ABSTRACT. Cement and concrete have an important role to play in enabling Denmark to fulfil its obligation to reduce the CO_2 emission by 21 % of the 1990 level before 2012 as agreed at the Kyoto and the Bonn Conference. It is also possible to use residual products – thus reducing the need to landfill these materials – while still maintaining a high concrete quality.

The entire life cycle of a concrete structure has to be taken into account to obtain environmental improvements. This highlights the need for a united business effort. This has been achieved by the creation of the Centre for Green Concrete. New technology is developed for all phases in the design, construction and use of concrete structures. Results so far indicate that the environmental goals set up will be achieved.

Keywords: Green concrete, $CO_{2,}$ residual products, Life cycle inventory, Durability, Mechanical properties, Workmanship, Bridge.

Mette Glavind is head of section for Materials and structures at the Concrete Centre at Danish Technological Institute. The section deals with research/development and consultancy for concrete. Mette Glavind received her M.Sc. in 1989 in civil engineering and her Ph.D. in 1992 from the Technical University of Denmark. Since 1992 she has been employed at Danish Technological Institute and been involved in research/development related to amongst others fibre reinforced concrete, optimization of concrete mix design and green concrete.

Christian Munch-Petersen is employed in Construction Management for large infrastructure projects; especially focused on selection of concrete materials, workmanship and repair. Christian Munch-Petersen is chairman for the Danish Concrete Association and member of the board of ACI-Copenhagen Chapter. His expertise is gathered during two decades by direct involvement in the very large projects of Storebælt (the largest spanning bridge on the Western Hemisphere) and Øresund (including the Worlds largest immersed tunnel for both train and higway). He is a member of several national and international standardisation committees.

INTRODUCTION

BACKGROUND FOR GREEN CONCRETE

Concrete and the environment

The concrete industry is faced with new challenges. Legislation, environmental levies, voluntary agreements and demands from the customers mean that the industry must continuously improve its environmental performance. There is often an economic benefit from these activities. Costs savings may be achieved by e.g. saving cement, reducing the energy consumption, saving water, improving the working environment or even reducing the amount of environmental levies paid.

By volume alone, concrete is the world's most important construction material. Furthermore, concrete has a significant economic importance. Concrete is an artificial rock composed of aggregates, water and cement. The raw materials are readily available. By reinforcing the concrete with steel, a uniquely strong and durable material is obtained which in terms of shape and size can be designed almost at will by architects and civil engineers. Annually, approximately 5 km^3 is used for construction worldwide. In Denmark alone, 8,000,000 t of concrete is produced annually. This corresponds to 1.5 t of concrete per capita annually.

Concrete is an environmentally friendly material and the overall impact on the environment per ton of concrete is limited [1]. The CO_2 emission related to concrete production, i.e. primarily from cement production, is between 0.1 and 0.2 t per tonne of produced concrete. However, the absolute figures for the environmental impact are quite significant, due to the large amounts of cement and concrete produced. From cement and concrete production a total quantity of CO_2 of 800,000-1,600,000 t per year is emitted. This corresponds to approximately 2 % of Denmark's total CO_2 emission.

The solution to this environmental problem is not to replace concrete with other materials but to reduce the environmental impact of concrete and cement. Again, even a small reduction of the environmental impact per tonne of concrete will result in large environmental benefits because of the vast amount of concrete produced today.

Concrete is also interesting in relation to other environmental problems than those related to CO_2 emission. It may be possible to use residual products from other industries in the concrete production while still maintaining a high concrete quality. During the last few decades, society has become aware of the problems associated with landfilling of residual products, and limits, restrictions and taxes have been imposed. As several residual products have properties suited for concrete production, there is a large potential to increase material recycling by investigating the possible use of these for concrete production.

The environment has been a serious issue in the Danish concrete industry for several years. Matters addressed include environmental reading, environmental management, environmentally correct design and life cycle inventories, see e.g. [2], [3] and [4]. There is considerable knowledge in Denmark about how to produce concrete with reduced environmental impact, the so-called green concrete. However, the challenge is to develop a new technology for that type of concrete and this is the background for the Danish Centre for Green Concrete.

Life Cycle Inventories as a Tool to Guide the Green Concrete Development

When assessing the environmental compatibility of concrete it is essential to consider all life cycle phases. This means that it is no longer sufficient to address environmental issues associated with the production of the individual building materials. The environmental impacts associated with the use and disposal of a structure has to be considered. The energy consumption and CO_2 emission associated with the use of a structure are generally in the same magnitude or larger than the energy consumption and CO_2 emission associated with production of the individual construction materials. Use, maintenance and durability are therefore important aspects, which have to be considered. A European project has demonstrated the use of life cycle inventories, i.e. a listing of all environmental impacts in the life cycle, as a tool to guide the green concrete development, [5].

A result of this is new qualifications are needed for the actors in the concrete construction sector. It is not enough for the individual producers to know the environmental performance of their own materials. Knowledge of the total environmental performance from cradle to grave is needed. Furthermore, a united business effort involving the relevant actors is needed in order to achieve real environmental improvements.

With this background it is important to reduce the environmental impact of the materials themselves not least because environmental improvement is a competitive parameter. Building materials with reduced environmental impact are often less expensive to produce. Furthermore, environmental performance is increasingly taken into account in tenders. The material with the best environmental parameters it the most likely to be used.

The life cycle inventory results of concrete-based products show that the concrete mixture proportions – primarily the type and amount of cement - have a major influence on the total life cycle impact [5]. Combined with reducing the environmental impact of the constituent materials, improved mixture design may result in concrete with significantly improved performance.

CENTRE FOR GREEN CONCRETE – A UNITED BUSINESS EFFORT

The goal of the Centre for Green Concrete is to reduce the environmental impact of concrete. To enable this, new technology is developed. The technology considers all phases of a concrete constructions´s life cycle, i.e. structural design, specification, manufacturing and maintenance, and it includes all aspects of performance, i.e.

- mechanical properties (strength, shrinkage, creep, static behaviour etc.)
- fire resistance (spalling, heat transfer etc.)
- workmanship (workability, strength development, curing etc.)
- durability (corrosion protection, frost, new deterioration mechanisms etc.)
- thermodynamic properties (input to the other properties)
- environmental aspects (CO_2-emission, energy, recycling etc.)

The Danish Centre for Green Concrete was established on July 1,1998 with the aim of creating a united business effort towards reducing the environmental impact of concrete. Participants are: The Concrete Centre, Danish Technological Institute; Aalborg Portland A/S;

Unicon Beton A/S; COWI; Højgaard & Schultz a/s; AB Sydsten; the Department of Buildings and Energy, Technical University of Denmark; The Department of Building Design, Building Energy and Energy Planning, Aalborg University; and The Danish Road Directorate.

The Ministry of Trade and Industry funds the centre through a so-called centre contract. The partners form a "centre without walls" with a formalised management structure and an agreed work programme, but with the work carried out by the partners at their own facilities. The centre has a budget of approximately DKK 22 million – one of the largest Danish concrete development projects ever. The duration of the centre contract is 4 years.

The industrial partners and the Danish Road Directorate finance their own contribution. The contribution from the Danish Technological Institute is 25 % financed by the institute itself, whilst the Ministry of Trade and Industry supplies 75 % of the contribution. The universities are 100 % financed by the Ministry of Trade and Industry. The Ministry of Trade and Industry supplies an amount equivalent to the industrial partner's contribution.

The centre has defined a number of alternative environmental requirements with which green concrete structures must comply:

- CO_2 emissions shall be reduced by at least 30 %.
- At least 20 % of the concrete shall be residual products used as aggregate.
- Use of concrete industry's own residual products.
- Use of new types of residual products, previously landfilled or disposed of in other ways.
- CO_2-neutral, waste-derived fuels shall substitute fossil fuels in the cement production by at least 10 %.

In addition to the environmental goals there are a number of environmental intentions. Most important are: To avoid the use of materials which contain substances on the Danish Environmental Protection Agency's list of unwanted materials, not to reduce the recycling ability of green concrete compared with conventional concrete and not to increase the content of hazardous substances in the wastewater from concrete production compared with wastewater from production of existing concrete types.

The technical goals for the centre are to obtain the same technical properties for the green concretes compared to conventional concretes – or to determine in what way the properties differ. The compressive strength goals for the concretes are:

- Aggressive environmental class (outdoor, horizontal): 28-day strength > 35 MPa and 56-day strength > 85 % of a reference concrete
- Passive environmental class (indoor): 28-day strength > 12 MPa and 56-days strength > 85 % of a reference concrete.

The compressive strength goals for the 28-day strength corresponds to the minimum requirements in the Danish standard for concrete materials, DS 481, (7). A reference concrete is defined as conventional concrete produced in large amounts.

FOUR WAYS TO PRODUCE GREEN CONCRETE

Four ways to produce green concrete are being investigated, see Figure 1:

1. To increase the use of conventional residual products, i.e. fly ash.
2. To use residual products from the concrete industry, i.e. stone dust (from crushing of aggregate) and concrete slurry (from washing of mixers and other equipment).
3. To use residual products from other industries not traditionally used in concrete, i.e. fly ash from bio fuels and sewage sludge incineration ash (from sewage treatment plants).
4. To use new types of cement with reduced environmental impact.

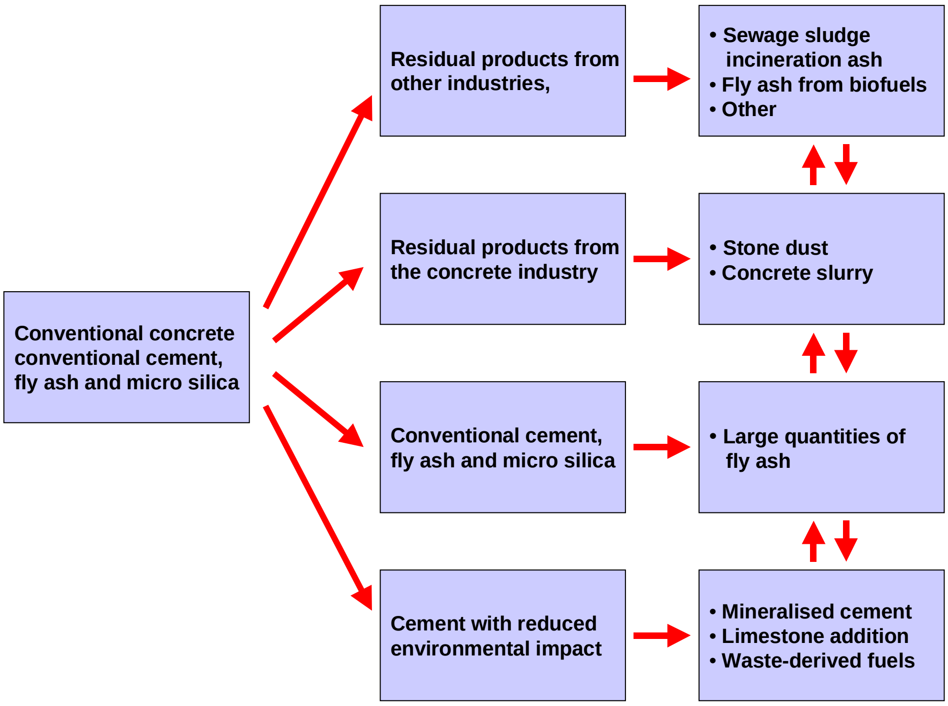

Figure 1. Overview – concrete developments in the Centre for Green Concrete.
New types of cement and binders can be utilised in combination with the residual products.

Altogether 14 concrete types have been tested in a basic green concrete test programme for workability, changes in workability after 30 min., air-content, compressive strength development, E-modulus, heat development, homogeneity, water separation, setting time, density and pumpability. Furthermore, frost testing, chloride penetration and an air void analysis have been carried out for the concretes in the aggressive environmental class. Furthermore, the water/cement ratio, water/binder ratio and the chloride content have been calculated from the mixing report of the precise mixture proportions and from the chloride content in the different raw materials

From the results of the basic green concrete test programme the most promising green concrete types have been selected and have been exposed to more advanced testing for mechanical properties (E-modulus, creep properties, splitting tensile strength), workmanship (loss of workability, sensitivity to vibration, determination of resting time before finishing etc.) and durability (chloride resistance, frost resistance etc.). The concrete types selected are shown in Table 1 and Table 2 for concrete in passive and aggressive environmental class respectively. It can be seen that the four principles of producing green concrete are combined in order to achieve the most environmentally friendly concrete.

Table 1 Mix design characteristics for concretes in passive environmental class
SSIA: Sewage sludge incineration ash, FA: Fly ash, SF: Silica fume,
SPT: Superplasticizer, KD: Kiln dust

	PR Reference	P2 50 % FA + 10 % KD	P3 17 % SSIA	P5 Concrete slurry	P6 100 % stone dust	P7 30 % FA from bio fuels
Cement, kg/m^3	143	90	137	141	267	191
FA, $kg/\ m^3$	51	128	15	52	-	-
SF, kg/m^3	10	14	10	10	-	-
SPT, kg/m^3	-	1.1	3.2	-	1.8	1.9
Equiv. w/c	0.73	0.66	0.78	0.77	0.72	0.69

Table 2 Mix design characteristics for concretes in an aggressive environmental class
SSIA: Sewage sludge incineration ash, FA: Fly ash, SM: Silica fume,
SPT: Superplasticizer, CREP: Cement with reduced environmental impact

	AR Reference	A0 CREP	A1 40 % FA + CREP	A3 10 % SSIA + CREP	A5 Concrete slurry	A6 50 % stone dust
Cement, kg/m^3	288	287	189	277	398	397
FA, $kg/\ m^3$	34	32	137	-	-	-
SF, kg/m^3	17	17	18	17	-	-
SPT, kg/m^3	-	-	3.4	3.2	4.0	6.8
Equiv. w/c	0.45	0.47	0.46	0.45	0.38	0.37

The reference concretes, that are representative of typical Danish concretes, contain both fly ash and silica fume. Both of these materials are residual products from another production, i.e. production of electricity and production of silicon steel respectively. In short, Portland cement is used to obtain early strength, silica fume to give 28-day strength and fly ash to give pumpability. The reason for the relatively high cement content in concrete P6, P7, A5 and A6 is that they are typical Swedish concrete types. There is no tradition in Sweden for using fly ash and silica.

Table 3 shows the chemical composition of the sewage sludge incineration ash and of the fly ash from bio fuels. Further, the chemical composition of fly ash from coal combustion is shown for comparison.

Table 3 Chemical composition of sewage sludge incineration ash (from Lynette Fællesskabet) and of fly ash from coal combustion (Danaske type B1). DM: Dry-matter.

Chemical analysis	**Unit**	**Sewage sludge incineration ash**	**Fly ash from bio-fuels**	**Fly ash from coal combustion**
CaO	% DM	16,85	18,1	2,78
SiO_2	% DM	28,44	29,4	59,74
Fe_2O_3	% DM	13,89	4,23	7,57
Al_2O_3	% DM	7,90	14,7	21,31
TiO_2	% DM	1,61	8,15	0,98
P_2O_5	% DM	19,62	0,424	0,34
MgO	% DM	3,07	2,84	1,35
Chloride	% DM	0,098	1,5	0,004
SO_3	% DM	1,85	-	0,65
K_2O-total	% DM	2,54	2,91	0,65
Na_2O total	% DM	1,36	2,81	0,52
Na_2O-equiv. total	% DM	3,03	-	1,84
Cr	mg/kg	136	1050	137
Zn	mg/kg	2810	6920	181
Pb	mg/kg	534	1010	34
Cu	mg/kg	971	916	77
Ni	mg/kg	109	138	100
V	mg/kg	61	55,7	268
Co	mg/kg	49	<4,99	32
Mn	mg/kg	566	-	313
Tl	mg/kg	<20	-	<20
Cd	mg/kg	<10	31,3	<10
As	mg/kg	<30	189	<30
Hg	mg/kg	0,4	1,47	0,2
Loss on ignition	% DM	3,04	4,6	3,37

In terms of overall chemical composition, sewage sludge incineration ash and fly ash from bio fuels differ from normal fly ash in having a higher CaO content and lower SiO_2 and Al_2O_3 contents. A higher P_2O_5 content can be seen for the sewage sludge incineration ash, which may result in a retardation of the cement reaction. Fly ash from bio fuels has a significant higher chloride content, which is the reason for only investigating it for addition in concrete for passive environmental class.

The kiln dust is a residual product from cement production with a high alkali content, which is used in order to promote the fly ash reaction.

In order to achieve a satisfactory workability, i.e. a slump of approximately 100 mm, it was necessary to add superplasticizer to most of the green concretes. This must be seen in relation to the reference concretes that contain no superplasticizer.

When calculating the equivalent water-cement ratio an activity factor of 0.5 for fly ash and 2.0 for silica fume has been used. The activity factor for sewage sludge incineration ash and for fly ash from bio fuels has been set to the same as for conventional fly ash, i.e. 0.5. This will have to be verified.

In Table 4 and Table 5 an evaluation of the environmental goals and intentions and the compressive strength goals is shown for the concretes from Table 1 and Table 2. All the concretes fulfil one or more of the environmental goals. For the concretes fulfilling the goal regarding reduction of the CO_2 emission compared to the reference concrete this reduction is for e.g. the concrete with 50 % and 40 % of fly ash in passive environmental class and aggressive environmental class respectively, higher than the 30 % reduction goal.

Table 4 Evaluation of environmental goals and intentions and compressive strength goals for concretes in a passive environmental class
SSIA: Sewage sludge incineration ash, FA: Fly ash, KD: Kiln dust

Passive environmental class					
Name	P2 50 % FA + 10 % KD	P3 17 % SSIA	P5 Concrete slurry	P6 100 % stone dust	P7 30 % FA from bio fuels
Environmental goal					
• CO_2	37% √	-	-	-	30% √
• Residual product as aggregate	-	-	-	42% √	-
• Own residual product	-	-	√	√	-
• New type of residual product	-	√	-	-	√
• Waste-derived fuels	√	√	√	√	√
Environmental intentions	√	Wastewater quality? (Zn, V)	Wastewater quality? (Zn, Pb, Cu, P_2O_5)	√	Wastewater quality? Recycling? (chloride)
Compressive strength					
28-day, MPa	26 √	21 √	23 √	29 √	28 √
56-day, MPa (% of reference concrete)	34 (100) √	31 (93) √	27 (80) √	33 (97) √	32 (94) √

Table 5 Evaluation of environmental goals and intentions and compressive strength goals for concretes in an aggressive environmental class
SSIA: Sewage sludge incineration ash, FA: Fly ash, CREP: Cement with reduced environmental impact

Aggressive environmental class					
Name	A0 CREP	A1 40 % FA + CREP	A3 10 % SSIA + CREP	A5 Concrete slurry	A6 50 % stone dust
Environmental goal					
• CO_2	27% (√)	52 % √	29 % (√)	-	-
• Residual product as aggregate	-	-	-	-	20 % √

Aggressive environmental class					
Name	A0 CREP	A1 40 % FA + CREP	A3 10 % SSIA + CREP	A5 Concrete slurry	A6 50 % stone dust
• Own residual product	-	-	-	√	√
• New type of residual product	-	-	√	-	√
• Waste-derived fuels	√	√	√	√	√
Environmental intentions	√	√	Wastewater quality? (Zn, Pb, Cu, P_2O_5)	√	√
Compressive strength					
28-day, MPa	51 √	58 √	58 √	64 √	62 √
56-day MPa, (% of reference concrete)	58 √ (112)	61 √ (117)	68 √ (130)	68 √ (130)	63 √ (121)

On the other hand, for other concrete types where the reduction in CO_2 emission is lower or at the same level as the goal reduced CO_2 emission must be obtained from activities in the other life cycle phases. This applies for i.e. concrete with 30 % fly ash from bio fuels of powder and concrete with cement with reduced environmental impact,

Avoiding the use of materials that contain substances mentioned in the list of unwanted materials prepared by the Danish Environmental Protection Agency has been fulfilled by substituting the superplasticizer normally used at the participating concrete plants with a superplasticizer without free formaldehyde.

In general, there are no problems in achieving the compressive strength goals. For the concrete types in the aggressive environmental class the 56-day compressive strengths are much higher than the reference strength, that means that the environmental impact can be further reduced while still maintaining the same strengths as for the reference concretes. The only exception is the concrete with concrete slurry in passive environmental class where the 56-day compressive strength is only 80 % of the compressive strength of the reference concrete. However, it is known from the basic green concrete test programme that the goal for the 56-day compressive strength can be achieved.

EVALUATION OF GREEN CONCRETE TYPES

Results from investigation of mechanical properties of a green concrete show that these do not differ significantly from the mechanical properties of the reference concretes.

Results from investigation of workmanship show that some of the green concretes may lose workability more quickly than the reference concretes, be more adhesive or require a longer resting time before finishing can begin. It is expected that some of these problems can be solved by optimising the type and amount of chemical admixtures.

Nothing in the frost resistance test results indicates that normal test procedure and accept criteria can not be used when testing green concrete. However, the results have made it clear that it is difficult to put forth strict limits for the chloride diffusion coefficient at an early concrete age (e.g. 28 days after casting), because green changes in the mix design may influence the development in time of the chloride diffusivity, [8].

In the following an evaluation is given of each concrete type with focus on detected problems and significant deviations from the reference concrete and whether the concrete is selected for testing in the finial, expanded testing programme in the Centre. This testing programme includes amongst others testing of fire properties (mechanical properties under fire and risk of explosive spalling), mechanical properties (temperature expansion coefficient, moisture movements, reinforcement anchorage and constructive investigations such as shear and bending load carrying capacity of beams and instability of columns) and workmanship (plastic shrinkage etc). Furthermore, some of the tests from the basic and the advanced testing programmes are repeated such as frost resistance and chloride resistance.

P2 – Concrete with High Volumes of Fly Ash and Kiln Dust for Passive Environmental Class

The kiln dust contains higher amounts of Zn, V, Pb, Cu and P_2O_5 as compared to Portland cements and fly ash from coal combustion and one should be aware of the problems associated with an increased content of these substances in the wastewater from the concrete production plant. This will have to be investigated. However if the wastewater is being recycled – as it is at many concrete production plants – the problem may not exist.

The only bad result of P2 is related to workmanship. P2 has a tendency to bleed, which makes it difficult to finish and therefore might result in a not so good surface finish of the hardened concrete compared to the reference concrete. However, it is believed that this problem can be overcome with modifications of the mix design with chemical admixtures.

P2 will not be exposed to the final, expanded testing programme. The concrete can be implemented in Danish concrete production when it has been documented that the added kiln dust does not promote reinforcement corrosion or deteriorates other concrete properties according to the Danish Concrete Materials Standard, DS481, [7].

P3 – Concrete with Sewage Sludge Incineration Ash

The sewage sludge incineration ash also contains higher amounts of Zn, V, Pb, Cu and P_2O_5 as compared to Portland cements and fly ash from coal combustion and the same comments as for the P2 concrete regarding waste water are valid.

P3 has in general a lower compressive strength compared to the reference concrete even though the compressive strength goals are fulfilled. It is remarkable that the aggressive concrete with sewage sludge incineration ash has not lower compressive strengths, see the text for A3. Further testing have confirmed these observations, however no clear conclusion has been drawn about the reason for the different effect of the sewage sludge incineration ash in passive and aggressive environmental class.

In the mechanical testing programme it was observed that creep fracture occurred at 80 % of the maximum compressive strength whereas all other concrete types in the passive environmental class obtained creep fracture at a compressive strength higher than 90 % of the maximum compressive strength.

Another significant difference between P3 and the reference concrete is that the time before finishing can be started is double as long (9,4 hours compared to 5,1 hours).

P3 will be exposed to the final, expanded testing programme.

P5 – Concrete with Concrete Slurry for Passive Environmental Class

As already mentioned P5 can not fulfil the compressive strength goal at 56 days, however it is known from the basic test programme that it is possible to produce concrete with concrete slurry where the 56-days strength goal can be fulfilled.

The workmanship testing programme showed that the workability disappeared quicker than for the reference concrete (at 1,5 maturity hour). However, the time before finishing could be started was only 70 % of the time needed for the reference concrete.

P5 will be exposed to the final, expanded testing programme.

P6 – Concrete with Stone Dust for Passive Environmental Class

There are no significant deviations of P6 compared to the reference concrete.

P6 will not be exposed to the final, expanded testing programme. P6 is in accordance with the Danish concrete materials standard, DS481, [7]. However, it is recommended that investigations related to mechanical properties (moisture movements, reinforcement anchorage, shear load bearing capacity) be carried out before the concrete is implemented in concrete production.

P7 – Concrete with Fly Ash from Bio Fuels for Passive Environmental Class

P7 has an increased chloride content compared to concrete containing conventional fly ash. It makes it necessary to investigate both the chloride content in the wastewater at the concrete production plant and the consequences of recycling the concrete.

The only technical remark to P7 is that the time before finishing can be initiated is a little longer than for the reference concrete (6,4 hours compared to 5,1 hours) and that the concrete is sticky.

P7 will be exposed to the final, expanded testing programme.

A0 - Concrete with Cement with Reduced Environmental Impact for Aggressive Environmental Class

There are no significant deviations between A0 and the reference concrete. A0 will be exposed to the final, expanded testing programme.

A1 – Concrete with High Volumes of Fly Ash for Aggressive Environmental Class

With regard to durability, results indicate that A1 has problems with obtaining a satisfactory frost resistance. This is probably because the air void system was too coarse Furthermore, increased carbonation is observed in relation to the reference concrete. On the other hand the chloride resistance is good.

A1 will be exposed to the final, expanded testing programme. Adjustments of the mix to obtain satisfactory frost resistance are carried out.

A3 – Concrete with Sewage Sludge Incineration Ash for Aggressive Environmental Class

The same comments regarding wastewater as for P3, which also contains sewage sludge incineration ash, are valid.

A3 has limited frost resistance but also good resistance to chloride penetration. Because of the high P_2O_5 content and the low strengths in the passive environmental class it can not be rejected that a new durability problem or deterioration problem might occur. This is currently being investigated.

A3 will be exposed to the final, expanded testing programme.

A5 – Concrete with Concrete Slurry for Aggressive Environmental Class

Like it is the case for P 5, the workability is lost quickly. Furthermore, separation is observed at finishing.

Results indicate slightly reduced resistance to chloride penetration. This may not be due to the addition of the concrete slurry but could be because the concrete type (Swedish, i.e. high cement content and no fly ash and silica fume, in general, has a lower resistance to chloride penetration than a concrete with pozzolans such as the Danish reference concrete.

A5 will not be exposed to the final, expanded testing programme. A5 is not legal according to the Danish concrete materials standard DS481, [7] because the dry matter content in the concrete slurry is 10 % and the maximum content is 2 %. Alternatively, the dry matter can be considered as an additive where it as for the kiln dust has to be documented that it does not promote reinforcement corrosion or deteriorates other concrete properties. According to the Swedish standard BBK94 concrete slurry can be used when it is documented that the setting is not significantly changed and that the compressive strength is minimum 90 % of a reference concrete with tap water. This can not be documented in the centre for green concrete because no Swedish reference concrete is used.

A6 – Concrete with stone dust for aggressive environmental class

Comments related to durability are similar to the durability comments for A5. A6 will be exposed to the final, expanded testing programme.

DEMONSTRATION BRIDGE

The results will be implemented in a pilot project involving the dimensioning and construction of a road bridge. Currently the bridge for a highway in Jutland, Denmark is being designed. The different concrete types for aggressive environmental class will be tested in the bridge, i.e. A0 with cement with reduced environmental impact, A1 with high volumes of fly ash and A3 with sewage sludge incineration ash (though not for load carrying construction elements due to the fear for new, unknown durability problem) and AR, the aggressive reference concrete. In addition to using green concrete types, green structural solutions will be used. Such a green structural solution is e.g. to avoid a moisture membrane. Other examples of green structural solutions can be seen in the chapter Case study – Life cycle screening.

An environmental screening of the bridge will be carried out.

On the basis of the results of the testing programmes in the Centre and on the experience from the demonstration bridge, a Danish Road Directorate special concrete specification for green concrete structures will be prepared.

CASE STUDY – LIFE CYCLE SCREENING

As an example of the use of life cycle inventories, a case study has been performed for a column made of three different design principles compared to at reference principle, see table 6.

Table 6 Details for columns made from three different design principles (A, B and C) and a reference (column R)

Specification	**Column R**	**Column A**	**Column B**	**Column C**
Concrete material	Ref. Concrete, AR	Green concrete, A1	Green concrete, A1	Green concrete, A1
Geometry	h=6 m, d=0.7 m	h=6 m, d=0.74 m	h=6 m, d=0.7 m	H=6 m, d=0.7 m
Concrete cover	50 mm	50 mm	30 mm	30 mm
Steel	Black	Black	Stainless	Black
Construction	Traditional, in-situ	Traditional, in-situ	Traditional, in-situ	Cladding with stain-less steel that replaces traditional shuttering, in-situ

Specification	Column R	Column A	Column B	Column C
Maintenance and repair	Cleaning/washing every year Surface treatment every 3. Year Repair after 25 years	Cleaning/washing every year Surface treatment every 3. Year Repair after 25 years	None	None
Lifetime	50 years	50 years	75 years	75 years

The objective of the screening was to identify significant resource consumption and environmental loads of traditional concrete/design compared to green concrete/design occurring during the entire service life, this includes the environmentally viewed most critical maintenance/repair stage.

The performed lifecycle screenings quantify material usage (consumption of concrete) as well as CO_2-emissions generated at the involved stages during the lifecycle of the columns. In order to limit the analysis, the environmental screening comprises only those issues where the environmental impacts of the green concrete columns differ from those of the traditional one.

The results of the environmental screening for the 3 green concrete columns (A, B, C) and the traditional concrete column (R) is presented in Table 7 with to the CO_2-emission and in Table 8 with regard to the consumption of concrete.

Table 7 CO_2-emissions for different designs of concrete columns

Design solution	Column R	Column A	Column B	Column C
kg CO_2 per year	281	144	88	82

Table 8 Consumption of concrete for different designs of concrete columns

Design solution	Column R	Column A	Column B	Column C
kg concrete for construction	5897	5897	5266	5266
kg concrete for maintenance/repair	775	775	0	0
kg concrete, total	6672	6672	5266	5266

The comparison demonstrates that column B (stainless steel reinforcement) and column C (stainless steel cladding) present the most environmental-friendly design solutions both with regard to the CO_2-emissions and the consumption of concrete.

In figure 2 the sources for the CO_2-emission is shown for the four column types. It can be seen that concrete raw materials and repair are the main sources to the CO_2-emission and that the use of green concrete significantly reduces the CO_2-emissions. Reinforcement and shuttering become significantly CO_2-sources for solution B and C, respectively, but the total CO_2-emission is still low compared to the reference and solution A.

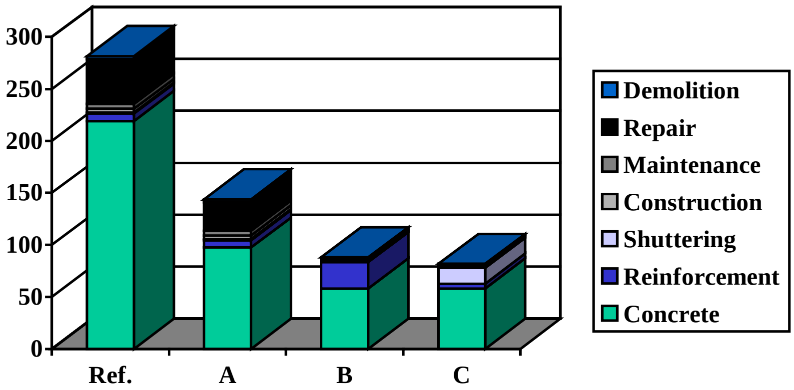

Figure 2 Sources of CO_2-emission for four types of columns

An even more environmental-friendly solution is if the selected concrete at column C would be substituted by a more environmental-friendly (greener) concrete type, e.g. a concrete suitable for passive environment, provided that the steel cladding assures the long-term protection of the reinforced concrete. It should be noted that the results stated above are strongly related to the assumed service life expectations as defined in Table 4.

CONCLUSION

The Danish Centre for Green Concrete is a united business effort demonstrating a life cycle approach of reducing environmental impact of concrete structures.

The results obtained by the Danish Centre for Green Concrete points to ways of significantly reducing the environmental impact of concrete by using “greener cements”, by substituting cement with residual products and by green design methods. The results so far indicate that the environmental goals set up for the Centre will be achieved.

Cement and concrete have an important role to play in enabling Denmark to fulfil its obligation to reduce the CO_2 emission by 21 % of the 1990 level before 2012 as agreed at the Kyoto conference. It is also possible to use residual products – thus reducing the need to landfill these materials – while still maintaining a high concrete quality.

REFERENCES

[1] Jochen, Stark and Wicht, Bernd, “Environmental compatibility of concrete”, Betonwerk+Fertigteil-Technik, 3, 2000, pp. 50-62.

[2] Glavind, M., Damtoft, J.S. and Röttig, S., “Cleaner technology solutions in the life cycle of concrete products”, accepted for publication in Proceedings from Three-Day

International Symposium on Sustainable Development and Concrete Technology, San Fransisco, U.S.A. 2001.
[3] "Håndbog i miljøriktig projektering, (in Danish, Handbook on environmentally correct design)", Volume 1 and 2, BPS Centre DTI, 1997.
[4] "Industry Analysis, Concrete – Cleaner Technology in Concrete Production", Environmental Project 350, Ministry of Environment and Energy, Denmark, Danish Environmental Protection Agency, 1997. 55 pp.
[5] Olsen, G.S. and Glavind, M., "Guidance in Environmental Management according to ISO 14001", Danish Technological Institute, Concrete Centre, 1999, 48 pp.
[6] Glavind, M. and Munch-Petersen, C., "Green concrete in Denmark", Structural Concrete 2000, No. 1, March, pp. 19-25.
[7] DS 481, "Concrete – Materials", 1st ed. (in Danish: "Beton – Materialer"), Danish Standards Association, Copenhagen 1999.
[8] Jepsen, M.T, Mathiesen, D., Munch-Petersen, C. and Bager, D.: "Durability of Ressource Saving "Green" Types of concrete", Accepted for publication in Proceedings from Fib-Symposion Concrete and Environment, Berlin, October 2001.