and also as a result of increased transportation) induce a global CO_2 emissions increase. Public policy efforts should provide positive incentives to build structures with the same final use-performance while using less CO_2-intensive raw materials such as cement or steel; but the emphasis should be on developing and comparing accurate full life-cycle analyses of the environmental impacts of alternative structural approaches.

7. Conclusion

In this study, we have shown that it is possible to design concretes to achieve factor 2 objectives whatever the evolution of cement production. Clinker substitution is a promising solution as it is a low-cost option that has not yet been used to the greatest possible extent, and, as such, still has great potential. Technological barriers to produce concrete with clinker substitution levels as high as 50% are not important and the other technological options are less efficient and more expensive. However, this study has also shown that a technological shift seems necessary to achieve factor 4 goals, because even the highest investment in Ordinary Portland Cement production cannot permit us to reach such objectives without a drastic reduction in cement production. Therefore, this study has evidenced that the necessary technological turnaround for factor 4 objective must affect both the material itself and the way in which it is used, i.e. that it must make use of new low-CO_2 binders and also make use of new building techniques, using less material for the same final structural-performance objectives.

Acknowledgment

The authors wish to thank the French competitiveness cluster Advancity and the Region Ile de France for their financial help and the

French cement union for data availability. The authors acknowledge an anonymous reviewer for constructive comments and an amazing rewording in the text.

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