Danish Experiences with a Decade of Green Concrete


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1. Background and scope

Since the early 1990ies the DTI has been involved in several national and international R&D projects on environmentally friendly concrete production. These activities have resulted in a high level of know-how and a large degree of awareness in the cement and concrete industry towards increased sustainability. One reason for this trend is found in the fact that the R&D activities concerning durability and quality of concrete peaked in the early 1990ies with the construction of the Great Belt tunnel/bridge and the Øresund tunnel/bridge being carried out in 1992～1998. These major infrastructure projects still set the standard for concrete specifications in the Nordic countries.

Instead of carrying on developing high quality concrete for durable civil structures the concrete and cement industry started to focus on environmental issues. The focus was partly initiated by increased demands from the authorities with respect to:

(1) Land-fill taxes, taxes on waste water and tax on imported aggregates, etc.
(2) Reduced greenhouse gas emissions according to the Kyoto protocol (especially a concern for the Danish cement producer).

This means that the Danish activities on the subject have been firmly founded on a specific need and active participation from the cement and concrete industry. Furthermore, the Danish Road Directorate has contributed with structures to be used as full-scale experiments in order to obtain valuable experience.

The scope of this article is to give an overview of the results obtained in Denmark, in Scandinavia and in Europe over the past two decades. The article focuses on concrete production and it is not meant to including all phases in a concrete structure's life. The overview is not a detailed description due to the limited space available and the reader is welcome to contact the authors for more information and further references.

Before going into a more specific description of the green concrete activities a brief overview of the Danish concrete sector is given. The annual concrete production amounts to 10 million tonnes in 2004 (Jonsson 2005) and the estimated 2006-figure is closer to 15 million tonnes. This corresponds to about one m^3 per capita. <Fig. 1> gives the distribution on various concrete types. It is seen that ready mixed and precast concrete almost split the market in halves. The share of precast is relatively high compared with the general European picture where precast only contributes with about one third of the total production. Furthermore, the Danish ready-mix

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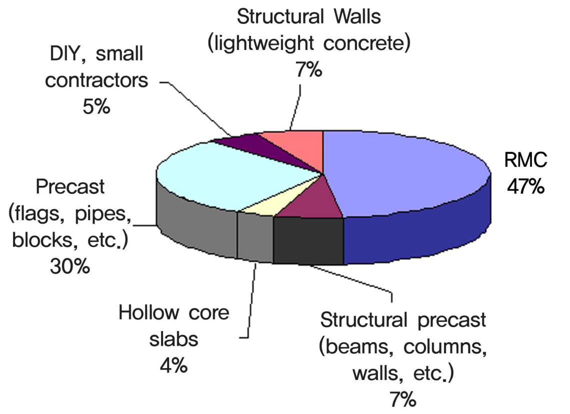

Fig. 1. Distribution of danish concrete production based on 2004 figures. Total = 10 million tonns.

concrete industry has really adopted self-compacting concrete, producing more than 1 million tonnes SCC annually, corresponding to a 25% share in 2004. The same applies for the structural precast concrete industry when it comes to production of walls, columns and beams.

It should be said that Denmark is dominated by a single cement producer, which supplies most of the domestic cement consumption. Concrete mix design in Denmark is traditionally carried out at the concrete plant by mixing pure Portland cement with mineral additions (fly ash and microsilica). There is only a very limited amount of blended cement available in Denmark and typically the blending is carried out by the concrete manufacturer at the concrete plant. Note also that GBFS is not available in Denmark and it is not considered a plausible constituent at present.

1.1 Why is green concrete interesting?

In order to avoid misunderstandings it should be made clear that the term 'green concrete' in the present article covers concrete being produced and used in an environmentally friendly manner. It should not be mixed up with fresh concrete, which is also sometimes referred to as being 'green'.

Concrete is generally considered a sustainable construction material due to its local nature and due to the fact that the raw materials are distributed in large quantities world-wide. Furthermore, concrete has eminent durability and by the end of its life span it may be recycled completely back into construction works. Furthermore, it is the only plausible material when it comes to large infrastructures. Concrete also saves the society for depositing of industrial waste materials such as fly ash from coal combustion and slag from steel production. These residual materials are mixed into concrete in large quantities which also improves performance and durability.

It is also well-known that the energy embodied in the construction materials itself becomes marginal when compared to the energy consumption during operation of a building. Therefore, green concrete is only interesting when it is combined with sustainable structural design. However, due to the large quantities of concrete being consumed it makes perfect sense to promote a more sustainable attitude in the construction industry in general. Moreover, it is estimated that the world-wide cement consumption will more than double by 2050 compared with 2005 due to increased building activities in the third world.

It is of course very optimistic to think that a small country like Denmark has any significant impact on the world-wide construction industry, but it is believed that the trend is slowly spreading both in Northern America (Malhotra 2006) and internationally through various networking activities (see e.g. ECOserve 2004 and fib 2004).

The image of concrete in the general public has been strongly influenced by the traditional assumption that concrete is a grey, uninspiring, unhealthy building material. However, in Denmark we have discovered a change in this opinion as a result of scientifically well-documented observations of the interaction of concrete buildings and the environment. These results have been disseminated and distributed to decision makers, authorities, architects and consultants to promote a more sustainable image of concrete as a building material. In the following sections some of these observations are referred.

Finally, it should be mentioned that concrete producers as well as building owners are beginning to see the benefits in green concrete both as a brand but also as a way to produce cheaper and more economic buildings-seen in the life-cycle perspective.

1.2 Green concrete R&D projects

In the mid 1990ies the activities mainly concerned specific items regarding recycling of waste water and demolished concrete and masonry back into new concrete. Furthermore, several projects were carried out in order to determine the LCA parameters for various building materials.

In 1997 a European Brite/EuRam grant was given to DTI together with several European partners under the acronym TESCOP. The three-year project focused on cleaner technologies for the concrete producer in the full life-cycle perspective and it still forms the basis for the R&D activities on the subject.

The activities in TESCOP helped to secure a Danish 4-year grant in 1998. "Centre for resource saving concrete structures" was formed with participants from the Danish concrete industry (Glavind and Munch-Petersen 2000). The working title of the project was "Green Concrete" and this brand has been used ever since for this type of concrete (Damtoft et al. 2001). The most important outcome of "Green Concrete" as documentation for environmentally friendly concrete mix designs based on high-volumes of fly ash and other industrial residual products such as:

1) Stone dust from quarry industry.
2) Ash from incinerated sewage slurry
3) Ash from incinerated bio fuel.

"Green Concrete" also participated in developing new low-CO_2 cement clinker by means of alternative fuels to the cement kiln. The green mix designs where implemented in a highway bridge, which was designed without asphalt pavement. This bridge was cast in 2002 (Nielsen and Berrig 2005).

In 2001 a Nordic network on "Concrete for the Environment" was formed to discuss and define green concrete (Glavind et al. 2006). It was financed for a 3-year period by Nordic Innovation Centre and after the funding stopped the network members still meet annually to discuss relevant topics. More information is found on www.ConcretefortheEnvironment.net.

During 2003-2006 DTI has been one of the dominating performers within the European network ECOserve, which was funded from the fifth framework under the EU. The network comprises more than 60 partners spanning from research institutions to aggregate, concrete and cement manufacturers as well as the European industry organisations. The scope was to identify the needs for the European construction industry in its endeavour towards improved sustainability. The results are reported on the ECOserve web site (ECOserve 2004).

With respect to concrete production ECOserve has helped to spread the thoughts and ideas about green concrete in a larger forum. Furthermore, a certain consensus was reached across Europe on how to define green concrete (Glavind et al. 2005).

As a spin-off from the Nordic Concrete for the Environment network a Nordic R&D-project was carried out in 2003-2005 partially financed by the Nordic Innovation Centre. This project was titled "CO_2 uptake during the concrete life-cycle" and its purpose was to quantify and document the effect of concrete carbonation on the CO_2 footprint of concrete taking into account the full life-cycle. DTI headed the 3-year project, which had participation from the Nordic cement producers and the Nordic building research institutions. More information is found on the DTI web site.

Most recently a Danish R&D-project, partly financed by the Danish environmental Protection Agency, took place in the period 2003-2006. The project was carried out by the DTI with a large group of participants from the Danish cement and concrete industry. First, an action plan was produced in 2003 where the most important environmental issues were formulated. These issues where then prioritised by the industry and the highest ranking subjects were investigated further. These subjects were:

1) Hydrocarbons in concrete slurry.
2) Application of crushed concrete for recycled aggregate in structural concrete.
3) Concrete effects on indoor climate.
4) Drying of moisture during the construction phase.
5) Leaching from concretes with industrial residual materials.
6) Effect of concrete surfaces to absorb exhaust gases with photo catalytic reaction.
7) Concrete advantages for heat storing. Effect of thermal mass on indoor thermal comfort.

All of these subjects were treated through the course of the project. Some of the important results are summarised in the following sections.

2. Reducing greenhouse gas emissions

The most direct way to cut down on CO_2 emissions from the construction sector has been by means of lowering the Portland clinker content of the cement. Here the word cement is used to describe the binder of the concrete, i.e. a mix of cement clinker and supplementary mineral additions. The most common ways to lower the clinker content is by substitution with materials such as:

(1) fly ash from coal fired power plants.
(2) ground granulated blast furnace slag from steel production.
(3) micro silica.
(4) pozzolanic materials and limestone powder.
(5) other ash types from incineration of domestic waste and bio-fuels.
(6) crushed glass waste.

Since many of these materials are residual products from other industries the concrete industry also plays an important role for society in utilising these residual materials rather than depositing them.

2.1 Green concrete with reduced clinker content

In Denmark the blending of Portland clinker with supplementary materials mainly takes place at the concrete plant whereas the trend in central and southern Europe goes towards blended cements (ECOserve 2006b) where the blending takes place at the cement plant. There are cons and pros for both approaches but basically it has more or less the same effect on the environment with regard to lower CO_2 emissions.

The application of various types of supplementary materials depends strongly on the availability and traditions in the various countries. For instance in North America the concept of environmentally friendly concrete is closely related with high volume fly ash concrete where about half of the cementitious material consist of fly ash (Malhotra 2006, Obla et al. 2003).

In Denmark fly ash and micro silica have been applied to concrete since the late 1980ies mainly for durability reasons. The existence of highly efficient plasticising admixtures also made it possible to reduce the water demand and optimise the mix design. During the "green concrete" project in 1998-2002 focus was shifted from durability towards sustainability and reduced greenhouse gas emissions. It was exploited how far it was possible to go along the line of substitution of Portland clinker with supplementary materials without impairing the performance of the concrete. The results from "green concrete" have since then been accepted as best available technology in the area and it should be applied in all concrete productions to a certain extent (ECOserve 2004, 2006a). The green concrete project provided valuable documentation for the possibilities to produce environmentally friendly structures without causing any troubles with regard to load capacity, frost/thaw resistance, chloride penetration, fire performance, etc.

It has since then been documented that high substitution rates of up to say 50% of the cement content should be possible at least for concrete meant to moderate durability classes and grades up to 20 - 30 MPa (ECOserve 2006a). Such concrete type accounts for about half of the European concrete production according to the European ready-mix concrete organisation ERMCO. Therefore, it would be a positive contribution to the concrete industry's environmental footprint if these everyday concrete were to become green concrete. However, it is recognised that there may be limits for structural precast elements where early-strength is of paramount importance to obtain a cost-effective utilisation of the production line.

The background for reduced CO_2 emissions is described frequently in the literature. The Portland clinkers emit CO_2 during production due to calcination. Furthermore, the thermal energy in the cement kiln emits CO_2 and finally the process requires electricity which also emits CO_2 indirectly. The production of one kg clinker cost 800～900 g of CO_2 (ECOserve 2006b, fib 2004), however, the figures are subject to some variation from country to country (Josa et al. 2004).

In 2003 the EU produced almost 200 million tonnes of cement and it is estimated that the associated CO_2 emission is 1.6 million tonnes (ECOserve 2006a, 2006b). If we could reduce the clinker consumption with say 30 million tonnes it would mean a CO_2 reduction of approximately 15 million tonnes annually.

Finally it is summarised that available technologies make it possible to lower the Portland clinker content in everyday concrete from a level around 220 kg/m^3 to a level just above 150 kg/m^3. This is in good correspondence with the North American experiences (Malhotra 2006). This type of green concrete should not impair the performance with respect to strength and durability but there may be challenges to be solved in the construction industry in order to obtain sufficient early-age strength.

2.2 Uptake of carbon dioxide from carbonation

Throughout the last two years a Nordic R&D project lead by the cement companies in Norway, Sweden and Denmark has investigated the effect of CO_2 uptake of concrete (Pade and Guimaraes 2006, Pommer and Pade 2005). The main objective of the project was to assess the effect of carbonation of concrete especially the part taking place after demolition and crushing (secondary life).

Models have been established for rate of carbonation, the influence of concrete grade, the influence of size grading curve. The well-known square root model for carbonation rate is applied and laboratory experiments are used to verify the models. For a thorough theoretical description of the models reference is made to Pade and Guimaraes (2006).

In theory the amount of CO_2 emitted during calcination in the cement kiln is going to be reabsorbed eventually. However, it has been chosen to allow for an upper limit of 75 % in practical calculations. This is due to the fact that the final carbonation is not obtained until after many years and the reaction rate decreases steadily. It is found that carbonation is rapidly increasing after the demolition phase due to the increased specific surface. Therefore, it is of great importance whether demolition waste is crushed down to small fractions or if it is left in large rubble piles.

Since recycling of concrete demolition waste is almost completely in Denmark (90%) the effect of carbonation is significant <Fig. 2>. It is seen that after 70 years service life the concrete is demolished and the secondary life starts with an almost

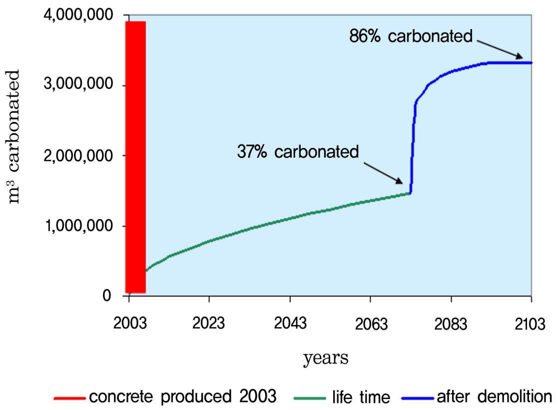

Fig. 2. Danish CO_2 uptake in 100 year perspective (Pade and Guimaraes 2006). Based on 2003 figures (Jonsson 2005). The red column indicates the total CO_2 emitted during calcination in Denmark.

momentarily increase of the CO_2 uptake. The calculations are performed for the Nordic countries under various assumptions regarding concrete grades, exposure conditions and recycling percentages.

However, the investigation is also controversial since carbonation is traditionally considered a degradation process impairing the concrete durability. Therefore, the industry has mixed emotions to promote a process having counteracting effects. One of the reasons for performing such a controversial investigation is to draw parallels to bio-materials such as timber. For wood CO_2 is absorbed throughout the growth period. After cutting down and turning into building material the degradation process starts and CO_2 is emitted until the wood is completely deteriorated or incinerated. Thus, wood first absorbs CO_2 and later on emits it again and for cement the order is reversed.

3. Green concrete production

Production of green concrete is not just a matter of choosing a plausible mix design with reduced Portland clinker content. It is also strongly associated with awareness towards the primary resources and a responsible consumption of energy. In many situations these principles are in good correspondence with a manufacturer's wishes to produce concrete with minimum production costs. However, it is also recognised that these principles are depending on local conditions which may vary significantly from plant to plant. For instance they may lead to increased investments in the plant equipment such as storage facilities and water treatment systems.

3.1 Concrete plant energy

Production of concrete requires energy like all other building materials. At the concrete plant electricity and fuel are needed to mixers, conveyors, pumps, trucks and so forth. Each concrete constituent also requires energy for quarrying and processing and since concrete is a heavy material the transportation also is an important energy consumer. In <Fig. 3> the various energy contributions are calculated into CO_2 emissions. It is obvious why cement clinker are considered to be the most important indicator to describe the environmental footprint of concrete.

The energy consumption at a concrete plant and the transportation energy are important factors that need to be controlled since it is equal to production costs. It is difficult to describe the best method to reduce energy consumption. It is very much dependent on the energy sector in each country. Electricity causes various green house gas emissions for various fuel types (ECOserve 2004). In Europe it varies from below 0.1 kg/kWh in Sweden and France (due to large share of nuclear power plants and hydro power) up to almost 1 kg/kWh in Estonia, Poland and Greece. The average in EU-25 is 0.5 kg/kWh. A concrete plant operates on electricity as well as mineral based fuels, which causes green house gas emissions around 0.1 kg/MJ. These figures all include transmission losses according to normal assumptions.

It is estimated that production of one m^3 ready-mix concrete takes about 100 MJ of energy and sometimes more than the double (fib 2004). It is very much depending on the local conditions at the location of production (e.g. climate conditions) and also on the state of the production equipment. <Fig. 4> contains an illustration of how the green house gas emissions depend on the mixture of electricity and mineral based fuels. Furthermore, the European differences in

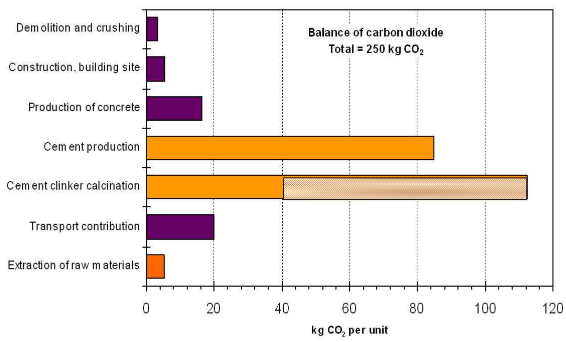

Fig. 3. CO_2 emissions distributed on the phases in a concrete life-cycle (ECOserve 2006a). The shaded column indicates the amount of uptake during life-cycle and secondary life.

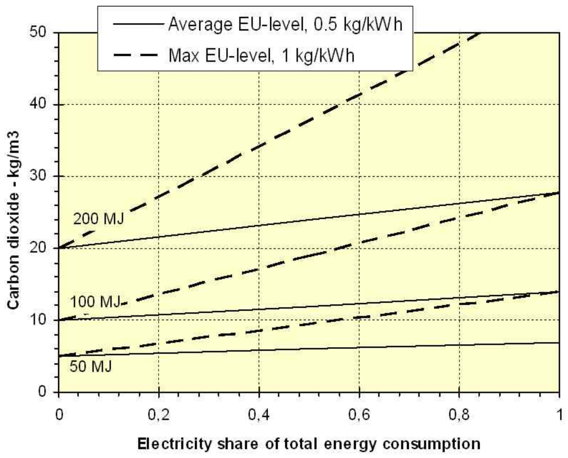

Fig. 4. CO_2 emissions in concrete plant (ECOserve 2006a). The figures indicate the energy consumption (50, 100 and 200 MJ) for the production of one m^3.

electricity production are illustrated by means of the two levels of green house gas emissions. Such curves may be useful for the concrete producer in order to evaluate the impact of a certain energy reduction.

Transportation also requires energy and thereby emits green house gases. The amounts depend on the type of vehicle. A diesel truck normally used for transportation of aggregates and concrete emits about 0.1 kg per tonne·km, while an ocean tanker emits less than one tenth of this. It is estimated that in Denmark the transport needs for one m^3 of ready-mix concrete is about 100 tonne·km mainly by truck in total but again it is very much dependent on the local conditions and especially the origin of aggregates since they constitute the major part of concrete. On average the transportation energy consumption is of the same order of magnitude as the concrete plant energy consumption.

3.2 Mass balance

A concrete manufacturer should also have concerns about the mass flow through the plant. Production of concrete involves different residual products such as water with slurry and concrete remains from washing of mixer, equipment and trucks. Also hardened concrete waste from surplus production, rejected concrete and trial batches is being accumulated at ready-mix concrete plants as well as precast factories. The amount of hardened concrete waste is typically 1～3% of the total production. For precast element factories there are also waste materials such as steel, insulation, plastic, timber and so forth. It is needles to say that these other residuals should be sorted and properly recycled.

Concrete production requires large water consumptions for mixing and washing. Since water is a valuable resource it is important that concrete production act responsible when consumption of drinking water is considered. Danish water is supplied from the underground and it is a rather expensive resource due to sewage tax. Therefore, industry is urged to save water.

The average water consumption for the production of one m^3 concrete may be around 150 litres and it is assumed that at least the same amount is needed for washing purposes. The washing water is collected in a sedimentation basin where the concrete slurry is separated and natural aggregates are reclaimed. It is normal procedure for Danish concrete plants to reuse washing water from the sedimentation basin as mixing water or as washing water. A recycling water facility requires process equipment such as pipes and pumps and it also consumes a certain amount of energy but these investments are easily paid back in terms of reduced costs for neutralisation of the waste water and sewage tax. It is also possible to collect rain water from roof tops and pavements and to direct it into production saving water further.

The slurry from the sedimentation basin is typically drained and added to the hardened concrete waste for recycling as secondary aggregates (more about hydrocarbons in slurry in the following section).

The hardened concrete may be used for recycled aggregates mainly to the road construction industry. It is estimated that about 90% of all heavy building material demolition waste is recycled in Denmark. This has great impact on the CO_2 uptake figures as it is demonstrated in section 2.2. It is also possible to include recycled aggregates into concrete production but it is not being utilised since the road construction industry tends to acquire all available construction waste at present but this may very well change if the aggregate tax structure is altered or if the market forces change. There are of course technical challenges to be dealt with in order to apply recycled aggregates into concrete production but they are not expected to be of any major significance.

4. Concrete and the environment

As for most industrial products concrete may have a certain impact on the environment. The green house gas emissions are the most dominating impact as it is described in section 2. However, there are also more direct impacts where concrete interacts with the surrounding environment. This subject has been treated in a Danish R&D project in 2003～2006 and the findings are resumed in the following.

4.1 Hydrocarbons in concrete slurry

The Danish concrete manufacturers had experienced problems with hydrocarbons in the concrete slurry being reclaimed from washing water at the ready mix or at the precast plant. The hydrocarbons mainly stem from release agents on form work and mixing equipment and trucks. It is estimated that the Danish concrete industry uses 1,000 tonnes of release agents annually. The precast industry has estimated that each m^3 of concrete elements requires about 0.5 kg of form oil (fib 2003). Other sources of hydrocarbons are hydraulic and lubrication oil and diesel fuel spillage. However, these contributions should be possible to avoid almost completely by careful work instructions and general environmental awareness at the concrete plant.

Early in the investigation it was clear that the hydrocarbons were coming from mineral based release agents, which was the preferred type in the industry. It was also realised that when the normal detection method (gas chromatography with flame ionisation detector, GC/FID) was used chemical substances such as free fatty acids and fatty acid esters are wrongly included in the total amount of hydrocarbons (Bødker 2006a). These substances originate from vegetable based form oil and they should not contribute to the hydrocarbon content. Therefore, slurry from factories using only vegetable oil may also be characterised as dangerous waste, which is wrong since vegetable oils are biodegradable and non-toxic. It was demonstrated that the analysis of slurry should be carried out by means of gas chromatography with mass spectros-copy (GC/MS) instead of GC/FID. This is a slightly more expensive test method that enables the hydrocarbons to be separated from the free fatty acids and fatty acid esters.

The amount of hydrocarbons in slurry from a hollow core production plant using mineral based release agents was found to 4.5 and 16g per kg dry matter on two samples tested at DTI. After the plant substituted mineral based with vegetable based form oils the figures dropped to 0.3 and 0.6g per kg dry matter, i.e. a significant reduction.

The Danish authorities often impose a limit of 100 mg/kg dry matter if slurry is to be treated without restrictions. However, there exists no true threshold value. <Fig. 5> shows how the hydrocarbons are reduced significantly after fully substitution from mineral based release agents to vegetable based release agents. It is seen that it takes a long period to obtain a stable level of hydrocarbons.

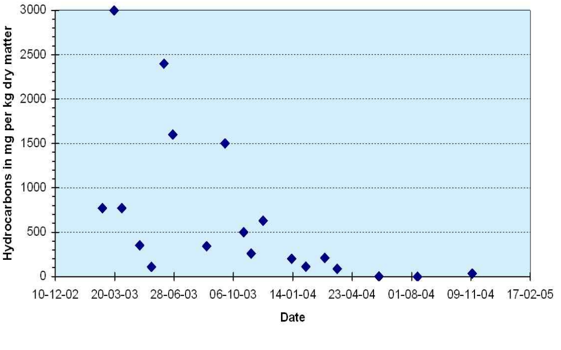

Fig. 5. Development of hydrocarbons in a precast concrete element plant (Bødker 2006a). Measured by means of GC/MS at DTI. Detection limit is 20 mg/kg.

The outcome of the investigation is a clear recommendation to the concrete manufacturers is simply to switch from mineral based release agents to vegetable based. It is also recommended to introduce a campaign amongst the employees in order to inform about the importance in being careful when handling hydraulic and lubrication oil at the production plant. It only takes a small amount of mineral oil to pollute the slurry. Finally, it is recommended that GC/MS is used instead of GS/FID to detect hydrocarbons.

The response from the industry is that such a switch is taking place and that there are no plausible technical reasons not to.

4.2 Concrete and indoor environment

There have existed several misconceptions of how concrete structures influence the indoor climate in buildings and offices. There are examples of people claiming that concrete causes asthmatic reactions. These alleged problems with indoor air quality have been investigated for typical danish concrete mix designs for indoor structures such as hollow core slabs and walls (both normal weight and lightweight concrete). Emissions from the concrete were determined experimentally at DTI to document if there are any emissions from concrete surfaces that compromise the indoor climate (Bødker 2006b).

Small test specimens were cast and placed in a climate chamber with controlled air flow (EN 13419-1 1999). Furthermore, samples of the concrete specimens were subjected to a test group of 20 people performing a sensory evaluation (odour test) during a 4-week period. The air in the climate chamber was analysed with respect to various volatile organic compounds (VOC), hydrocarbons and ammonium.

The following conclusions were drawn from the test programme (Bødker 2006b):

1) The VOC traces were practically all far below any health and safety limits. In most cases the concentrations were below the detection limit.
2) The odour tests supported this conclusion, characterising the degree of odour as moderate 2 weeks after casting to weak after 4 weeks.
3) Hydrocarbons were detected from test specimens cast against mineral based form oil (wall elements). However, the concentration decreased rapidly within a few weeks after casting to a level, which was completely harmless to the inhabitants.
4) Two concretes were tested for ammonium gases. One mix design based on pure Portland cement and one including fly ash from Danish power plants in a normal dosage. The concentration of ammonium was registered and depicted in <Fig. 6>.

Ammonium is present in the fly ash due to the smoke cleaning at the power plant. Ammonium is used as a catalyst and under special conditions there may be a risk of the ammonium concentration in the fly ash being up to several hundred mg/kg. There are examples of concrete being discarded in case of strong ammonium smell at the casting area of a precast plant. Therefore, the concrete manufacturers are very focused on this aspect. The normal concentration for fly ash is estimated to lie below 50 mg/kg under normal conditions at the power plant.

When the fly ash is mixed with water the

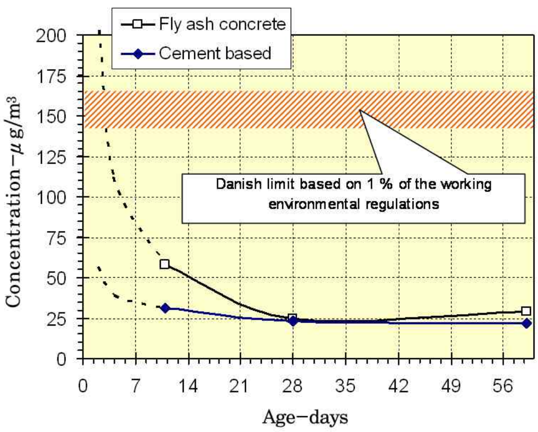

Fig. 6. Ammonium concentrations measured in climate chamber according to EN 13419-1 (Bødker 2006b). Threshold limit for working environment is 140 mg/m^3 in Denmark. Detection limit is 30 g/m^3.

ammonium dissolves and may cause an unpleasant smell in the vicinity of the concrete mixer. Under casting in confined spaced without sufficient ventilation there may be a risk for the concrete workers. However, under normal conditions the smell is hardly detectable and it is not considered to be of any concern for the working environment. It is noted that the Danish power plants are focusing on the ammonium issue, analysing samples regularly in order to detect abnormal conditions.

<Fig. 6> shows ammonium concentrations as a function of time after casting. The first measurement is after 2 days. The actual measurings have been converted into a normal room made of concrete walls and slabs. The fly ash contained a normal level of ammonium (about 60 mg/kg). Both the pure Portland cement based concrete and the one containing fly ash emitted ammonium from the start. After 3 weeks the concentration has dropped below $25\mu g/m^3$. When comparing with the Danish authorities limit for the working environment it is seen that we are way below 1% of this after a few days emission. It was also attempted to simulate the conditions with a fly ash batch where the initial ammonium content had been increased to about $200 mg/m^3$. In this case the initial concentration in the climate chamber increases but after 8 weeks the concentration is back to a level of $25\mu g/m^3$.

Based on these observations it is concluded that concrete does not contribute to an unhealthy indoor environment for the inhabitants of concrete buildings. On the contrary there are several benefits from concrete when it comes to the indoor climate:

1) Concrete thermal mass has positive influence on the thermal comfort. Due to its high density and its heat conductivity concrete structures can absorb heat and store it for later liberation. This has significant effect when overheating of a building is considered and cooling measures may be reduced improving the energy performance of the building.
2) Another advantage associated with high density is its ability to reduce noise transmittance through walls and floors.

4.3 Concrete as air cleaner

There are examples of TiO_2 being used to provide concrete with self-cleaning properties. Through photocatalytic reactions organic matter is removed when subject to UV-light (Cassar 2005). There are also examples of photocatalysts absorbing NO_x from exhaust gases. Such self-cleaning and air cleaning processes are of course very interesting to consider. For instance in terms of concrete pavements that help to lower the pollution in large cities and building facades staying clean without the need for maintenance. Danish major cities typically has a concentration of NO_2 in the order of magnitude of 40 $\mu g/m^3$ in its most trafficked streets (Bødker 2006c).

A simple verification experiment was performed at the DTI on concrete flags supplied from a precast plant. Some of the flags had a 10 mm mortar top layer with TiO_2. The TiO_2 dosage in this layer was 30% of the cement weight and the TiO_2 was a commercially available brand. Other flags were cast without any top layer for reference (Bødker 2006c). Tests were conducted 3.5 months after casting.

The concrete flags were then placed in a closed airtight steel container fitted with a UV-light source similar to sunlight. The air in the container is homogenised by means of a small ventilator. In this container the NO_2 concentration was monitored over time <Fig. 7>. Measures of both NO_x and NO_2 showed that the gas mixture consisted almost solely of the latter. It is seen that there is an insignificant effect of both the presence of TiO_2 and UV-light exposure conditions. On the contrary the effect is present even in complete darkness, which is surprising but promising <Fig. 7>.

However, it should be kept in mind that the tests are rather limited in number and that they contradict with other experiments, reporting a much more pronounced effect of the catalyst (Cassar 2005). It is

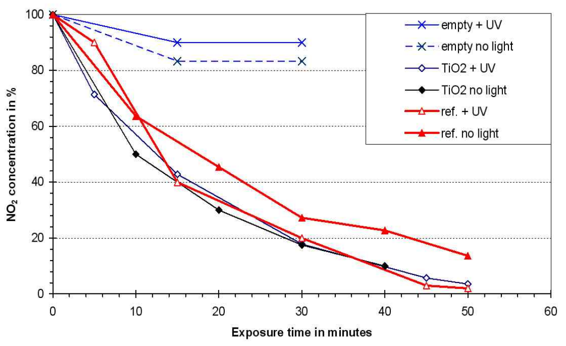

Fig. 7. NO_2 concentrations measured under various light exposures (Bødker 2006c). Initial NO_2 concentrations determined between 10 and 15 ppm.

therefore an area which needs further investigations with regard to the chemical mechanisms and the effect and influence of age and dirt and degree of soiling.

5. Conclusions

Throughout more than 10 years of research and development the Danish cement and concrete industry have worked together with the Danish Technological Institute towards a more sustainable concept for concrete production. The main results is summarised into the following statements:

(1) Concrete with reduced Portland clinker content may give better performance and at the same time it provides a better CO_2 footprint.

(2) Portland clinkers are mainly substituted with fly ash and micro silica and the substitution is say 20 % of the cementitious materials. It is believed that this substitution can be increased without impairing the performance of everyday concrete grades. This may be of great importance especially for self-compacting concrete due to its increased need for fines.

(3) The effect of carbonation on the CO_2 footprint of concrete is quantified and models to include this effect in life-cycle analyses are suggested.

(4) Guidelines for sustainable production of concrete are drawn up. Focus items are reduced energy consumption and recycling of washing water and surplus concrete production. Furthermore, it is recommended to use only vegetable based release agents.

(5) It has been documented that concrete is harmless to the indoor air quality. On the contrary it may act as an air cleaner in cities with high exhaust gas pollution.

Finally, it is recognised that green concrete concept can not stand alone. It needs to be backed up by a sustainable design concept taking into account the full life-cycle and also the aspects of energy performance of the building and maintenance. Concrete is one of the few building materials offering decades of practically maintenance-free service life but it requires proper design to meet the requirements of the users over a full life-cycle. Therefore, we still have a job to do implementing sustainable design concepts in order to serve the society.

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References

1. Bødker, J. (2006a), Hydrocarbons in concrete slurry. Danish Environmental Protection Agency, Report 17.
2. Bødker, J. (2006b), *Emissions from concrete to the indoor environment*. Danish Environmental Protection Agency, Report 18.
3. Bødker, J. (2006c), Photocatalytic absorbtion of NO_x on concrete. Danish Environmental Protection Agency, Report 32.
4. Cassar, L., "Sunlight as concrete protection-Cementitious materials and photocatalysis", BFT International, Bauverlag BV GmbH. Vol. 71, No. 1, 2005, pp. 10～16.
5. Damtoft, J.S., Glavind, M. and Munch-Petersen, C., "Danish Centre for Green Concrete". *Proceedings of 3rd*

CANMET/ACI International Symposium on Sustainable Development and Concrete Technology, Malhotra, M. ed., San Francisco, 2001. 9.
6. ECOserve, *Baseline report for the aggregate and concrete industries in Europe*, Cluster 3 Report. Downloadable from www.Eco-serve.net, 2004.
7. ECOserve (2006a), *Best available concept for sustainable aggregate and concrete production*, Cluster 3 report. Downloadable from www.Eco-serve.net.
8. ECOserve (2006b), Blended cements-the sustainable solution for the cement and concrete industry in Europe, Cluster 2 report, Downloadable from www.Eco-serve.net.
9. EN 13419-1, Building products-Determination of the emission of volatile organic compounds, CEN, 1999.
10. Environmental issues in prefabrication, Federation International du Beton, fib Bulletin No. 21, 2003.
11. Environmental design, Federation International du Beton, fib Bulletin No. 28, 2004.
12. Glavind, M., Mathiasen, D. and Nielsen, C.V., "Sustainable concrete structures-a win-win situation for industry and society". *Achieving sustainability in Construction*, Thomas Telford Publishing, 2005, pp. 1 ~ 14.
13. Glavind, M., Mehus, J., Gudmundsson, G. and Fidjestøl, P., "Concrete-the sustainable construction material". *Concrete International*, ACI, Vol. 28, No. 5, 2006, pp. 41 ~ 44.
14. Glavind, M., and Munch-Petersen, C., "Green concrete in Denmark", *Structural Concrete*, Federation International du Beton, Vol. 1, No. 1, 2000, pp. 19 ~ 25.
15. Jonsson, G., Information on the use of concrete in Denmark, *Sweden*, Norway and Iceland, Icelandic Building Research Institute, 2005.
16. Josa, A., Aguado, A., Heino, A., Byars, E. and Cardim, A., "Comparative analysis of available life cycle inventories of cement in the EU", *Cement and Concrete Research*, Vol. 34, No. 8, 2004, pp. 1313 ~ 1330.
17. Malhotra, M., "Reducing CO_2 emissions", *Concrete International*, ACI, Vol. 28, No. 9, 2009, pp. 42 ~ 45.
18. Nielsen, C.V., "Environmental performance of danish precast factory", *Proceedings of 18th BIBM International Congress*, bfbn, Amsterdam.
19. Nielsen, C.V. and Berrig, A., "Temperature calculations during hardening", *Concrete International*, ACI, Vol. 27, No. 2, 2005, pp. 73 ~ 76.
20. Obla, K., Hill, R.L. and Martin, R.S., "HVFA-Concrete-an industry perspective", *Concrete International*, ACI, Vol. 25, No. 8, 2008, pp. 29 ~ 34.
21. Pade, C. and Guimaraes, M., "The CO_2 uptake of concrete in a 100 years perspective", Submitted for publication in *Cement and Concrete Research*, 2006.
22. Pommer, K. and Pade, C., "*Guidelines-Uptake of carbon dioxide in the life cycle inventory of concrete*", Danish Technological Institute, 2005.

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