Available online at www.sciencedirect.com
ScienceDirect
Cement and Concrete Research 38 (2008) 115–127
Cement and Concrete Research

Sustainable development and climate change initiatives

J.S. Damtoft [a,*], J. Lukasik [b], D. Herfort [a], D. Sorrentino [b], E.M. Gartner [b]

[a] Aalborg Portland, Denmark
[b] Lafarge, France

Received 15 August 2007; accepted 10 September 2007

Abstract

In the present paper we argue that the cement and concrete industry is contributing positively to the Climate Change Initiative by:

- Continuously reducing the CO_2 emission from cement production by increased use of bio-fuels and alternative raw materials as well as introducing modified low-energy clinker types and cements with reduced clinker content.
- Developing concrete compositions with the lowest possible environmental impact by selecting the cement type, the type and dosage of supplementary cementitious materials and the concrete quality to best suit the use in question.
- Exploiting the potential of concrete recycling to increase the rate of CO_2 uptake.
- Exploiting the thermal mass of concrete to create energy-optimized solutions for heating and cooling residential and office buildings.

Keywords: Sustainability (new); Cement manufacture (E); Clinker (D); Blended cement (D); Concrete

1. Introduction

Sustainable development has been defined by the World Business Council for Sustainable Development (WBCSD) as: "Forms of progress that meet the needs of the present without compromising the ability of future generations to meet their needs" [1].

The WBCSD continues: "Given the scale of world poverty today, the challenge of meeting present needs is urgent. But we must look ahead and do our utmost to ensure that what we do today for our ever-growing population does not compromise the environmental, social and human needs of our descendants".

Concretes made with hydraulic binders (almost all based on Portland cement) are by far the most widely employed construction materials worldwide in terms of volume, and as such have a huge impact on the environment and also on sustainable development. Produced using readily available raw materials, being easy to use and possessing good strength and durability, concrete is indispensable for meeting modern society's needs for infrastructure, industry and housing. The fast growth in developing economies such as China or India can only be sustained if an inexpensive construction material with low environmental impact is available. Concrete fulfils these requirements.

In the present paper we argue that the cement and concrete industry is contributing positively to the Climate Change Initiative by:

- Continuously reducing the CO_2 emission from cement production by increased use of bio-fuels and alternative raw materials as well as introducing modified low-energy clinker types and cements with reduced clinker content.
- Developing concrete compositions with the lowest possible environmental impact by selecting the cement type, the type and dosage of supplementary cementitious materials and the concrete quality to best suit the use in question.
- Exploiting the potential of concrete recycling to increase the rate of CO_2 uptake.
- Exploiting the thermal mass of concrete to create energy-optimized solutions for heating and cooling residential and office buildings.

* Corresponding author.
E-mail address: jsd@aalborgportlandgroup.com (J.S. Damtoft).

0008-8846/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconres.2007.09.008

Much scientific evidence links climate change to greenhouse gas (GHG) emissions of which carbon dioxide (CO_2) ranks amongst the most important, accounting for 82% of the total. It is estimated that the cement industry produces approximately 5% of global manmade CO_2 emissions, but it emits almost no other GHGs. When all GHG emissions generated by human activities are considered, the cement manufacturing industry is found to be responsible for only about 3% of total anthropogenic GHG emissions.

Apart from emissions linked with the energy used for clinker burning, grinding and other operations, there is a natural release of CO_2 associated with the de-carbonation of limestone to give the calcium silicates and aluminates in clinker. This "Raw Materials CO_2 Emission" is roughly equal to 0.53kg per kg of clinker. The total CO_2 emitted in cement manufacture includes, in addition, the "Fuel-Derived CO_2" and also takes into account the dilution of clinker by other cement ingredients. Humphreys and Mahasenan [2] report that the cement industry emitted in 2000, on average, 0.87kg of CO_2 for every kg of cement produced (worldwide cement production in 2000: 1.57billion tonnes, in 2004: over 2billion tonnes).

>An analysis carried out by Battelle [2] shows that cement sector CO_2 emissions are set to rise dramatically in the coming decades. Demand for cement in industrial nations is increasing slowly, but in developing countries it rose by 55% in the 1990s. It is expected that, by 2020, global demand will have increased by 115–180% from 1990 levels, with a four-fold increase likely by 2050. It is critical that the CO_2 emissions associated with such growth in cement production be reconciled with international efforts to reduce GHG effects. The cement industry is fully aware of the sustainable development stakes and, over the past decades, has been actively involved in seeking ways to consume less energy and natural resources, and emit less CO_2 per unit of cement produced. Recent innovations such as self-compacting concrete, high-performance concrete and surface-active materials further contribute to sustainable development by reducing the costs of construction and maintenance, improving health and safety as well as the outdoor and indoor environment.

2. Global warming

Climate change has become an issue of global prominence and, in today's society, often provokes animated debates over its origins. Most of the scientific evidence, however, links increased GHG emissions to the average warming of our planet.

How do GHG emissions affect the climate? The Sun's radiation heats the surface of the Earth, which in turn radiates energy back to space. Some of this radiation (almost all in the infrared spectrum) is trapped in the atmosphere by GHGs, which have strong absorption bands in the infrared range. The trapped radiation warms the lower atmosphere (troposphere). This heat then finds its way back down to the Earth's surface, making it hotter than it would otherwise be. This is similar to what happens in a greenhouse.

There is strong evidence which suggests that a significant proportion of the warming observed over the past century is attributed to human activities. Here are a few key examples of trends and projections [3]:

- *GHG concentrations*: CO_2 concentration has increased from its pre-industrial level of 280ppm to the 2003 level of 375ppm (+ 34%), with an accelerated rise since 1950. The total rise in all GHG since the pre-industrial era amounts to 170ppm CO_2-equivalent, with contributions of 61% from CO_2, 19% from CH_4, 13% from CFCs and HCFCs, and 6% from NO_2. If no climate-driven policy measures are implemented, a further increase to 650–1215ppm CO_2-equivalent is projected to occur by 2100.
- *Global and European air temperature*: The Earth's average surface temperature has increased by 0.7 ± 0.2°C over the past 100years. Europe has warmed more than the global average, with a 0.95°C increase since 1900. The 1990s were the warmest decade in the observational record; 1998 was the warmest year, followed by 2002 and 2003. Without policy measures, from 1990 to 2100, the global average temperature is projected to increase by 1.4–5.8°C and 2.0–6.3°C for Europe.
- *Glaciers, snow and ice*: From 1850 to 1980, glaciers in the European Alps lost approximately one third of their area and one half of their mass, a trend that is continuing. By 2050, about 75% of the glaciers in the Swiss Alps are likely to have disappeared. The northern hemisphere's annual snow cover extent has decreased by about 10% since 1966. It is projected to decrease further during the 21st century. The total area of Arctic sea ice shrank by more than 7% from 1978 to 2003. Projections show a predominantly ice-free Arctic Ocean in summer by 2100.
- *Rise in sea level*: It is estimated that the current rise in sea level of 0.8–3.0mm/year will continue over the 21st century and intensify by 2.2 to 4.4 times the present value.

The climate change issue is, however, only a part of the larger challenge of sustainable development. As a result, climate policies can be more effective when consistently embedded within broader strategies designed to make various development paths more sustainable.

World leading cement producers are fully aware of their part of the responsibility in implementing all the necessary measures and, in 2002, ten international companies set out to help the industry play a stronger role in support of sustainable development. In June 2005, under the auspices of World Business Council for Sustainable Development (WBCSD), a Progress Report was published which was undersigned by 16 companies.[1] It lists the *Key Performance Indicators of the Cement Sustainability Initiative*:

- Climate change management
  - Number of facilities and percentage using WBCSD CO_2 protocol
  - Company-wide total CO_2 emissions, tons/year
  - Company-wide gross and net CO_2 emissions per ton of cementitious product

[1] The sixteen companies were: Ash Grove Cement Company, Cemex (including RMC), Cimpor, Corporacion Uniland, CRH plc, Gujarat Ambuja Cements, HeidelbergCement, Holcim, Italcementi, Lafarge, Secil-Companhia Geral de Cal e Cimento, Shree Cement, Siam Cement Industry, Taiheiyo Cement, Titan Cement, Votorantim.

- Fuels and materials use
  - Energy use
    - Specific heat consumption of clinker production in MJ/t of clinker
    - Alternative fossil fuel rate: AF consumption as% of thermal consumption
    - Biomass fuel rate: consumption of biomass as % of thermal consumption
  - Raw materials use
    - Alternative raw materials rate: use of ARM as a % of total RM for cement and clinker production
    - Clinker/cement factor
- Health and safety
  - Fatalities
    - Number of fatalities and fatality rate of industry employees
    - Number of fatalities amongst indirectly employed personnel (e.g. contractors)
    - Number of fatalities involving 3rd parties (not employed)
  - Lost-time injuries (LTI)
    - LTI and injury frequency rate (per 1,000,000 man-hours directly employed)
    - Number of LTI for indirectly employed (e.g. contractors)
- Emission monitoring and reporting
  - % of clinker produced by kilns covered by a monitoring system, either continuous or discontinuous, for main and other pollutants
  - % of clinker produced by kilns which have installed continuous measurements for main pollutants
  - Company-wide specific (g/t of clinker), and total (t/year) releases for:
    - NOx
    - SOx
    - Dust
- Local impacts
  - % of sites with community engagement plans in place
  - % of active sites with quarry rehabilitation plans in place
  - Number of active sites where biodiversity issues are addressed.

A transparent and sincere follow-up of the above indicators proves the cement industry's commitment to provide business leadership as a catalyst for change toward sustainable development, and to promote the role of eco-efficiency, innovation and corporate social responsibility.

3. Reduced CO_2 emissions from cement production

3.1. Alternative fuels and raw materials

A typical modern rotary cement kiln with a specific heat consumption of 3.1GJ/t clinker, burning traditional carbon based fuels such as coal, oil or petroleum coke, emits approximately 0.31kg fuel derived CO_2/kg clinker. Given a more realistic world average specific heat consumption of 3.8GJ/t clinker, fuel derived CO_2 emissions would amount to approximately 0.37kg/kg clinker. Towards the top end of the scale, inefficient long rotary kilns burning wet raw materials typically operate at a heat consumption of about 6GJ/t clinker, and a fuel derived CO_2 emission of about 0.6kg/kg clinker.

Compared to fuel derived CO_2, CO_2 derived from the raw materials is relatively high at approximately 0.53kg/kg clinker. This is much more constant than the fuel derived emissions because the contents of limestone, from which essentially all the raw material derived CO_2 originates, fall within a narrow range of 1.2 to 1.3kg/kg clinker regardless of the type of process involved.[2] Total CO_2 emissions from kilns burning conventional fuels and raw materials therefore range from 0.84 to 1.15kg/kg clinker depending primarily on the heat consumption of the kiln. Apart from ongoing efforts to improve the thermal efficiency of kiln and cooler systems, which can under optimum conditions reduce heat consumption to less than 2.9GJ/t clinker, the greatest scope for major reductions in CO_2 emissions lies in the replacement of conventional carbon based fuels by alternative low fossil carbon based fuels, and where possible by replacing the limestone with raw materials high in non-carbonate calcium sources.

3.1.1. Bio-fuels and other alternative fuels

Alternative fuels are being increasingly used to reduce the cost of production and to lower CO_2 emissions. The breakdown of the alternative fuels used in Europe is shown in Fig. 1 where they account for 14% of all fuels based on calorific value. However, as indicated, most alternative fuels are not approved as carbon neutral. Carbon neutral fuels with no net release of CO_2, e.g. as defined by the European Commission, or in the "U.S. Climate Change Technology Program", are essentially biomass from sustainable managed systems where the amount of CO_2 released by combustion and the amount absorbed by photosynthesis are at equilibrium. These include agricultural and forestry biomass, and waste materials such as biodegradable municipal waste, animal waste, paper waste etc. In fact, in many cases the burning of carbon neutral wastes can be regarded as a GHG sink, where these would otherwise decay to form methane which is a much more powerful GHG than CO_2. Waste materials derived from fossil fuels such as solvents, plastics and the synthetic rubber component in used tires, etc., are not regarded as carbon neutral. It is important to note, however, that transferring waste fuels not classified as carbon neutral from incineration plants to the cement kiln results in significant net reductions in CO_2 emissions. In the case of incineration plants without energy recovery, the effect is the same as replacing fossil fuels with carbon neutral fuels on a one to one basis. Where the waste fuel is transferred from dedicated incineration plants with power generation, substantial CO_2 emission reductions are still achieved because the cement kiln is invariably more efficient in terms of energy recovery than the incineration plant. Another major advantage of burning waste materials in cement kilns is that no residues are generated, since the ash is completely incorporated in the clinker.

[2] Regardless of limestone purity, total calcium carbonate contents in the raw materials are very uniform due to the narrow range of calcium contents in Portland cement clinkers.

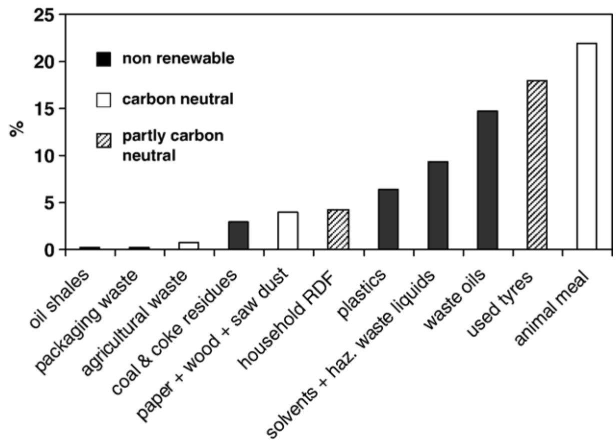

Fig. 1. Relative amounts of alternative fuels sued for clinker production in Europe [4].

3.1.2. Alternative raw materials for the replacement of limestone in kiln feed

Waste materials from other industries are increasingly being used to replace the traditional raw materials used in the production of Portland cement clinker. These include foundry sands, fly ash and bottom ash from coal fired power plants, spent catalysts and filter clays, mill scales, etc. Although the cement kiln provides a convenient and environmentally friendly means of disposing of these waste materials, reductions in CO_2 emissions are limited because these materials are rarely high enough in calcium to replace significant amounts of limestone. An exception to this is blast furnace slag (BFS), which is rich in calcium oxide. However, although the CaO content in BFS is generally in the region of 40%, high Al_2O_3 and/or MgO contents limit the maximum level of limestone replacement between 20 and 30%. In practice, replacement levels of about 10% are more commonly reported. When concomitant reductions in fuel consumption are also considered (since less heat is needed to de-carbonate the limestone), total CO_2 reductions can in theory be as high as 25%. In addition to chemical constraints, the major factor limiting the widespread use of BFS is availability. In 2005 world wide production of ungranulated BFS was probably in the region of 150 million tonnes compared to a global limestone consumption for clinker production of 2500 million tonnes. This gap is likely to increase as existing steel plants are replaced by more efficient electric arc furnaces (which do not produce BFS), and Portland cement production continues to increase. Steel slags are invariably too high in iron for significant direct limestone replacement, but can have other indirect applications (see later). High CaO (class C) fly ashes can also be used to replace limestone by up to 10%, however, the widespread use of class C fly ash is also limited by availability with the global output only 5% of the amount of limestone used in clinker production. In all, 100% utilization of current sources of BFS and class C fly ash, worldwide, would result in CO_2 emission reductions of 10% at most. In practice, their use will inevitably remain much lower, as high transport costs and energy requirements restrict their use and offset some of the environmental benefits.

4. Reduced CO_2 emission and energy consumption in clinker production

The CO_2 emissions directly resulting from clinker production fall into two main categories: those derived from de-carbonation of the raw materials, which we denote as RM-CO_2, and those derived from the fuel burned in the kiln, which we denote as FD-CO_2 [5]. The CO_2 emissions associated with the generation of the electric power used to operate cement plant machinery (most of which is required for grinding operations) vary widely, depending on the nature of the local electric power industry, but average about 0.08tons of CO_2 per ton of cement [6]. However, under the Kyoto framework they are considered to be the responsibility of the electricity generating industry, unless the electricity is generated on site by the cement manufacturer.

The separation of CO_2 emissions from clinker production into two main categories is very important in understanding the constraints to which the cement manufacturer is subject when attempting to reduce such emissions [5]. In summary:

1. RM-CO_2 depends only on the chemistry of the raw materials, including fuel.
2. FD-CO_2 depends on several independent factors, the most important of which are the thermal efficiency of the kiln system and the chemistry of the fuel and raw materials.
3. Modern cement plants usually have the highest thermal efficiencies.

The thermal efficiency issue is relatively easy to treat in the sense that reducing fuel consumption usually also results in direct manufacturing cost reductions, the only barrier therefore being the investment cost of the new plant, if needed. However, most modern plant designs have come very close to the thermodynamic barrier imposed by the chemistry of the process with the fuels typically used. A clinkering energy efficiency of about 3GJ/t is not very far above the real thermodynamic limit for a kiln system operating with reasonably dry raw materials, with coal or coke as the fuel and air as the oxidizer, and emitting exhaust gases at > 120°C to avoid condensation in the ductwork [5]. The first-law theoretical efficiency, i.e. the enthalpy change in the clinkering reactions for typical dry raw materials, is only about 1.8GJ/t, but this does not consider the realities of fossil fuel combustion in air and the practical need to keep the exhaust gases well above their dew point. In order to improve significantly on 3GJ/t we would have use special fuels, or oxygen-enriched combustion air, or already de-carbonated lime sources, or some form of condensation heat exchanger on the exhaust gases, or a combination of the above.

The use of pure oxygen instead of air can in theory result in a very significant improvement in thermal efficiency, because it reduces the volume of the exhaust gases (and their associated heat losses) by a factor of about 3. It also leads to exhaust gases that are essentially a simple mixture of CO_2 and water vapor, which could then easily be separated by condensation, the resulting pure CO_2 then being readily transportable or directly injectable into underground aquifers or other such potential disposal sinks. This type of approach is currently under consideration by the electric power generating industries for a new generation of coal-burning power plants, and the cement industry could in theory try to apply the same approach. However, the electrical energy required to produce pure oxygen from air with current technology is about 420kW h/t-O_2 [7]. Based on this, we estimate that oxygen enrichment would not actually save a lot of energy or CO_2 generation in cement manufacture. This situation will evidently improve as the primary-energy-efficiency of electric power generation plant and air separation plants improves, but this is likely to be a slow process.

The above estimates also ignore the very real engineering problems involved in the design of a cement kiln system that could run on pure oxygen or highly oxygen-enriched air, and in which the kiln exit gases would also have to be condensed and separated in liquid form. Conceptual approaches to the design of such a plant are currently under study, but for the moment it remains somewhat of an environmentalist's dream but a chemical engineer's nightmare! Such approaches would almost certainly require large investment costs.

The problem of reducing RM-CO_2 is a much simpler one to understand, if not to solve. Almost all modern Portland cement clinkers contain 65% or more by mass of calcium as oxide, and the source of almost all of this calcium is calcium carbonate from natural limestones. Thus, the production of 1ton of a modern OPC clinker emits, on average, about 0.53tons of RM-CO_2. The only way this figure can be reduced is by reducing either the amount of CaO in the clinker or by using alternative raw materials that contain a significant fraction of their calcium in a non-carbonate form. However, as noted earlier, few such alternative calcium sources exist in a form that can readily be used for cement manufacture in existing kiln systems. So, if we wish to reduce this figure significantly, we must consider alternative clinker chemistries.

The simplest approach to this problem, and one that has been extensively studied, is to produce clinkers that are rich in belite and poor in alite [8]. Given that alite (C_3S) usually represents at least 60% by mass of a modern OPC clinker, and its production from $CaCO_3$ emits 0.578 parts of CO_2 by mass, its total substitution by belite (C_2S), the production of one part of which only emits 0.511 parts of CO_2 by mass, could reduce total RM-CO_2 emissions by about 8% to about 0.49kg/kg clinker. As we have shown [5], the reduction in kiln fuel requirement that can also result from the fact that a belite-rich clinker can be burned at a significantly lower temperature than a conventional clinker is insignificant, the main energy saving coming from the fact that we can reduce the amount of limestone that must be decarbonated (a very endothermic process). Thus, FD-CO_2 emissions should also be reduced by about the same percentage (8%) as RM-CO_2 emissions. Unfortunately, belite is much less reactive than alite, so belite-rich Portland cements generally suffer from very low setting and hardening rates, which would not be acceptable in most modern concrete applications. Despite many decades of study, no-one has succeeded in finding a practical and cost-effective way to activate pure belite when it is made in a conventional kiln system, and, given the rather small total CO_2 emission savings involved, there is currently little interest in pursuing such an approach.

An alternative technology which has been known for several decades but which has not until recently been considered as an approach to reducing CO_2 emissions is that of calcium sulfoaluminate (CSA) based clinkers [5]. Calcium aluminate cements in general have a much lower embodied RM-CO_2 content than Portland cements due to their significantly lower total CaO contents. However, the manufacture of pure calcium aluminate cements is relatively expensive since concentrated alumina sources are not sufficiently abundant in nature. A better approach is to compromise by making mixed calcium silicate/CSA cements, such as the "Third Cement Series" developed in China [9]. Such cements can contain as much as 75% CSA (yee'limite, $C_4A_3\$$), which has a RM-CO_2 content of only 22%, compared to 53% for a modern OPC clinker. They have already been studied as "Low-Energy Cements" [10] and also have interesting applications in precast concretes, self-stressing concretes, and in concretes for low placing temperatures [11].

However, production of such cements requires bauxite as a major raw material, with high resulting costs. One of us has therefore recently developed an alternative range of compositions that contain less CSA and more belite and ferrite phase, which represent a better compromise in terms of raw materials cost versus RM-CO_2 emissions. By suitable choice of raw materials and the appropriate minor components, such clinkers can be made into cements that give concrete rheology and strength development profiles not very different from those typical for OPCs [12]. Another advantage of this type of clinker is that it can in principle be manufactured using existing high-efficiency (preheater) cement kilns, leading projected total CO_2 manufacturing emissions reductions of about 25% with respect to pure OPCs. This represents the same order of CO_2 reduction that can conventionally be obtained by blending OPCs with suitably reactive pozzolans, such as high-quality fly ashes or natural pozzolans. It is thus an alternative solution in cases where high-quality supplementary cementitious materials are not available. Of course, additional CO_2 emission reductions could be obtained by making blended cements based on such CSA-rich clinkers, diluted with a variety of supplementary cementitious materials.

5. Reduced clinker contents in cement

Given the limitations involved in reducing CO_2 emissions from alternative raw materials and fuels, and by improving kiln efficiency, probably the most effective means of achieving significant reductions lies in the replacement of Portland cement clinker by other suitable materials. These replacement materials can be added separately to the concrete allowing a reduction in the content of clinker for the same concrete performance, or used to replace the clinker in composite cements. The latter is more commonly the situation in Europe as reflected by the European harmonized cement standard EN 197-1, whilst in the US, for example, replacement materials are more commonly added to the concrete. Regardless of the relative merits of each approach, the overall reduction in CO_2 emissions associated with the reducing the amount of Portland cement clinker per m^3 of concrete is of course essentially the same, with the amount of clinker needed to achieve a given concrete performance dependent on the relative reactivity of the replacement material, the overall cement content required, the size distribution of the cement constituents for optimum concrete consistency and minimum water content, etc.

5.1. Supplementary cementitious materials, SCMs

Replacement materials that react with calcium hydroxide are commonly termed "Supplementary Cementitious Materials", (SCMs). They include fly ash, granulated blast furnace slags (GBFS), and natural pozzolans, and to a lesser extent silica fume, metakaolin, etc.

5.1.1. GBFS and fly ash

Global cement production in 2003 was 1880Mt with a cement/clinker ratio of 1.17 [13] (current production is thought to be well over 2000Mt/year). Additions to Portland cement clinker therefore amounted to about 275Mt, including about 110Mt of "gypsum". The total amount of "hard coal fly ash" and BFS used in concrete amounted to about 280Mt, but about half of this was added directly into concrete and not sold as part of the cement. According to the same source, the global average CO_2 emission per mass of cement in 2003 was 0.81 (81%). If, for the sake of argument, all of the global production of hard coal fly ash and BFS currently not utilized was used as a one to one clinker replacement, overall CO_2 emissions associated with clinker production could be reduced by 17%. If it was all blended in Portland cement the cement/clinker ratio would increase to 1.41. Europe and South America with cement/clinker ratios of 1.30 and 1.32 respectively are closest to achieving this, whilst North America, with a ratio of 1.09 and only 25% utilization of BFS and fly ash, has the greatest potential for clinker replacement. In practice the increased global use of traditional SCMs such as fly ash, GBFS and natural pozzolans is limited by several factors, but mainly by transport costs, and in the case of slag and fly ash competition by other applications such as their increased use as a raw material in clinker production, so the effective limit on the global cement/clinker ratio is more realistically about 1.3.

In fact, since fly ash and slag are themselves associated with high CO_2 emissions the supply of these materials in the long run is bound to fall as coal fired power stations and blast furnace plants are replaced by more CO_2 efficient processes. Reductions in clinker must, therefore, be based on other materials.

5.1.2. Pozzolans

As natural pozzolans are abundant in certain locations, their use will surely be extended, but it presents some technical difficulties such as high water demand, poor workability retention, low early strengths, etc. However, recent research into the formulation of complex multi-component cements, such as ternary, quaternary blends, has shown that these often have the potential to overcome many of these perceived difficulties.

Calcined clays and shales also offer the possibility of creating pozzolans in a wider range of locations. However, there is a significant cost- and CO_2-penalty to be paid for the calcination process.

5.1.3. Silica fume

This is an industrial by-product, but it has been found to be so useful in high-performance concrete applications that it is often treated as a key component in the mix design of such concretes. Due to its limited availability it is "sold out" and alternative products are now being used and new ones actively being researched ("nano-silica particles"). Its early use in Scandinavian countries close to the major sources (silicon metal manufacture in electric arc furnaces) led to important research on optimal particle packing that led initially to "Densit" and "CRC" and ultimately to "BPR" and "Ductal" [14].

The amount of silica fume in cement is limited to 10% under CEM II/A-D, but it is now recognized to have additional value in cements made with more slowly reacting SCMs (GBFS, PFA, Pozzolans). The high reactivity of silica fume (which is due to its very high specific surface area) leads to the formation of significant amounts of additional C-S-H at early ages, which can compensate at least partly for the slow reaction rate of the other SCMs. This can be used to increase the total proportion of SCMs and thus reduce the clinker content. This type of cement is often referred to as a "ternary blend" and synergetic effects have been reported in the mitigation of alkali–silica reaction [15]. Despite its many useful properties, however, silica fume cannot really be considered as an effective means of reducing energy consumption or CO_2 emissions in cement manufacture, due to the very limited supply of by-product silica fumes. Silica fumes of equivalent properties could be manufactured deliberately if desired, but the energy costs of manufacture are extremely high compared to clinker, and this would probably negate all of the other advantages.

5.1.4. Limestone additions

The most readily available mineral additive for cement is limestone. In Europe, more limestone is used in Portland-based cements than all other mineral additions combined, notably in the European CEM II L class (24.6% of all European cement manufactured in 2003, as published by CEMBUREAU) and to a lesser extent in the M class, and as a minor addition of up to 5% in almost all other Portland cements. It has been shown that much of the alumina from the clinker can react with the limestone to form calcium carbo-aluminate hydrates, which can result in a significant decrease in porosity [16]. However, the alumina in a typical OPC clinker is only enough to react with at most about 5% limestone, even if catalysts are used [17]. Both the European cement standard, EN 197-1, and ASTM C150 allow up to 5% limestone [18]. Limestone added in excess of this amount, although constituting essentially a "filler", can also act as an accelerator for alite hydration, so that, with suitable grinding techniques, cement strengths up to 28days are often not much reduced even at limestone contents as high as 20%. In addition to this, limestone additions can improve concrete consistency by reducing cement water demand, and provided that a low w/c concrete mix design is used, high limestone replacement levels can result in almost the same concrete performance as some "pure" Portland cements [19].

Long field experience with limestone cements has proven their good long-term performance and durability. France, where much of the early research was done before the introduction of such cements, now has more than 40years of good records [20]. The most serious weakness, a low resistance towards sulfate attack, has been taken in account in the standards, which do not permit the use of such cements in concretes under certain conditions of potential sulfate attack [21].

Given that limestone reacts with calcium aluminates, it is to be expected that the amount of limestone that can react will increase if SCMs with a high reactive alumina content are used. This has recently been demonstrated for slag-Portland cements [22]. Increased developments of composite cements can be expected and should be encouraged.

5.1.5. Principal routes for progress

- Add additional materials to the list of approved SCMs (under existing standards).
- Extend the cement standards to allow for more complex composite cements. Clearly, the domain of binary, ternary and even quaternary blends can offer many routes for progress and should be given great attention.
- Develop the scientific methodology, from both the chemical and physical viewpoints, that will facilitate the design of blended cements for optimal performance.

The performance of concrete should be defined in a much broader way, in terms of all of the important performance criteria, such as set time, workability, durability, etc., as well as strengths. Factors of importance should be attributed to each usage value, according to the type of construction and environment in which the cement will be used.

6. Contribution to sustainable development in the concrete industry

6.1. "Green" concrete

The idea behind "green concrete" is to formulate and use concrete formulations which are optimized for the lowest possible environmental impact in all phases of the concrete structure's life cycle, which include:

- Extraction of raw materials
- Production of constituent materials (cement, additives, reinforcement, etc.)
- Production of concrete
- Transport and erection of the structure
- Maintenance
- Demolition and recycling.

A number of principles may be used to reduce the environmental impact of concrete:

- *The right concrete for the right application*. For example, there is no need to use a very strong and durable concrete with a high cement content and a high-grade aggregate for less demanding applications, such as indoor partitions.
- *High content of recycled materials*. Concrete's unique capability to utilize large quantities of waste and residual products can be used both to solve societal waste problems and to reduce the consumption of non-renewable natural resources.
- *Optimize cement content in concrete*. By optimizing particle packing and use of supplementary cementitious materials the content of Portland cement can be optimized to the exact quantity necessary to ensure the desired properties.
- *Use cement with reduced environmental impact*. Cement with the lowest possible clinker content should be used, and clinker produced using a high proportion of bio-fuels should be preferred.

A recent Danish study concluded that a 30% CO_2 reduction was achievable by carefully selecting the environmentally most beneficial concrete composition [23]. The Danish Centre for Green Concrete developed a number of environmentally optimized concrete compositions. The highlight of the project was the construction of a road bridge, demonstrating the most promising concrete composition in full scale. The bridge was completed in 2002.

The concretes tested were based on blends with high contents of fly ash and Portland cement based on low-energy mineralized clinker (Table 1). The reference concrete was a standard Danish concrete specified by the Danish Road Directorate for use in road bridges. A low-alkali sulfate resistant cement was used.

All concrete types except A3 were used in both bridge deck and pillars. In A3, fly ash was substituted with ash obtained by incineration of sewage sludge. This concrete was only used in connecting plates at both ends of the bridge deck.

Durability of the concretes was tested with respect to chloride ingress, carbonation, freeze–thaw resistance and alkali–silica reaction. No significant differences between reference and "green" concretes were found.

An environmental screening has been performed based on these concretes [24]. CO_2 emission and other environmental parameters were calculated for model bridges composed of the reference concrete and the three "green" concretes, respectively. The reinforcement in the "green" model bridges were made of stainless steel, whereas conventional reinforcement was used in the reference bridge. Choice of stainless steel enables reduced maintenance, including replacement of concrete. Finally, whereas the reference bridge had a conventional asphalt pavement, the pavement of the "green" bridges was made of concrete. This enabled further reductions in maintenance, as the asphalt pavement was predicted to have only a 25-year lifetime, compared to over 40years for a concrete pavement.

Table 1
"Green" concrete types for demonstration road bridge

	Reference	A0	A1	A3
Sulphate resisting cement	317			
Ordinary Portland cement		317	238	320
Fly ash	32	32	135	
Sewage sludge incineration ash				32
Micro-silica	18	18	18	18
Superplasticizer	3,6	3,6	9,3	6,13

Simplified concrete recipes (kg/m^3).

Table 2
Calculated CO_2 emissions from “model” bridges over 74 years

(tons of CO_2)	Reference	A0	A1	A3
Concrete	120	80	60	80
Reinforcement	40	40	40	40
Asphalt	5			
Construction	20	20	20	20
Misc. maintenance	5			
Concrete replacement	25	20	20	20
Asphalt replacement	10			
Total tons of CO2 for bridge:	225	160	140	160
CO_2 from traffic over 74 years:	390	390	390	390

The results of the screening were that the replacement of a low-alkali sulfate resistant cement with an ordinary Portland cement based on mineralized clinker gave the largest environmental benefit. The sulfate resistant clinker requires around 30% more energy in the clinker burning process and hence a significantly higher CO_2 emission. As the concrete contains fly ash and silica fume the extra safety against deleterious alkali–aggregate reactions is superfluous. Furthermore, the sulfate resistance is not needed, as the Danish subsoil is poor in sulfides.

The reduced maintenance requirements resulting from the use of stainless steel reinforcement also resulted in reduced CO_2 emissions, as did the omission of asphalt pavement. The lowest CO_2 emission was given by the concrete with the highest fly ash content. This concrete was, however, difficult to produce and place in full scale.

The estimated CO_2 emissions from traffic on the bridge are shown in Table 2. They are significantly higher than the emission from the construction of the bridge. The benefit from less friction on concrete than on asphalt has not been taken into account.

6.2. Improved sustainability through use of self-compacting concrete

Generally, attention is focused on the environmental “pillar” of sustainability, but concrete innovation also has an important role to play in the other two pillars: the societal and the economic.

Self-compacting concrete (SCC) is probably the most important innovation within concrete technology for the last 50years. SCC has been defined as: *Concrete which without any mechanical action is able to fill a given form without separation*. The SCC concept was developed in Japan around 1980, benefiting at that time from the development of a new generation of superplasticizers by the Japanese chemical industry. The use of SCC has since spread around the world, although it is still considered an exotic material in many countries. According to ERMCO, only 1% of European ready-mix concrete production was SCC in 2004. However, in Denmark the production of SCC accounted for around 25% of all ready-mix concrete in 2005, and almost all precast concrete [25].

The environmental impact of optimized SCC compositions is similar to conventional concrete, but SCC contributes to the other pillars of sustainability:

Economical

- An SCC casting demands less manpower than conventional concrete, hence reducing costs and increasing productivity.
- The quality of the concrete is improved: large voids and granular inhomogeneities can be avoided. This reduces the need for repairs and replacement, which also results in increased productivity (Fig. 2).

Societal

- The work environment is improved by eliminating concrete vibration and the associated noise.
- SCC presents new aesthetical possibilities for in-situ cast concrete. More complicated geometries are possible than for conventional concretes, for which all parts of the formwork must be accessible for vibration.

There are still barriers to a more widespread use of SCC. The material is less forgiving with respect to variations in concrete production, and contractors often experience problems at the

Fig. 2. Left: White SCC slump flow test. Right: White SCC provides flawless surfaces.

work site. In Denmark, a consortium of producers, contractors and research institutes have undertaken to make SCC the most used concrete type before 2008. The necessary technologies for material design, production and execution with SCC will be developed. The economical and societal benefits will be quantified. Finally, the new technologies will be tested at full scale in a road bridge.

The benefits to the working environment and productivity will be documented during the projects. Preliminary results of the investigation of the working environment are:

- Vibration may be a contributing factor in hearing loss. Hearing impairment resulting from vibration is a common health complaint amongst concrete workers
- If the work is distributed amongst the work crew, the effect of vibration should be below the danger limit. However, in reality, vibration work is often performed by only one or two specialists in the crew.
- Lifting the heavy vibration equipment results in a significant risk of back problems.

6.3. Ultra-high performance cement-based materials

Innovation is unquestionably an important driver for sustainable development. However, in the cement-based construction materials sector innovation is often hindered by such constraints as industrial fragmentation, inherent conservatism (but with some justifiable concern over new product liability risks), the very slow rate of change of national and international standards and regulations, and of course the ever-present need for short-term profit performance under pressure from the global financial markets.

Yet, many exciting opportunities exist to be seized. In buildings and civil works, designers aim for ever more slender structures and sophisticated forms, for more aesthetically-pleasing surfaces, for lighter and more durable materials with longer service lives and lower maintenance costs.

In spite of the above mentioned constraints, these challenges have been met and a breakthrough innovation in concrete has been achieved. A class of new high-performance materials which possess unique structural and aesthetic potential has been developed.

One of these materials, CRC (Compact Reinforced Composite) is a special type of fibre reinforced concrete with high strength (150–400MPa) and closely spaced reinforcing bars developed in 1986 [26], www.crc-tech.com. For the last 10years CRC has been used in structural applications and typically for precast elements such as balcony slabs and staircases. In the recent years, the use of CRC has increased significantly as a number of dedicated producers have been established in Denmark (Fig. 3).

Ductal®, a similar material with improved rheological properties, was developed as the result of an intensive R&D effort by three French companies, Lafarge, Bouygues and Rhodia, in collaboration with 10 public research laboratories under a grant from the French Ministry of Research and Industry.

A thorough description of Ductal® can be found on the web site: www.ductal-lafarge.com. This product is a major technological breakthrough giving birth to a material with a unique combination of superior characteristics:

- Compressive strength: 6 to 8 times that of a conventional concrete,
- Flexural strength: 10 times that of a conventional concrete,
- Ductility: capability to deform under excessive loads, without rupture,
- Aesthetics: superior surface aspects,
- Durability: 10 to 100 times that of standard references.

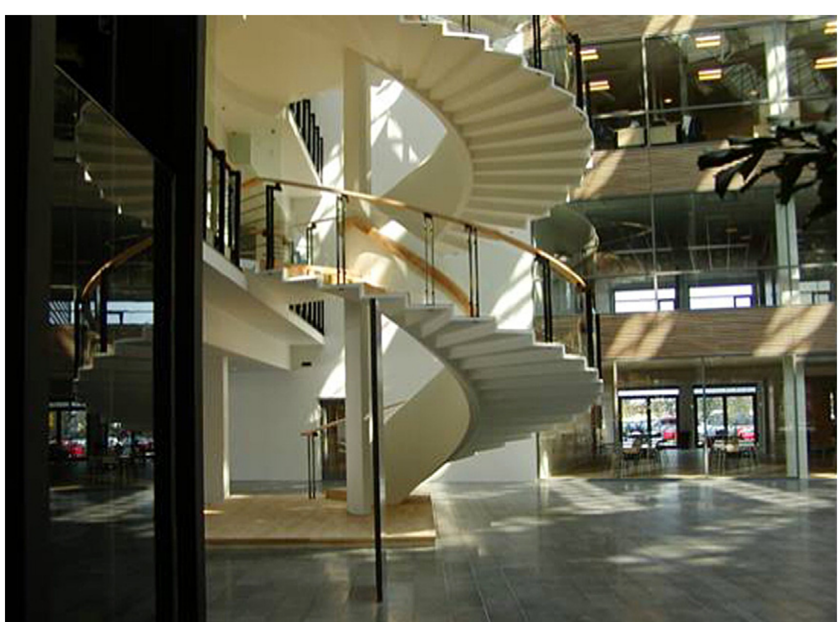

Fig. 3. Spiral staircase with cantilevered steps produced in CRC.

Fig. 4. Seonyu Footbridge in Ductal® (2003, Seoul, Korea), architect: Rudy Ricciotti; photo: © Philippe Ruault.

Moreover, the exceptional rheological properties of products in the Ductal® range allow for all possible placing methods: gravity casting, pumping, injection.

Numerous, various and spectacular applications of Ductal® in France, Korea, Japan, Canada and the United States have already demonstrated its exceptional properties.

In order to provide the environmental profile of this material, a Life Cycle Analysis (LCA), using ISO 14040–14043 references, has been carried out in an independent study by ECOBILAN, a subsidiary of PriceWaterhouseCoopers. The segments analyzed included the production of Ductal® constituents and the production of Ductal® itself. Factors taken into account included:

- Non-renewable consumption of energy resources (oil-petrol, natural gas, coal...)
- Renewable constituents (lime, clay...)
- Water consumption
- GHG emissions
- Acidic emissions
- Eutrophication
- Production of solid residual wastes.

An internal LAFARGE study compared a hypothetical bridge design using a conventional approach (steel girders and a standard 30-MPa concrete deck), on the one hand, and Ductal® only, on the other. Without going into the details of the study, at equivalent mechanical performance and load capacity specifications, it was found that the Ductal® approach required only 65% of the raw materials, 51% of the primary energy and 47% of the overall CO_2 emissions of the conventional approach. The predicted service life of the Ductal® bridge was also significantly longer than that of the conventional structure (Figs. 4 and 5).

7. Closing the CO_2 cycle: CO_2 uptake by concrete

When considering the environmental performance of materials one needs to consider effects taking place during the entire life cycle of the material. Failing this may lead to erroneous conclusions when selecting materials based on perceived environmental-friendliness. Some of these effects may be fairly obscure.

One such issue seldom considered is the ability of cement-based materials to permanently absorb ("sequester") CO_2 from the atmosphere. This process is termed carbonation and occurs during the normal service life of a concrete structure and also after demolition. On a geological time frame, the cement in hardened concrete will bind approximately the same amount of CO_2 as was originally liberated by the calcination of its raw materials (mainly limestone) in the cement kiln.

However, the impact that concrete carbonation has in the assessment of overall CO_2 emissions from cement manufacture is generally overlooked, due to the difficulty in estimating its rate. Depending on the concrete composition, the type of concrete structure, and the environment to which the concrete is exposed, total carbonation will take place over years to millennia. Therefore it is necessary to analyze the factors affecting the rate of carbonation. This is difficult to do in a precise manner, and the environmental benefit of this effect is still open to debate. However, a recent Nordic study point to that concrete recycling, in which the concrete is crushed, unexpectedly may lead to significant CO_2 uptake [27–30]. The significance of these results is still controversial and is under discussion.

The Nordic study points to an opportunity to improve the environmental performance of concrete over its life cycle by enhancing carbonation when this has no negative durability effects. Most effectively, promoting concrete recycling and

Fig. 5. LRT Train Station (Calgary, Canada): 24 thin-shelled Ductal®-FO canopies (architects: CPV Group Architects & Engineers Ltd; photo: Courtesy ARR Medialibrary Lafarge).

adapting recycling practices for optimal CO_2 uptake would have a positive environmental benefit.

8. Using concrete to save energy

8.1. Thermal properties of concrete buildings

From a life-cycle perspective, the energy consumption and resulting CO_2 emissions from the operation of buildings are much larger than the energy consumed and CO_2 emitted during production of the building materials. It has been calculated [31] that the energy consumption needed to produce a typical reinforced concrete office or residential building is 500MJ per m^3 space. Over a 50-year lifespan, however, 15,000MJ per m^3 space will be used for heating and electricity consumption. In other words, only 3% of the total energy consumed during the life of the building comes from the concrete and other building materials used in its construction.

Contrary to general beliefs, there is no significant difference between the embodied energy consumption for different building materials. For instance, Adalberth [32] compared steel, timber and concrete alternatives for Swedish multi-family residential buildings. It was found that the production required around 1000kW h/m^2. Half of this was associated with the structural frame, but no consistent relationship with the type of frame material was found.

Concrete has a high thermal conductivity, 1.8W/m K, compared to other building materials such as brick, 0.6W/m K, and timber, 0.14W/m K. This result in a poor intrinsic insulating ability, so care must be taken to avoid thermal bridges to the outside of the building. But the high heat capacity of concrete also enables it to buffer and utilize a large part of the free heat gains, such as solar radiation and heat from occupants and office equipment, provided that the building is designed with this in mind. Correct design for daily thermal cycles can result in greatly reduced energy consumption for heating and cooling as well as an improved thermal comfort. Another positive aspect of concrete buildings is a high degree of air-tightness, which also is attractive from an overall energy standpoint.

Comparative calculations have been conducted on a theoretical building with a simple geometry to clarify the difference in energy performance between heavy and lightweight buildings [33]. Five different computer models were applied, three based on a simplified gain utilization-factor method, one general dynamic program and one with both computation methods in parallel. All five programs gave similar results. In the case of a standard window orientation in the dwelling the “light” building consumes 2 to 9% or (1.5 to 6kW h/m^2 year) more energy than the “heavy” building. For the office building the difference ranges from 7 to 15% but is always in favor of heavy buildings. The difference increases when more windows are oriented towards the south. The difference in cooling energy is more pronounced than the difference in heating energy, being up to 20% for the dwelling and 25% for the office.

To confirm the relevance of these theoretical calculations, real buildings in different climates were analyzed, with their specific operating conditions. The results showed good agreement with the computer models. For intermittent heating, (as in the UK/Irish case), the difference in energy consumption between heavy and light structures was insignificant, but under a constant heating regime heavy buildings performed better. The gain by use of intermittent heating is dependent on the drop of indoor temperature. With increased insulation, tightness and thermal mass this drop is reduced. Furthermore, high-energy sources are required for a quick rise in temperature.

8.2. Using the thermal properties of concrete to save energy

The energy advantage of concrete may be used to achieve very significant energy savings. Several case studies on energy performance of concrete buildings in different parts of Europe and in the USA have been collected in order to highlight this [34]. The case studies provide an insight into the exploitation of

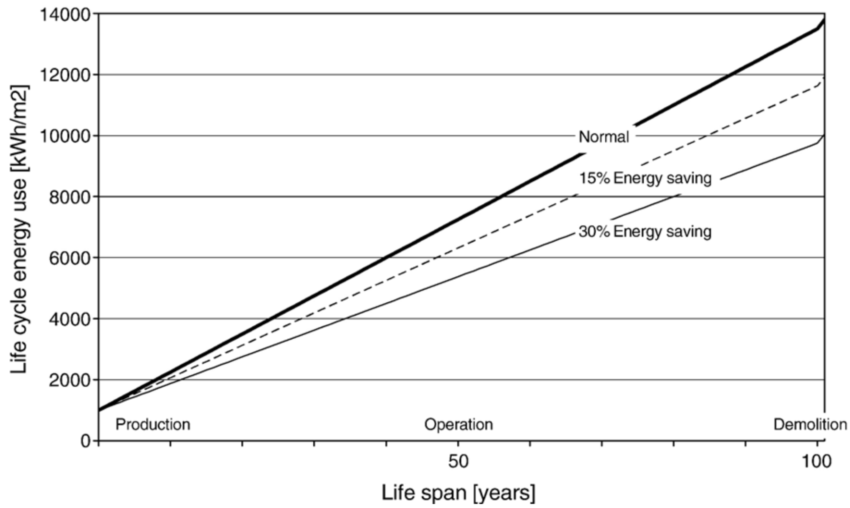

Fig. 6. CO_2 savings by utilizing the thermal properties of concrete in a multi-family residential building. After Öberg [37].

thermal mass of concrete to decrease the energy consumption of a building. Some of the examples of how to exploit the thermal mass of concrete are:

- Exposed concrete parts, e.g. coffered floor slabs, and night ventilation, e.g. under-floor ventilation, to provide free passive cooling during daytime.
- Use of free cooling in an air conditioning system by the use of hollow core concrete slabs through which air is distributed [35].
- Use of precast concrete elements as outer walls to provide very low transmission losses and excellent air-tightness.
- Use of water-cooled slabs containing pipe-work linked to the heating and cooling system.

A project with the aim of demonstrating energy efficient technologies integrated into three new low-energy European cultural buildings currently at the design stage has been implemented [36]. Some of the objectives of this project are to:

- Reduce energy consumption and CO_2 emission related to cooling by 75–80%
- Reduce heat consumption and related CO_2 emission by 35–50%
- Reduce the energy for ventilation and related CO_2 emission by 35–50%
- Use of renewable supply sources, i.e. seawater, ground water, air and solar energy.

One of the three buildings is the new Royal Danish Playhouse Theatre in Copenhagen. The proposed design uses surplus heat from the auditorium and sea water, respectively, to heat and cool the building via concrete slabs containing plastic pipe-work linked to the heating and cooling system. The circulating fluid can be cooled by free cooling or heat pumping into the seawater. In the winter, surplus heat from the auditorium can be transferred to the thermo-active slabs for storage.

8.3. Energy savings achievable

Öberg and Damtoft [33] have discussed the benefits of the thermal properties of existing concrete structures as well as the potential for further reductions if new energy saving solutions based on concrete are used. Fig. 6 shows that the lifetime energy, and hence CO_2 benefit of conventional concrete construction is close to the energy consumption for the production of the building. If concrete is used in modern energy saving building systems, the benefits can be much higher.

9. Concluding remarks

The current examples of self-compacting concrete, ultra-high performance cement-based materials and surface-active materials show how well-directed R&D can bring innovation into the traditionally conservative concrete construction technology. However, further important R&D efforts are necessary to develop concretes with a wider range of attractive properties, such being as self-cleaning, self-repairing, with better insulating properties, and even more resistant to environmental degradation and to extremes of temperature.

The scientific approach to concrete is rather recent. Concrete is a product which even today is still poorly understood. Cement and concrete science is largely interdisciplinary, often involving nano- and micro-scale phenomena. Until the introduction of modern investigation techniques, little fundamental progress had been made in elucidating relevant chemistry and physics required to control material properties and performance.

In 2004, 12 industrial partners[3] and 19 academic institutions[4] in Europe, convinced of the necessity to improve the fundamental

[3] Lafarge, Holcim, Italcementi, Heidelberg, Aalborg, VDZ, ATILH, Elkem, Sika, CEA, Oxand, Salonit. Cemex joined NANOCEM in 2006.

[4] CH/EPFL, EMPA, CZ/CTU, D/BAM, U-Kassel, DK/DTU, DTI, U-Aarhus, E/CSIC, UPC, F/EP, ESPCI, U-Dijon, S/LIT, SL/ZAG, UK/IC, U-Aberdeen, U-Leeds, U-Surrey. U-Florence joined NANOCEM in 2005.

understanding of cement-based materials, created a Research Consortium named NANOCEM. The network, involving 120 permanent academic researchers from 9 countries, has now been in existence for 3years and is exclusively funded by the industrial partners. They believe that the newly-generated pre-competitive knowledge will lead to new technological breakthroughs that will provide value to the whole cement-based construction industry. Industrial application of this knowledge will impact the overall performance and sustainability of cement-based materials and, given the huge quantities used worldwide, will have a significant influence on environmental, social and economic progress — the three pillars of sustainable development.

References

[1] http://www.wbcsd.ch.

[2] K. Humphreys, M. Mahasenan, Toward a sustainable cement industry. Sub-study 8: climate change, An Independent Study Commissioned to Battelle by World Business Council for Sustainable Development, March 2002.

[3] Impacts of Europe's changing climate, European Environment Agency Report no. 2/2004.

[4] Cembureau Internal Document, Consumption of alternative fuels used in kiln — 2003.

[5] E. Gartner, Industrially interesting approaches to low-CO_2 cements, Cem. Concr. Res. 34 (9) (2004) 1489.

[6] L. Price, E. Worrell, D. Phylipsen, Energy use and carbon dioxide emissions in energy-intensive industries in key developing countries, Proceedings of the 1999 Earth Technologies Forum, Sep. 27, 1999, Washington, DC.

[7] O. Bolland, S. Sæther, New concepts for natural gas fired power plants which simplify the recovery of carbon dioxide, Energy Convers. Manag. 33 (5–8) (1992) 467–475.

[8] C. Popescu, M. Muntean, J. Sharp, Industrial trial production of low energy belite cement, Cem. Concr. Compos. 25 (7) (2003) 689–693.

[9] L. Zhang, M. Su, Y. Wang, Development and use of sulfo- and ferro-aluminate cements in China, Adv. Cem. Res. 11 (1999) 15.

[10] K. Quillin, Performance of belite-sulfoaluminate cements, Cem. Concr. Res. 31 (9) (2001) 1341–1349.

[11] F. Glasser, L. Zhang, High-performance cement matrices based on calcium sulfoaluminate-belite compositions, Cem. Concr. Res. 31 (12) (2001) 1881–1886.

[12] G. Li, E. Gartner, French patent application 04-51586 (publication 2873366, 27/01/2006).

[13] Cement substitutes focus, Market Report by OneStone Intelligence GmbH, 2004.

[14] L. Hjorth, Development and application of high density cement based material, Philos. Trans. R. Soc. Lond., A 310 (1983) 167–173.

[15] R. Bleszynski, R.D. Hooton, M.D.A. Thomas, C.A. Rogers, Durability of ternary blend concrete with silica fume and blast-furnace slag, laboratory and outdoor exposure site studies, Mater. J. 99 (5) (2002).

[16] T. Matschei, B. Lothenbach, F.P. Glasser, The role of calcium carbonate in cement hydration, (CCR), submitted for publication.

[17] M. Ichikawa, M. Kanaya, S. Sano, Effect of triisopropanolamine on hydration and strength development of cements with different character, Paper 3iii005 in the Proceedings of the 10th ICCC, Gothenburg, Sweden, 1997.

[18] ASTM C 150 – 06, Standard Specification for Portland Cement, 2006.

[19] D.P. Bentz, Modelling the influence of limestone filler on cement hydration using CEMHYD3D, Cem. Concr. Compos. 28 (2) (2006) 124–129.

[20] J. Baron, C. Douvre, Technical and economic aspects of the use of limestone addition in cements, World Cem. 18 (3) (April 1987).

[21] XP P 15-319, French Standard for Sulphate Resisting Cement, 1995.

[22] K. Yamada, S. Hoshino, H. Hirao, H. Yamashita, Hydration analysis of blast furnace slag blended cement by a XRD–Rietveld method, Presented at the 10th ECI Conference on Advances in Cement and Concrete, Davos, Switzerland, July 2006.

[23] J.S. Damtoft, M. Glavind, C. Munch-Petersen, Danish Centre for Green Concrete, supplementary papers, Third CANMET/ACI International Symposium, Sustainable Development of Cement and Concrete, September 2001, pp. 401–418.

[24] K. Tølløse, Environmental Screening of Concrete Bridge (in Danish), Center for Ressourcebesparende Betonkonstruktioner, 2002 32 pp., May be downloaded from http://www.gronbeton.dk.

[25] http://www.voscc.dk.

[26] B. Aarup, CRC — a special fibre reinforced high performance concrete, Presented at the International Symposium, Advances in Concrete through Science and Engineering, Organized by the Center for Advanced Cement Based Materials and Rilem, Northwestern University, Illinois, March 21–24, 2004.

[27] B. Lagerblad, Carbon Dioxide Uptake During Concrete Life Cycle, State of the Art, Swedish Cement and Concrete Research Institute — CBI, Stockholm ISBN 91-976070-0-2, 2005, http://www.cbi.se.

[28] G. Jonsson, O.H. Wallevik, Information on the Use of Concrete in Denmark, Sweden, Norway and Iceland, Icelandic Building Research Institute, Reykjavik ISBN 9979-9174-7-4, 2005, http://www.ibri.is.

[29] C.J. Engelsen, J. Mehus, C. Pade, Carbon Dioxide Uptake in Demolished and Crushed Concrete, Norwegian Building Research Institute, Oslo ISBN 82-536-0900-0, 2005, http://www.byggforsk.no.

[30] K. Kjellsen, M. Guimaraes, Å. Nilsson, The CO2 Balance of Concrete in a Life Cycle Perspective, Danish Technological Institute — DTI, Copenhagen ISBN 87-7756-758-7, 2005, http://www.teknologisk.dk.

[31] K. Kuhlmann, H. Paschmann, Beitrag zur Ökologischen Positionierung von Zement und Beton, ZKG Int. 50 (1) (1997) 1–8.

[32] K. Adalberth, Energy use and environmental impact of new residential buildings, Ph.D. Thesis, University of Lund, 2000, http://www.lub.lu.se/cgi-bin/show_diss.pl/tec_343.html.

[33] M. Öberg, J.S. Damtoft, Concrete buildings in view of the EC energy performance of buildings directive. To be presented at the conference Concrete: Construction's Sustainable Option, Dundee September 2007.

[34] Cembureau TF 5.4, Collected Case Studies for Low Energy Buildings, 2006.

[35] R. Bunn, Termodeck the thermal flywheel, Build. Serv. J. 5 (1991).

[36] http://www.cowiprojects.com/ecoculture.

[37] M. Öberg, Integrated life cycle design — application to Swedish concrete multi-dwelling buildings, Lund University, Division of Building Materials, Report TVBM-3103, Lund, Sweden, 2005, p. 117.