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'Green' concrete in Denmark

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Cement and concrete may have an important role to play in enabling Denmark to fulfil its obligation, agreed at the Kyoto conference, to reduce the total CO_2 emission by 21% compared to the 1990 level before 2012. This is because approximately 2% of Denmark's total CO_2 emission stems from cement and concrete production. There is considerable knowledge about how to produce concrete with a reduced environmental impact. However, it is not known to a sufficient degree – neither in Denmark nor internationally – on what scale, and with what technology, this 'green' concrete can be applied in practice in buildings and structures. For instance, there is not enough information about how the properties of green concrete, such as compressive strength, durability, fire performance, casting and execution, hardening and curing, are affected by the measures to reduce the environmental impact of concrete. This paper gives an overview of the present state of affairs in Denmark of concrete types that have reduced environmental impact. There is a description of among other things the possibilities of using green concrete within the existing standards and specifications. A special focus will be on a large Danish centre running from 1998 to 2002, involving leading universities, institutes, building owners, contractors, consultancies, and cement and concrete manufacturers. The potential environmental benefit to society of being able to build with green concrete is huge. It is realistic to assume that technology, which can halve the CO_2 emission related to concrete production, can be developed. This will potentially reduce Denmark's total CO_2 emissions by 0.5% and will contribute significantly to achieving the targets set up at the Kyoto Conference. Furthermore, green concrete might solve some of the societies problems with the use of inorganic, residual products which should otherwise be deposited.

The role of cement and concrete in relation to the environment

Concrete is the world's most important construction material. In Denmark alone, 8 000 000 t of concrete is produced annually. For the production of this amount of concrete, 1 400 000 t of cement is used. This corresponds to 1.5 t of concrete per capita annually.

Concrete is an environmentally friendly material, and the impact on the environment per tonne of concrete produced is small. The CO_2 emission related to concrete production, inclusive of cement production, is between 0.1 and 0.2 t per tonne of produced concrete. However, since the total amount of concrete produced is so vast 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 600 000–1 200 000 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 substitute concrete for 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.

The potential environmental benefit to society of being able to build with green concrete is huge. It is realistic to assume that technology can be developed, which can halve the CO_2 emission related to concrete production. With the large consumption of concrete this will potentially reduce Denmark's total CO_2 emission by 0.5–1%.

Concrete can also be the solution to environmental problems other 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 deposit problems connected with residual products, and demands, restrictions and taxes have been imposed. And as it is known that several residual products have properties suited for concrete production, there is a large potential in investigating the possible use of these for concrete production. Well-known residual products such as silica fume and fly ash may be mentioned.

Background to the establishment of The Danish Centre for Resource Saving Concrete Structures

Today, it is already possible to produce and cast very green concrete (see also the section 'State of affairs in Denmark for concrete with reduced environmental impact', below). Even a 'super green' type of concrete without cement but with, for example, 300 kg of fly ash instead can be produced and cast without any changes in the production equipment. But this concrete will not

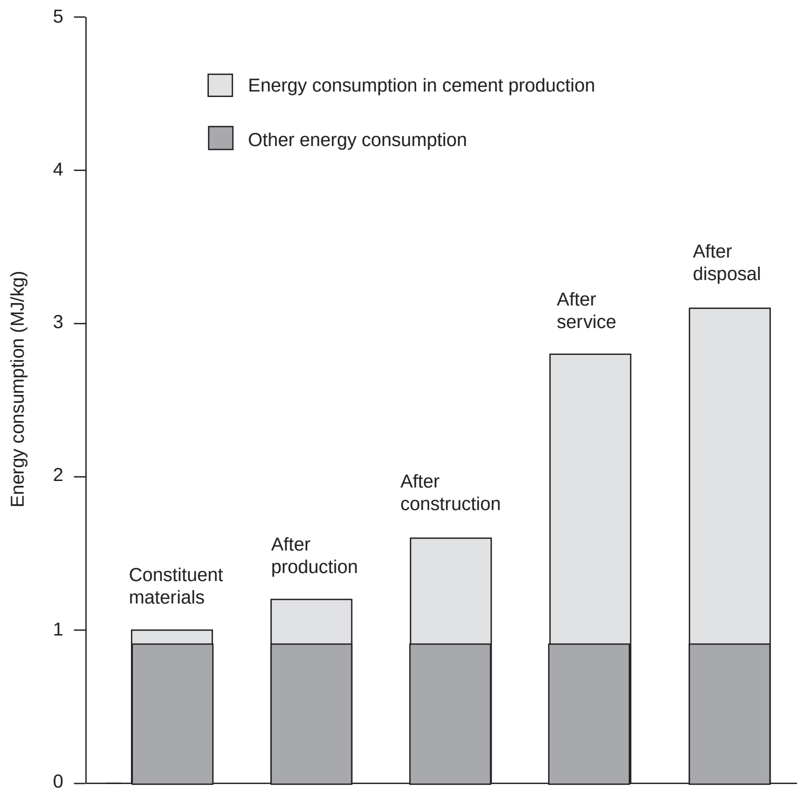


Fig. 1 Edge beam: total energy consumption through all the life cycle phases[1]

develop strength, and it will of course not be durable. Therefore, the challenge is to develop a new technology for this type of concrete. The technology must include all aspects of performance, including:

- 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 above)
- environmental impact (how green is the new concrete?).

Meeting these requirements is not an easy task, and all must be reached at the same time if constructors are to be tempted to prescribe green concrete. A constructor would not normally prescribe green concrete if the performance is lower than normal – for example, a reduced service life.

The new technology will therefore need to develop concretes with all properties as near normal as possible, and if any properties are not normal and are required to be dealt with in a new and special way, this must be clearly stated.

This is the objective of the Danish Centre for Resource Saving Concrete Structures.

State of affairs in Denmark for concrete with reduced environmental impact

There is considerable knowledge in Denmark about how to produce concrete with lower environmental impact, the so-called green concrete.

The concrete industry in Denmark has considerable experience in dealing with environmental aspects. It realized at an early stage that it is a good idea to be transparent with regard to documenting environmental aspects and working on improving the environment, rather than being forced to deal with environmental

Table 1 Typical Danish concrete mix design

Constituent	P	M	A	EA
Cement (C)	150	200	290	300
Fly ash (FA)	50	60	50	30
Microsilica (MS)	10	15	15	15
Water (W)	135	135	140	135
W/(C + 0.5 × FA + 2.0 × MS)	0.69	0.52	0.41	0.39

Table 2 Requirements for the contents of fly ash and microsilica according to the Danish concrete materials standard (%)[4]

	Passive (indoors)	Moderate (vertical outdoors)	Aggressive (horizontal outdoors)	Extra-aggressive (splash zones, etc.)
Maximum content of FA + MS as C + FA + MS	No requirements	35	25	25
Maximum content of MS as C + FA + MS	No requirements	10	10	10

C, cement; FA, fly ash; MS, microsilica

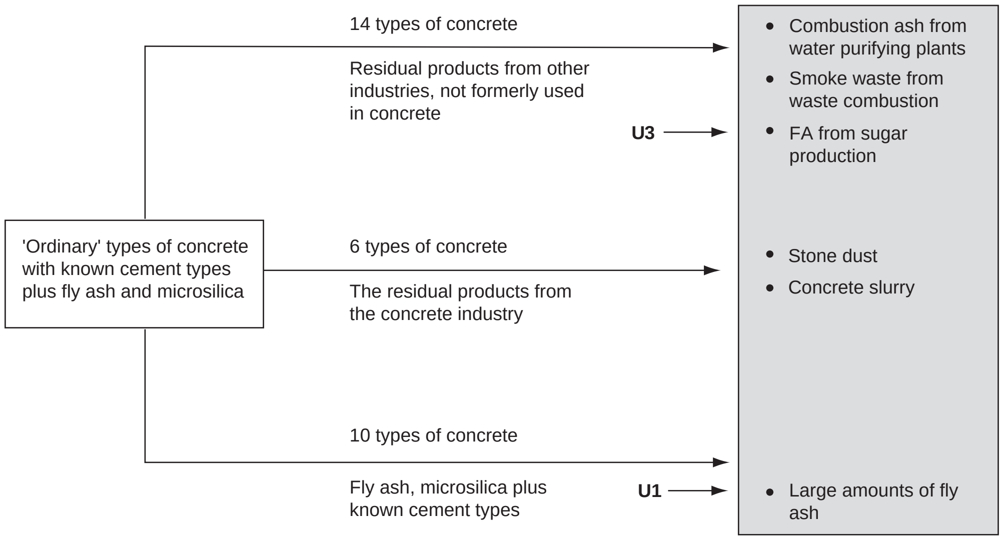


Fig. 2 Overview – concrete developments in the Centre for Resource Saving Concrete Structures. New types of cement and binders (U2) can be utilized in U1 as well as in U3

aspects due to demands from authorities, customers and economic effects such as imposed taxes, etc.

Furthermore, some companies in the Danish concrete industry have recognized that reductions in production costs often go hand in hand with reductions in environmental impacts. Thus, environmental aspects are not only interesting from an ideological point of view but also from an economic aspect.

The knowledge and experience in Denmark of how to produce concrete with lower environmental impact can be divided into two groups, concrete mix design and cement and concrete production:

- Concrete mix design:
  - using cement with reduced environmental impact
  - minimizing cement content
  - substituting cement with pozzolanic materials such as fly ash and microsilica.
- Cement and concrete production:
  - environmental management.

Concrete mix design

The type and amount of cement has a major influence on the environmental properties of a concrete. An example of this is shown in Figure 1, where the energy consumption in megajoules per kilogram of a concrete edge beam through all its life cycle phases is illustrated. The energy consumption of cement production make up more than 90% of the total energy consumption of all constituent materials and approximately one-third of the total life cycle energy consumption.

By selecting a cement type with reduced environmental impact, and by minimizing the amount of cement, the environmental properties of the concrete are drastically changed. This must, however, be done while still taking account of the technical requirements of the concrete for the type and amount of cement. Denmark’s cement manufacturer Aalborg Portland prioritizes development of cements with reduced environmental impact.[2]

One method of minimizing the cement content in a concrete mix is by using packing calculations to determine the optimum composition of the aggregate. A high level of aggregate packing reduces the cavities between the aggregates, and thereby the need for cement paste. This results in better concrete properties and a better environmental profile, due to a smaller amount of cement. When having determined the packing, the density and the grain size distribution of each aggregate material experimentally, it is possible to calculate the packing of any combination of aggregates using the DTI Concrete Centre’s computer program.[3]

Another way of minimizing the cement content in concrete is to substitute parts of the cement with other pozzolanic materials. In Denmark it is common to produce concrete with fly ash and/or microsilica. Both of these materials are residual products (from production of electricity and production of silicon, respectively) and both have a pozzolanic effect. Thus, a material with large environmental impact, i.e. the cement, is substituted with materials with reduced environmental impact.

It is important to realize that concrete in Denmark because of the widespread use of microsilica and fly ash, is already very green. Almost all the concrete produced in Denmark today contains one or more of these products, and most concrete contains all three. In short, cement is used to give early strength, microsilica to give 28 day strength and fly ash to give pumpability.

In Table 1 typical Danish mix design is stated for concrete for class P (passive, i.e. indoors), M (moderate, i.e. vertical outdoors), A (aggressive, i.e. horizontal outdoors) and EA (extra-aggressive, i.e. splash zones, etc.).

The restrictions on adding fly ash and microsilica laid down in the new Danish concrete materials standard[4] are as shown in Table 2.

Cement and concrete production

It is also possible to reduce the environmental impact of concrete by reducing the environmental impact of cement and concrete production. Danish cement manufacturers undertake many activities concerned with the reduction of environmental impact.[2]

As regards concrete production, experience with the reduction of primarily water consumption, energy consumption and waste production is available. Even though the contribution of concrete production to the environmental profile of concrete is minor, it does contribute, and is important – environmentally and economically – to the single concrete producer.

In a large Danish project, ‘Environmental Management in the Building and Construction Industry’, a guide to environmental reading, environmental management based on the ISO 14001

Table 3 Development project U1: concrete with minimal clinker content (passive environmental class)

	Control	PV1 (FA50MS0)	PV2 (FA50MS6)	PV3 (FA60MS6)	PV4 (FA70MS6)
Cement content (kg)	148	120	101	85	61
Content of fly ash (%)	24	50	50	60	70
Content of micro silica (%)	6	–	6	6	6
Content of special filler (%)	–	–	–	–	–
CO_2 reduction (%)	–	18	31	41	57
Equivalent water/cement ratio (–)	0.71	0.78	0.80	0.70	0.74

Table 4 Development project U1: concrete with minimal clinker content (aggressive environmental class)

	Control	AV1 (FA9MS5)	AV2 (FA18MS5)	AV3 (FA30MS5)	AV4 (FA40MS5)	AV5 (FA40MS5)
Cement content (kg)	309	274	272	219	190	189
Content of fly ash (%)	9	9	18	30	40	40
Content of micro silica (%)	5	5	5	5	5	5
CO_2 reduction (%)	0	33	33	46	54	54
Equivalent water/cement ratio (–)	0.37	0.421	0.42	0.42	0.42	0.42

standard, and a ‘get-started’ guide, are under preparation. The guide will help concrete producers reduce the environmental impact resulting from their production methods.[5–7]

The Danish Centre for Resource Saving Concrete Structures

The Centre for Resource Saving Concrete Structures (in short, the Centre for Green Concrete) is a cooperative venture between the Danish Technological Institute, Danish universities and private companies, representing all sectors related to concrete: aggregate, cement and concrete producers, a contractor, a consultant and a concrete user. The centre is funded by the Ministry of Trade and Industry through a so-called centre contract, in which the partners form a ‘centre without walls’ with a formalized management structure and an agreed work programme, but with the work carried out by the individual partners at their own facilities.

The centre has a budget of approximately DK K 22 million (approximately US $ 3.5 million) – one of the largest Danish concrete development projects ever. The industrial partners and the Danish Road Directorate finance their own contribution. The contribution of the Danish Technological Institute is 25% financed by the institute itself while the Ministry of Trade and Industry supplies the Danish Technological Institute and the universities with an amount equal to the investment made by the industrial partners. The centre was started 1 July 1998, and will run for 4 years.

The goal of the project is to reduce the environmental impact of concrete. This will be achieved through the development of new resource-saving binding systems, increased recycling and energy recovery of materials. To enable this, new technology will be developed for all phases in the design, construction and use of concrete structures. This applies to structural design, specification, manufacturing, operation and maintenance.

The centre participants are The Concrete Centre (Danish Technological Institute), Aalborg Portland A/S, Unicon Beton A/S, COWI Rådgivende Ingeniører AS, 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.

Environmental goals

The centre’s preliminary environmental goals which green concrete has to fulfil are as follows:

- Reduce CO_2 emissions by 21%. This is in accordance with the Kyoto obligation as described previously.
- Increase the use of inorganic residual products from industries other than the concrete industry by approximately 20%.
- Reduce the use of fossil fuels by increasing the use of waste-derived fuels in the cement industry. The reduction percentage has not yet been determined.
- Avoid the use of materials from the list of unwanted materials prepared by the Danish Environmental Protection Agency. These materials can, for instance, be form oil and additives.
- The recycling capacity of the green concrete must not be reduced compared to existing concrete types.
- The production of green concrete must not decrease the recycling applicability of discharged water.
- The production and use of green concrete must not worsen the working environment.

Three different ways to produce green concrete

In the various development projects in the centre, green concrete is examined in three different ways:[8]

- U1: concrete with minimal clinker content.
- U2: concrete with green types of cements and binders.
- U3: concrete with inorganic, residual products.

Figure 2 gives an overview of the green concrete types investigated. U1 mainly deals with high-volume fly ash concrete, and U2 deals with the cement development. U3 deals with inorganic residual products from the concrete industry and other industries, and is described more thoroughly in the next section.

Evaluation of inorganic residual products

Information about numerous inorganic residual products regarding suppliers, amounts, particle size distribution, chemical composition, etc., has been collected.

Fig. 3 Strength development for high-volume fly ash concrete in the passive environmental class (adjusted to the same water content; w/c, water/cement ratio)

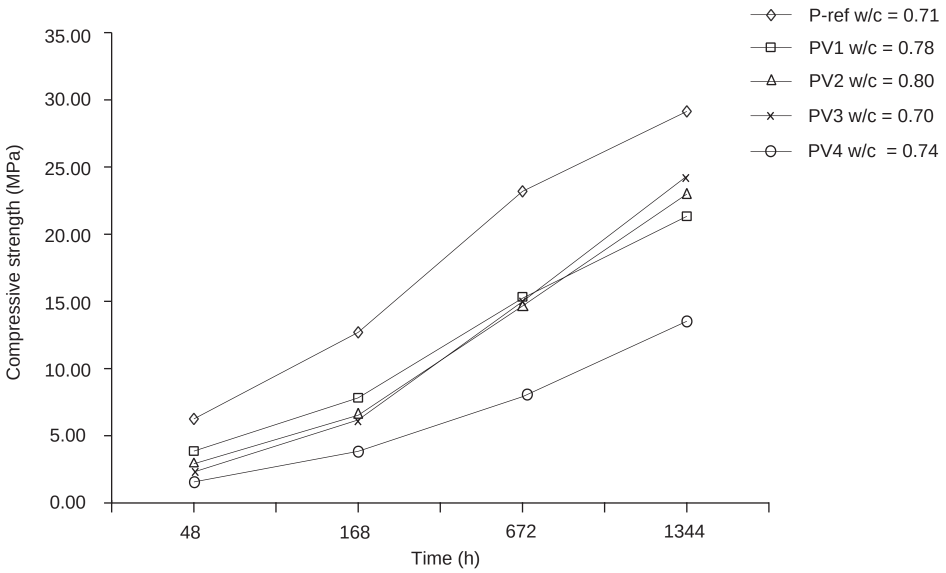
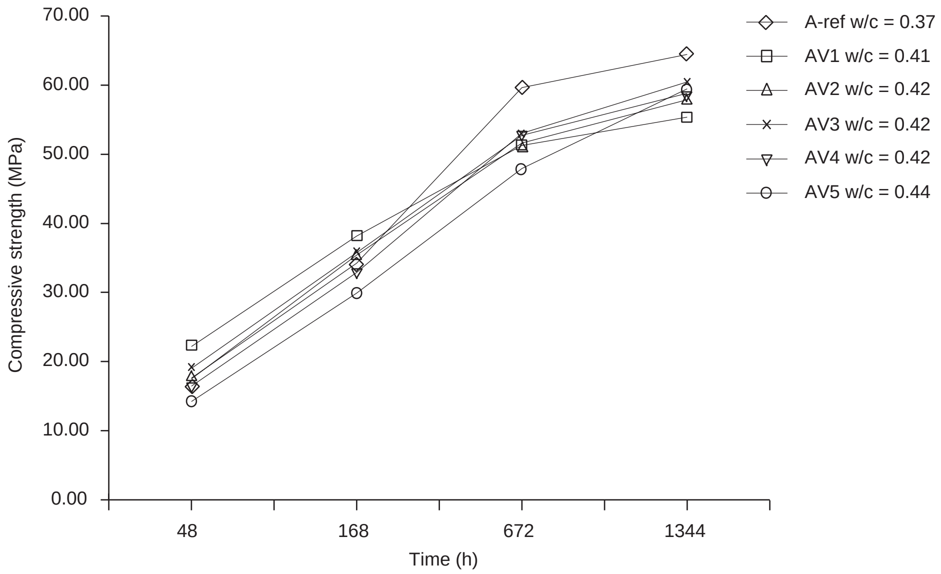


Fig. 4 Strength development for high-volume fly ash concrete in the aggressive environmental class (adjusted to the same water content; w/c, water/cement ratio)



The materials, which have been judged as useable for concrete production and selected for further development, are shown in Figure 2. The judgement was based on an evaluation concerning both concrete technology and environmental aspects.

Inorganic residual products from the concrete industry (e.g. stone dust and concrete slurry) and products which pose a huge waste problem to society and which are in political focus (e.g. combustion ash from water-purifying plants, smoke waste from waste combustion and fly ash from sugar production) have been given highest priority.

It should be mentioned that recycled concrete aggregate has been excluded because almost all of the concrete waste is used for road construction as it is perfectly suitable for this purpose. It is therefore not necessary to apply other resource saving measures to concrete aggregate.

Stone dust. Stone dust is a residual product from the crushing of aggregates. It is an inert material with a particle size between that of cement and sand particles. Stone dust is expected to substitute part of the sand.

Concrete slurry. Concrete slurry is a residual product from concrete production, i.e. washing mixers and other equipment. The concrete slurry is can be either a dry or wet substance, and can be recycled either as a dry powder or with water. In the case of recycling of the dry material, it is necessary to process it to powder. The concrete slurry can have some pozzolanic effect, and might therefore be used as a substitute for part of the cement or for other types of pozzolanic materials such as fly ash.

Combustion ash from water-purifying plants. This type of combustion ash has the same particle size and shape as fly ash particles. The content of heavy metals in the slurry is expected to be approximately at the same level as for fly ash. The slurry can have some pozzolanic effect, and might therefore be used as a substitute for part of the cement or for other types of pozzolanic materials such as fly ash.

Smoke waste from waste combustion. This smoke waste can have some pozzolanic effect. The content of heavy metals is significantly higher than that of ordinary fly ash. Furthermore, the content of chlorides, fluorides and suzlfates can result in negative effects in connection with reinforcement corrosion, retardation and possible thaumasite reactions. Further processing will be necessary before its use in concrete.

Fly ash from sugar production. The fly ash from this source is not expected be very different from ordinary fly ash.

The green concrete test programme

All the above mentioned green concrete types will be tested for workability, changes in workability after 30 min, air content, compressive strength development, E modules, heat development, homogeneity, water separation, setting, density and pumpability. Furthermore, the water/cement ratio, water/binder ratio and the chloride content will need to be calculated.

Following on from these tests the most promising green concrete will be selected and exposed to more advanced testing.

Example results of investigations into green concrete

Tables 3 and 4 show concrete mixes tested with high-volume fly ash for the passive and aggressive environmental classes. In the passive environmental class the fly ash content was increased from 24 to 70%, resulting in a reduction of CO_2 emission from 18 to 57%.

In the aggressive environmental class the fly ash content was increased from 9 to 40% resulting in a reduction of CO_2 emission from 33 to 54%. AV5 is a modified version of AV4 with an increased air content.

The control parameters for the mixes were a slump of approximately 100 mm and, for the aggressive environment, an air content of 5.5%.

Strength development is shown in Figures 3 and 4. The figures show that PV4, which has a fly ash content of 70%, has strength that is far too low: it appears that the fly ash content must not exceed approximately 60%. Even so, the strength development is still too slow. Therefore, studies have been initiated to improve the strength development.

As regards the concrete in the aggressive environmental class, the strength development is similar for all concrete types. This indicates that the maximum fly ash content has not been reached with a content of 40%. However, preliminary testing indicates that the high-volume fly ash concrete might have problems with frost resistance. Further studies have been initiated to investigate this issue.

Currently, testing is being performed on concrete containing concrete slurry, stone dust, and ash from the combustion of slurry from water-purifying plants.

Cement-stabilized foundations

A particular focus of the Centre for Green Concrete is on cement-stabilized foundations. This activity includes investigation of:

- The possibility of casting cement-stabilized foundations with a high content of materials which should otherwise be deposited, e.g. slurry from waste combustion as a substitute for ordinary gravel.
- The use of crushed waste asphalt as a substitute for aggregate. Experience shows that the use of crushed asphalt as part of the aggregate can eliminate the development of macrocracks in a foundation, eliminating reflection cracks in the next layer. Therefore, the use of crushed asphalt in a cement-stabilized foundation can improve the quality of the entire casting.
- The use of fillers such as stone dust, smoke waste from waste combustion, slurry from waste combustion and special chalk fillers.

Design, operation and maintenance, research activities and the construction of a demonstration bridge

The final two development projects of the centre concern the operation and maintenance of green concrete structures and green structural solutions/structural solutions for green concrete.

Other activities concerned with specific topics include increased research and development. This includes examination of mechanical properties, fire resistance, execution, durability, and physical and thermal dynamic examinations.

Implementation of the results

The results are expected to be implemented in a Road Directorate special concrete specification for resource-saving concrete structures. This will be used in carrying out a demonstration project which includes the dimensioning and construction of a bridge in green concrete.

Conclusion

This overview of the present state of affairs in Denmark of concrete types with reduced environmental impact has shown that there is considerable knowledge and experience on the subject. The Danish and European environmental policies have motivated the concrete industry to react, and will probably also motivate further development of the production and use of concrete with reduced environmental impact.

The somewhat vague environmental requirements that exist have resulted in a need for more specific technical requirements, and this is the focus of a recently started large Danish research project, where the most important goal is to develop the technology necessary to produce and use resource-saving concrete structures, i.e. green concrete. This applies to structure design, specification, manufacturing, the performance, operation and maintenance.

Cement and concrete may have an important role to play in enabling Denmark to fulfil its obligation to reduce the total CO_2 emission by 21% compared to the 1990 level before 2012, as agreed at the Kyoto Conference.

The potential environmental benefit to society of being able to build with green concrete is huge. It is realistic to assume that the technology can be developed which can halve the CO_2 emission related to concrete production, and with the large energy consumption of concrete and the following large emission of CO_2 this will mean a potential reduction of Denmark's total CO_2 emission by 0.5–1%.

Furthermore, green concrete might solve some of society’s problems by the use of inorganic residual products which would otherwise be deposited in the environment.

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