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Equivalent performance concept - green concrete

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Introduction

Green concrete has nothing to do with color – it is a concept of thinking environment into concrete considering every aspect from raw materials manufacture over mixture design to structural design, construction, service life, and even the secondary life of concrete e.g. demolition and re-use of the demolished concrete. In Denmark we are committed through the Kyoto agreement to reduce CO_2-emission by 21% of the 1990 level before 2012. The large innovation consortium project "Resource saving concrete structures" was launched in 1998 with the objective of demonstrating that concrete structures with lower environmental impact could be made without compromising durability and economy. The present paper will, with the focus on raw materials, mixture design and use of fly ash, present some of findings from the original innovation consortium project as well from later projects dealing with the production of more environmentally friendly concrete.

Green concrete – the background

The concrete industry is faced with new challenges. Legislation, environmental levies, voluntary agreements, demands from the customers, and general public awareness 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. Given the vast amount of concrete produced even a small reduction of the environmental impact per ton of concrete will result in large environmental benefits because of the vast amount of concrete produced.

Concrete is an environmentally friendly material and the overall impact on the environment per ton of concrete is limited [1]. In general environmental impact can not be reduced by replacing concrete with other materials. The remaining means of reducing the environmental impact of the use of concrete is thus to reduce the environmental impact of the concrete itself. Life cycle inventory results of concrete-based products have shown that the concrete mixture proportions – primarily the type and amount of cement - have a major influence on the total life cycle impact because of the associated CO_2-emissions [2]. The CO_2 inventory of different designs of a bridge column provided in Table 1 and Figure 1, and in Figure 2 a CO_2 inventory of the production of a hollow core slab is provide. Both inventories illustrate the importance of the concrete composition on the environmental impact. For this reason use of blended cements, substitution of cement by other materials, and mixture design optimization in general are the most obvious ways to improve the environmental performance of concrete.

Table 1. Details of bridge columns made from three different green concrete design principles (A, B and C) and a reference design (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 stainless steel that replaces traditional shuttering, in-situ
Maintenance and repair	Cleaning/washing every year Surface treatment every 3. Year Repair after 25 years	Cleaning/washin g every year Surface treatment every 3. Year Repair after 25 years	None	None
Lifetime	50 years	50 years	75 years	75 years

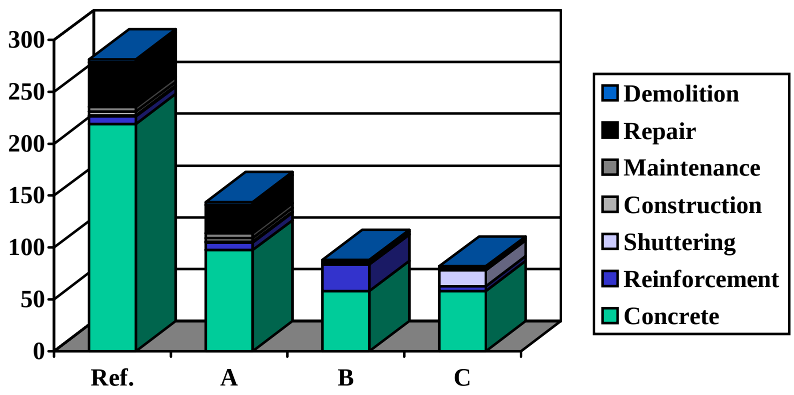

Figure 1. Sources of CO_2-emission (kg/year) of four types of bridge column design.

Use of residual products from other industries in the concrete production has gained increasing interest during the last few decades as 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 materials in concrete production.

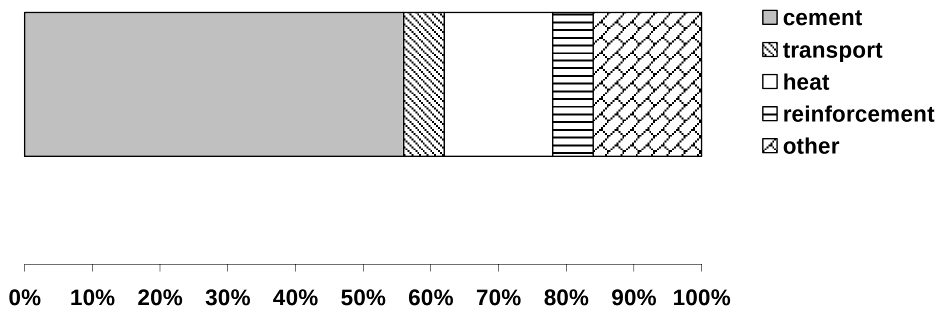

Figure 2. CO_2 inventory of the production of a precast hollow core slab.

Ways to achieve green concrete

In the Green Concrete Project the term green was assigned to a concrete if it satisfied one of the following five criteria:

- CO_2 emission caused by concrete production is reduced by at least 30%
- The concrete contains at least 20% residual products, used as aggregate
- The concrete industry's own residual products is used in the concrete production
- New types of residual products, previously landfilled or disposed of in other ways, are used in the concrete production.
- CO_2-neutral, waste-derived fuels are replacing at least 10% of the fossil fuels in cement production.

Furthermore, a green concrete has to meet the three environmental intentions given below:

- Use of materials in the concrete that contain substances on the Danish. Environmental Protection Agency's list of unwanted materials should be avoided.
- The recycling ability of the concrete should not be reduced compared to conventional concrete (in Denmark 95% of concrete is re-used).
- The content of hazardous substances in the discharge water from the concrete production should not be increased.

The five main green concrete criteria translate into four principal means of achieving a greener concrete by manipulating the concrete's composition:

1. To increase the use of conventional residual products, i.e. fly ash in large quantities.
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 (mineralized cement, limestone addition, waste-derived fuels).

All four means of greener concrete production were pursued in the Danish project. Concrete with large amounts of fly ash was investigated, as was concrete with incinerator sewage sludge ash and fly ash from incineration of bio mass (new residual product). Also, the use of new cement types requiring less energy for production was investigated for use in aggressive environmental class. Finally, use of slurry of concrete waste form the concrete production itself was investigated. Only, the experience gained with the use of very high amounts of fly ash in concrete will be dealt with in the proceeding sections.

Green concrete with large amounts of fly ash

In the Green Concrete Project ready mixed concrete for passive (w/c around 0.7) and aggressive environment (w/c around 0.4) was targeted. The mixture design development was based on a reference mixture in each of the two environmental classes and then divided into three testing phases namely; basic package, large package, extended package. Finally, a few selected mixtures were tested during casting of a highway bridge.

The reference concrete for passive environment contained 24% fly ash and 6% silica fume, and the green concretes tested contained 50-70% of fly ash. The reference concrete for aggressive environment contained 9% fly ash and 5% silica fume, and the green concretes tested contained 18-40% of fly ash. All mixtures in each environmental class had roughly the same volume of paste, the same equivalent w/c-ratio[1], and the same aggregate skeleton (3).

The fly ash used was Emineral B4. This ash is a low calcium ash resulting from pure coal combustion and conforming to EN 450. Fly ash contains small amounts of heavy metals. The normal concentrations of heavy metals do not influence the technical performance of concrete even when high fly ash content concrete is produced. However, heavy metals are unwanted as they lower the quality of the waste and wastewater from the concrete production. Just as important the heavy metals may reduce the potential reuse of the concrete after demolition. The worst case scenario being the heavy metal been leached from the concrete to the environment, a scenario that potentially could occur if the concrete is at some point subjected to sufficiently acidic conditions. However, not much knowledge exists about the leaching of heavy metals from concrete in a service life and secondary life perspective. On the other hand green concrete with large amounts of fly ash

[1] The activity factor of fly ash was assumed to be 0.5, and that of silica fume was assumed to be 2.

is considered to comply with the Danish regulations for heavy metal content in concrete structures that are being re-used in the construction industry, e.g. for road sub-base.

Mechanical properties

The mechanical properties of high fly ash content concrete were generally good. The fly ash was not found to change the relation between compressive strength and E-modulus or splitting tensile strength. However, the high fly ash content concrete appeared to behave more brittle than the reference concretes (3).

Even though all high fly ash content concretes had lower 28 and 56 days strength than the reference concretes, the strength development and final strengths were acceptable except for concrete with 70% fly ash for passive environment as this concrete had only about 1/3 the strength of the reference concrete (see Figure 3 and 4). However, for winter castings the low heat development of the high fly ash content concrete may pose a problem that require attention as the strength will develop too slow. On the other hand the low heat development can be an advantage during hot weather castings and for massive concrete structures.

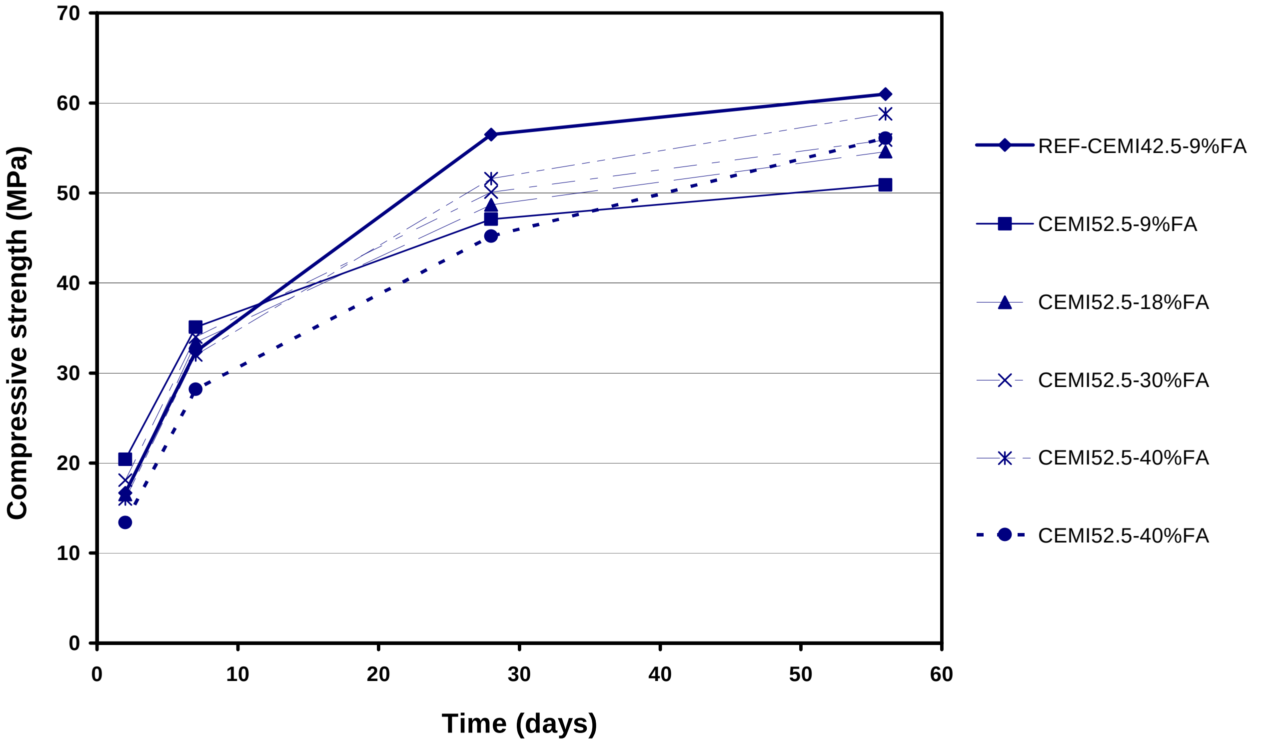

Figure 3. Strength development of concrete designed for aggressive environment. The equivalent w/c-ratio ranges from 0.37-0.44, and the air content ranged from 6.2-7.7. All concretes contained 5% silica fume by mass of total powder.

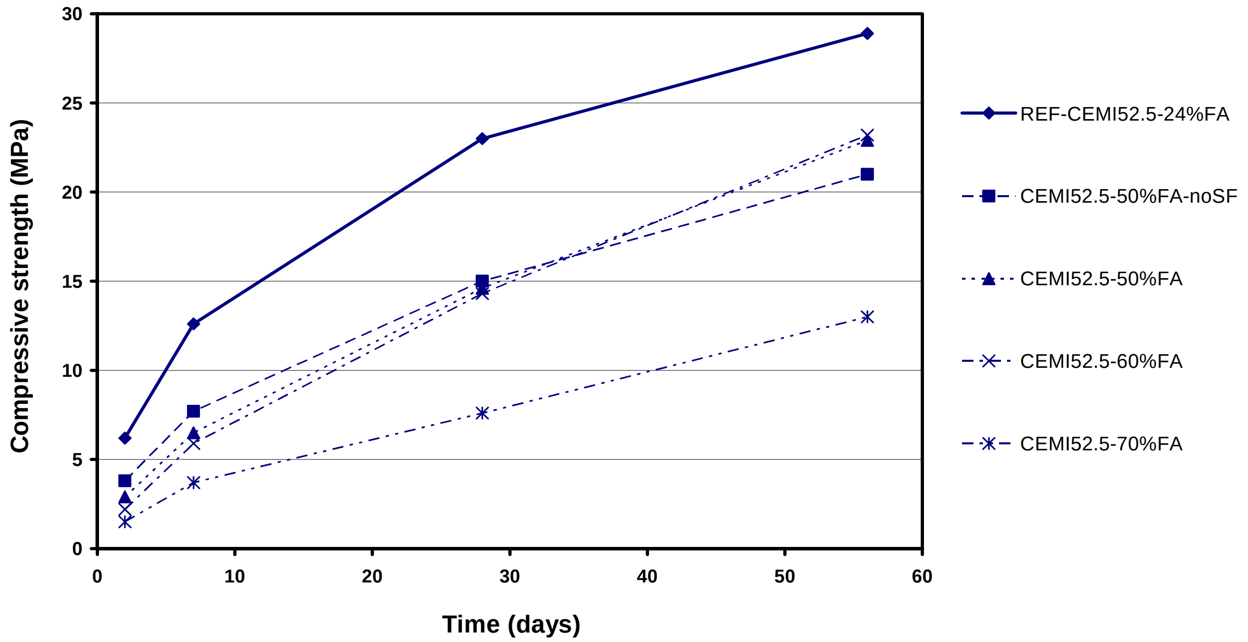

Figure 4. Strength development of concrete designed for passive environment. The equivalent w/c-ratio ranges from 0.70-0.80, and the air content ranged from 4.1-5.2. All concretes except one contained 6% silica fume by mass of total powder.

<u>Durability</u>

The classic durability problems of traditional concrete in Denmark are frost resistance, carbonation resistance, chloride ingress, and alkali silica reactivity. These durability issues are normally of greatest importance in association with concrete subjected to aggressive environment, i.e. wet outdoor environments. For this reason only the performance of concrete for aggressive environment was documented (4, 5).

The high fly ash content concretes showed better resistance towards chloride ion penetration than the reference concrete when tested according to the Swedish CTH-method. The results 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, i.e. the chloride diffusion coefficient is decreasing more rapidly with time for high fly ash content concretes.

The resistance towards alkalisilica reaction (ASR) was very good of the high fly ash content concretes. The test method used for ASR was a modified Danish TI-B 51.

The carbonation rate of high fly ash content concrete expressed as depth of carbonation versus time was found to be slightly higher than for the reference concrete when tested according to NT-BUILD 357. This test method uses young concrete exposed to accelerated carbonation conditions (3% CO_2), which may be unfavorable to high fly ash concrete where the pozzolanic reaction are still incomplete, i.e. the pore structure will tighten up over time reducing the diffusion rate of CO_2 into the concrete.

The greatest durability challenge to high fly ash content concrete was found to be the frost resistance. In all phases of the Green Concrete Project it is was found to be difficult to control the air void system of concrete with high fly ash content and poor frost resistance was often found using the Swedish SS 13 72 44 scaling method. The problem with frost resistance was attributed to fact that even tough some high fly ash content concretes had acceptable levels air contents the air bubbles where rather coarse, thus resulting in sub-par frost resistance (see Table 2).

Table 2. Air void parameters (EN 480-11) and concrete scaling measurements (SS 13 72 44) of concrete with high fly ash content.

	Air void analysis EN-480				**Freeze/thaw-test, SS 13 72 44**		
	Air content [%]	Micro-air [%]	Specific surface area [mm^{-1}]	Spacing factor [mm]	Scaling 28 days [kg/m^2]	Scaling 56 days [kg/m^2]	Evaluation
Basic package	3,6 5,4	1,0 1,9	26 24	0,22 0,20	0,64 0,60	1,25 0,90	Not acceptable acceptable
Large package	5,2	0,8	14	0,33	0,36	0,88	Not acceptable
Extended package	3,4	1,2	25	0,22	0,24	0,34	good
Demonstration bridge							
Trial casting, cast cylinder	4,0	1,2	24	0,22	0,28	0,33	good
Trial casting, drilled cylinder	3,5	0,9	17	0,31	2,22	2,25	Not acceptable
19.11.2001, Cast cylinder	5,3	2,1	24	0,18	-	-	-
11.01.2002 cast cylinder	5,1	2,4	24	0,19	-	-	-
06.02.2002 Cast cylinder	5,3	3,2	36	0,13	-	-	-

However, during the casting of the highway bridge extensive effort was put into obtaining a mixture design that had good air void characteristics, and it turned out to be possible for the ready mixed plant to consistently produce a frost resistant concrete with a good air void system.

<u>Execution</u>

Concrete with high content of fly ash will at fixed equivalent w/c ratio contain significantly more solid matter in the paste on a volume basis. This is due to that the activity factor of fly ash being only 0.5 and that the density of fly ash is lower than the density of cement. At an equivalent w/c ratio of 0.40 the change from pure Portland cement paste to a paste with 60% Portland cement and 40% fly ash on a weight basis is, on a volume basis equivalent to reducing the w/c ratio of pure Portland cement paste from 0.40 to 0.28, i.e. a major change.

As a consequence concrete with high content of fly ash require more admixture to obtain a desired fluidity (slump). This was indeed found to be the case in the Danish Green Concrete Project (6). An unwanted side-effect of the increased use of admixture (plasticizer and superplasticizer) is often increased setting time of the concrete. For the concrete designed for aggressive environment a modest increase in setting time from 7 to 9 hours was observed for the concrete with 40% fly ash. More drastic was the increase in setting time of the concrete for passive environment, where the increase was form 8 hours for the reference concrete to 11-12 hours for concrete with 50% fly ash all the way up to 18-19 hours for the concretes with 60% and 70% fly ash. The latter clearly being an unacceptably long setting time. The increase is probably a combined effect of the increased amounts of admixture and that the large amounts of fly ash (replacing cement) does not contribute to formation of hydration/reaction products at early age.

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. All of these observations can be tracked to the higher solid content of the paste and the inherent high amounts of admixture. It is expected that some of these problems can be solved by optimizing the type and amount of chemical admixtures in the concrete.

Concrete with co-combustion fly ashes

The approval of the EN 450-1 standard last year has opened up for the use of co-combustion fly ash in concrete. A co-combustion ash may result from combustion of maximum 20% by weight of bio mass and 80% coal, and the a maximum of 10% by mass of the ash are allowed to result from the bio mass. Co-combustion fly ash is more environmentally friendly than traditional coal ash, as the bio mass is renewable, and thus the net CO_2-emission from production of the ash is less.

Within the last 18 months Danish Technological Institute, the Danish fly ash producing industry, and the Danish ready mixed concrete industry has collaborated in documenting the performance of different co-combustion fly ash (7, 8, 9, 10, 11). The co-combustion materials that were investigated were straw from agriculture and wood pellets from wood industry. The testing has comprised chemical and physical performance corresponding to EN 450-1, and trial casting corresponding to the requirements for new mixture designs set forth in DS 2426. The testing was run in parallel with a traditional fly ash produced at the same power plant.

The results so far have been encouraging. The fresh concrete properties, the hardened concrete properties and the concrete durability of the co-combustion fly ash concrete have been very similar to those of concrete with pure coal combustion fly ash.

Co-combustion will inherently introduce changes in the chemical composition of a fly ash as the elemental composition in ash from the various bio masses vary from that of coal. Straws contain considerable amounts of potassium that will boost the alkali content of the resulting co-combustion fly ash, but level are still well below the limit in EN 450-1. Wood pellet also contain more potassium leading to increased alkali in the co-combustion ash. Moreover, co-combustion of wood pellets leads to increased sulfate content, and also the concentration of some heavy metals was found to be significantly higher in ash from wood pellet co-combustion.

The physical performance of the co-combustion ashes including the important activity index showed no significant difference between traditional fly ash and co-combustion fly ash. The activity indexes of the ashes tested are shown in Table 3 below.

Table 3. Activity indexes for pure coal and co-combustion fly ashes.

Days	EN 450-1 Limit (min)	Plant1 coal	Plant1 10%wood	Plant2 coal	Plant2 10%straw	Plant2 14%straw	Plant2 20%straw
28	75	84	81	88	86	95	90
90	85	99	98	103	97	110	

Conclusion

Much of the Danish work concerning green concrete has this far focused on limiting the CO_2-emissions and the waste to be landfilled. In this context it has been documented that concrete with less environmental impact can be produced, and that such concrete has satisfactory execution and durability properties, although some "fine-tuning" regarding in particular setting time and frost resistance are needed. Also, more strict control of the production process are needed as the properties of re-used waste materials (e.g. fly ash, incinerator sewage sludge ash) in order to accommodate variation in the raw materials. The future of concrete incorporating more waste material and having lower CO_2-emissions are no-doubt promising. However, a complete life cycles analysis requires more parameters to be evaluated than CO_2-emission and re-use of waste. This task is still ahead of us. Particularly, the potential leaching of heavy metal from concrete must be evaluated in a long term perspective.

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