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High-Strength Concrete Bridge Design: a Contribution to Sustainable Development?

Projet de ponts en béton à haute résistance: une contribution à un développement durable?

Bemessung von Brücken aus hochfestem Beton: Ein Beitrag zu nachhaltigem Bauen?

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SUMMARY

Nowadays more and more attention is being paid to sustainability. It is, however, difficult to assess the contribution of the different alternatives to the sustainability of concrete structures. A preliminary design was made for lightweight concrete, normal concrete and high strength concrete. The total energy content of the box girder was calculated for a concrete box girder bridge. Due to the small differences in energy content between the alternatives in relation to the poor reliability of input data, a conclusion on the sustainability of high strength concrete in bridge design could not yet be drawn.

RÉSUMÉ

De nos jours, les projets semblent être établis avec un plus grand respect pour l'environnement. Il reste cependant difficile d'évaluer les différentes options et leur impact sur l'environnement. Un dimensionnement préliminaire a été fait pour un pont en caisson en béton léger, normal et à haute résistance. Le contenu énergétique total dans le caisson a été calculé. La faible différence de contenu énergétique entre le béton normal et le béton à haute résistance, ainsi que la mauvaise qualité des données ne permet encore aucune conclusion à propos de ce projet.

ZUSAMMENFASSUNG

Heutzutage hat man für die Nachhaltigkeit immer mehr Interesse. Altenative Projekte von Betonbauwerken sind aber in Bezug auf die Nachhaltigkeit schwierig zu beurteilen. Für eine Kastenträgerbrücke ist ein Vorentwurf für Leichtbeton, Normalbeton und hochfestem Beton gemacht worden. Der gesamte Energieverbrauch für die Kastenträgerbrücke ist berechnet worden. Der Unterschied zwischen den Alternativen ist klein, insbesondere, wenn man die geringe Zuverlässigkeit der Ausgangsdaten berücksichtigt. Eine Aussage ob hochfester Beton zu nachhaltigem Bauen einen Beitrag leistet ist deshalb noch nicht machbar.

1. INTRODUCTION

The world at loan from our children, rather than owning it for our own benefits. This thought lies at the basis of much effort to realise sustainable development. With the aim to preserve the environment as much as possible, goals where formulated in the Netherlands on a national level in the "National Environmental Policy Plan" [1]. In this plan three main lines can be distinguished: Integrated life cycle management, Energy conservation and Quality improvement.

At Rijkswaterstaat (the directorate general for public works and water management) in the Netherlands it is felt as a dedication to translate the goals for sustainable development to reality in common practice. So, for the design of the so-called "Second Stichtse Bridge", three alternatives where considered. A preliminary design was made for respectively normalweight concrete (grade B65; cube characteristic compressive strength is 65 MPa), a lightweight concrete (grade B45) and a high strength concrete (grade B85). Apart form various structural considerations, the contribution of the alternatives to sustainability was investigated. In this respect particularly the energy-content of the concrete box girder bridge was compared for the three alternatives.

As far as environmental friendly design is concerned, it must be mentioned that there are various criteria. So it is possible that an alternative has a positive contribution to one criterion, while for another environmental criterion it has a negative effect. In this paper, first some general remarks will be given about sustainable design. Thereafter a short description of the project "Second Stichtse Bridge" is given, followed by a discussion about a possible contribution to a sustainable development by using high strength concrete for concrete box-girder bridges. Then the aspect energy-content is further elaborated for the three alternatives. For the sake of clarity it should be mentioned that sustainable development so far is seldom taken into account in the design process, where economics and performance aspects still play the major role. Nevertheless, it is hoped to show that with the contribution in this paper also considerations about environmental aspects can be incorporated in the design process.

2. OPTIONS FOR AN ENVIRONMENTAL-FRIENDLY DESIGN

2.1 General

Environmental aspects in the design process can pursue different environmental objects. Arbitrarily the following options can be distinguished:
a) design for a long functional life
b) use of fewer raw materials
c) design for recycling and re-use
d) minimizing disturbance of the surrounding
e) minimizing construction and demolition waste
Design requirements can be formulated for the different options. Here, only some examples will be given. Design requirements for a long functional life (a) are for instance: flexibility, easiness to repair, use of durable materials. Slender structures and demountable structures are respectively examples of the items (b) and (c).

The different options for an environmentally friendly design can be conflicting. For instance, a continuous beam over a number of supports is preferable from the point of view of a fewer use of raw materials (slenderness). However, for a design on recycling (of elements) or easy demolishing a row of simply supported beams can be preferred.

2.2 Bridge design

Fortunately, in many cases an economic design goes together with environmental-friendly design. In bridge design, for instance, the use of a box girder bridge with a non-constant height is common practice. In such a structure the capacity of the raw materials is utilized optimally firstly by bringing the material in the cross-section far from the neutral axis (box). Secondly, the amount of material is minimized by adaption of the height of the box girder to the moment distribution in a longitudinal direction.

Within the concept of a concrete box girder bridge it is still possible to choose for different materials. Even for the primary constituents of the concrete there are several possibilities. In this respect the type of cement, Portland cement (PC) or blast furnace slag cement (BFSC), the amount of cement (related to the concrete grade) and the type of aggregates can be mentioned. For the latter one there are e.g. river gravel, crushed natural stone and artificial manufactured lightweight aggregates. The question now arises which of these materials are preferable from the point of view of sustainability. In the subsequent paragraphs an attempt is made to answer this question for one of the environmental aspects, namely energy conservation.

For the design of concrete box girder bridges, traffic loads, dead load and temperature loading has to be taken into account. In general, the dead load is much larger than the traffic load. So, when the weight of the bridge can be reduced it will significantly influence the required amount of prestressing.

3. PROJECT "THE SECOND STICHTSE BRIDGE"

3.1 General

To obtain a good alternative traffic connection between the northern and southern provinces in the Netherlands, national highway 27 was built in the beginning of the eighties. For the crossing over lake "Gooimeer", a box girder bridge in lightweight concrete (called Stichtse Bridge) was used. Due to increased traffic intensity the capacity of the highway has to be enlarged and the national highway has to become a motorway with separated lanes. As a result a second box girder bridge has to be built besides the first one.

For aesthetical reasons a requirement for the Second Stichtse Bridge is that its shape (in longitudinal direction as well as in height) has to be identical to the first one. It concerns a three span bridge (see Fig. 1) with maximum middle span of 160 m. The structural height at the centre of the bridge is 2.5 m. For the First Stichtse Bridge a lightweight concrete (B32.5) with a sintered expanded clay for the aggregates was used. Due to new regulations it was not possible to use the same design. Therefore, a different type of concrete has to be used. In a feasibility study a lightweight concrete B45 (LWC) with sintered fly-ash aggregate, a normal-weight concrete B65 (NC) and a high strength concrete B85 (HSC) were compared. Due to the fact that the weight of these concretes was more than the weight of the original type of lightweight concrete and taking into account that structural height was fixed, the strength class had to be increased.

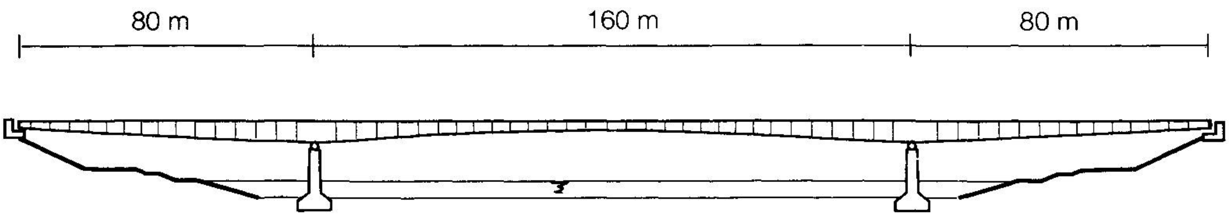

Fig. 1 Longitudinal cross-section of the "Second Stichtse Bridge"

For several reasons, of which a number are related to sustainability, it has been decided to built the bridge in high strength concrete.

3.2 Three alternatives

The preliminary design for the high strength concrete resulted in a cross-section near the support as presented in Fig. 2. The thickness of the bottom flange varies from 220 mm in the middle of the bridge to a maximum above the supports. This maximum thickness as well as the thickness of the webs can be obtained from Table 1. The thickness of the upper slab is almost equal for the three alternatives.

The amount of concrete and prestressing steel for the three alternatives is given in Table 2. The amount of mild steel reinforcement and prestressing in lateral direction is equal for all three alternatives. The weight only represents the concrete box-girder. As can be seen, the high strength concrete bridge has the lowest weight and gives a weight reduction of 14% compared to the bridge in concrete grade B65. Because the strength of HSC has already after 2 days a high value the prestressing elements can be placed with small anchorage-elements in the upper slab. Compared to the usual position of the elements in the web, this results in a simplified cable curve, giving a 8% reduction in losses of prestress. Also the reinforcement details are more simple.

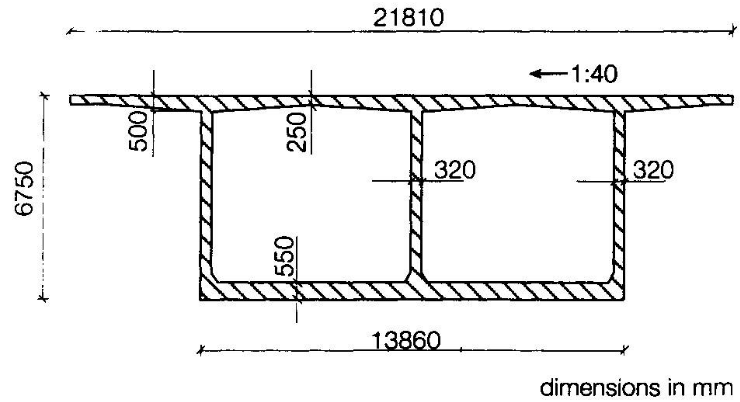

Fig. 2 Cross-section above support for B85 (HSC).

Table 1 Cross-sectional area dimensions of the box girder.

	B45 (LWC)	B65 (NC)	B85 (HSC)
varying bottom slab thickness (mm)	220 - 1000	220 - 650	220 - 550
web thickness (mm)	500	400	320

4. SUSTAINABILITY/ENERGY-CONTENT

4.1 General

As presented before the use of high strength concrete in a box-girder bridge results in a reduction of the concrete volume, number of prestressing cables and weight as compared to normalweight concrete (B65). So this gives a positive contribution to fewer use of raw materials. Furthermore, the piers and foundations of the bridge can be made less heavy due to the reduced weight of the box girder. Compared to the First Stichtse Bridge the length of the concrete segments will be enlarged from 3.4 m to 5 m, reducing the construction time with three months.

A method for comparison of products from an environmental point of view is the Life Cycle Analysis (LCA). In such an analysis all environmental impacts (e.g. depletion of energy sources, green house effect, acidification, waste production) during the total life cycle (from production of raw materials to demolition and reuse) are collected and weighed. Performing a total LCA is very laborious. Another problem is that the required information is not always available.

In the subsequent paragraphs the energy content (and thus its contribution to energy depletion) of the three bridges will be compared. In a way this can be seen as a very limited LCA. Though in case of high strength concrete the amount of concrete is less, the energy content can still be higher due to an increased cement content. Therefore it is interesting to see how the energy-balance works out for the three alternatives.

Table 2 Quantities of concrete and prestressing steel (only longitudinal direction) in the box girder and assumed concrete composition.

		B45 (LWC)	B65 (NC)	B85 (HSC)
Concrete	(m^3)	6582 (112%)	5893 (100%)	5145 (87%)
Prestressing steel	(ton)	418 (88%)	475 (100%)	380 (80%)
Weight*	(ton)	13950 (91%)	15320 (100%)	13430 (88%)
cement content PC	(kg/m^3)	90	90	238
BFSC (66.6% slag)	(kg/m^3)	270	270	237
total cement content in box girder	(ton)	2370 (112%)	2121 (100%)	2444 (115%)
type of coarse aggregate		sintered fly-ash	river gravel	crushed gravel
sand content	(kg/m^3)	750	750	750
Coarse aggregate content	(kg/m^3)	600	1050	1050

* Including lateral prestressing (97 ton) and reinforcement (600 ton). For the lightweight and normalweight concrete respectively a specific weight of 1.95 and 2.4 ton/m^3 is taken.

4.2 Energy-content of raw materials

Before presenting data for the energy content of the raw materials some comments have to be made. It is only intended to make a rough comparison of the energy content, rather then to find exact values. The values are taken from the literature, which sometimes originate from the beginning of the eighties. It may be possible that due to new techniques the energy consumption for a certain process is smaller nowadays.

Values for the (primary) energy content of the constituent materials of concrete and reinforcing and prestressing steel are presented in Table 3. As can be seen the energy content of sand and (crushed) gravel is very small as compared to the energy content of cement. If, however, lightweight aggregate is used, its contribution to the total energy content of concrete cannot be neglected. For an expanded clay a value of 3416 MJ/ton is given in [2]. The value for the sintered fly-ash aggregate in Table 3 is deduced from information by the manufacturer of the aggregate. Though the energy-content is significantly higher for sintered fly-ash aggregates than for gravel, it should be mentioned that the manufacturing of this type of aggregate helps to solve a waste problem.

4.3 Comparison of energy-content

In order to calculate the energy content of the bridge deck it is necessary to know the concrete composition. In the study the mixes were not yet defined in detail. For the design it is sufficient to know the type of concrete and the strength class. Given a certain strength it is still possible to vary the cement content or cement type, which influences the energy content of the concrete. The concrete compositions as assumed in this study can be found in Table 2. The total amount of cement in the bridge deck is highest for HSC, despite the lowest concrete volume.

Based on the information as presented before, a total energy content for the bridge deck can be calculated (see Table 4). It appears that the alternative in high strength concrete has the lowest energy content. However, due to the poor reliability of the input data, the influence of the assumed mix proportions on the energy-content and the fact that not everything has been taking into account (e.g. an increased mixing time in case of HSC), the differences in total energy content cannot be regarded as significant.

Table 3 Data for the (primary) energy content of concrete components, reinforcement and prestressing steel [2,3]

		reference	energy-content (MJ/ton)
Aggregates	- sand	[3]	16
	- gravel	[3]	16
	- crushed gravel	-	32[1)]
	- sintered fly-ash	[4,5][2)]	963[2)]
Cement	- Portland	[2]	4046
	- Blast-furnace slag		
	* 66.6 % slag	[2]	2590
Steel	- reinforcing steel	[2]	30000
	- prestressed	[2]	34000

1) Based on the assumption that for crushing as much energy is required as for winning and washing together.
2) According to the manufacturer [4] 7 kg oil, 10 kg coal and 42.5 kWh electricity is used to produce 1 ton sintered fly-ash aggregates. By assuming respectively 42.3 MJ/kg oil, 29.3 MJ/kg coal and 8.8 MJ/kWh electricity [5], the primary energy content for sintered fly-ash aggregates is calculated.

Table 4 Energy content (GJ) for the box girder bridge deck and the three alternatives.

	B45 (LWC)	B65 (NC)	B85 (HSC)
aggregates	3882	170	235
cement	7000	6267	8113
reinforcement	18000	18000	18000
prestressing elements			
- longitudinal	14212	16150	12920
- lateral	3298	3298	3298
total energy content (GJ)	46392 (106%)	43885 (100%)	42566 (97%)

5. CONCLUSIONS

From the point of view of sustainability there are different options in relation to the design of (concrete) structures. For the concrete box girder bridge in this study, it appears that the application of high strength concrete requires less concrete and steel, which is good for reduction of depletion of raw materials. As far as total primary energy content is concerned no conclusions can be drawn based on the performed analysis. The differences for the three alternatives are too small in relation to the reliability of the input data. Therefore, the question whether the application of high strength concrete in bridge design contributes to sustainable development cannot be answered from this point of view yet. However, HSC will result in an improved durability of the structure, so that from the point of view of 'designing for a long life' a positive contribution to sustainability is certainly made.

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