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E6 Rentvann Tunnel Oslo – CO_2 saving potential of tunnel segments using reinforced steel fibre concrete

In addition to the technical and economic requirements, the challenges facing the planning of tunnels are becoming ever greater due to ecological aspects. In order to comply with climate policy requirements, decarbonisation must continue to be driven forward in the construction sector. The construction materials and products used in tunnels have a significant impact on the environment. An Environmental Product Declaration (EPD) is often required in order to obtain a valid information basis for the life cycle assessment of a product. An EPD is based on the international standard ISO 14025 [1]. With regard to the construction industry, EPDs are based in particular on the EN 15804 [2] standard for construction products, services and processes. When it comes to the requirements for sustainable products, the focus today is primarily on the Global Warming Potential (GWP).

Steel fibres in tunnel construction

The use of concrete is unavoidable in tunnelling. There are currently no technically and/or economically viable alternatives either for sprayed concrete, for tunnel segments or for concrete structures produced on site in tunnelling. For this reason, the aim must be to significantly reduce CO_2 emissions from the concrete used.

The focus of this article is on the use of CO_2-reduced tunnel segments in which this is achieved through the use of reinforced steel fibre concrete.

On the one hand, CO_2 reduction can be achieved through a good design that minimises the volume of concrete. Furthermore, significant savings can be achieved through the design of the concrete mix. The main CO_2 emitter is the cement. The GWP of the cement is largely determined by the proportion of Portland cement clinker. The higher the proportion, the higher the GWP of the cement, so that cements with as little clinker as possible should be used.

The actual 28-day strength of the segments is often significantly higher than the design strength. This is due to the fact that high early strengths are to be achieved in order to enable short demoulding times and at the same time ensure high lift-off strengths. It may be possible to use the higher strength in the design to generate a reduction in the thickness of the segment and thus the concrete volume, which is reflected in a reduction in the GWP [3].

Therefore, the right choice of reinforcement can help to reduce the GWP. While tunnel segments made of conventional reinforced concrete usually contain a steel bar/mesh reinforcement content of 80 to 150 kg/m³, steel fibre contents of 30 to 45 kg/m³ are commonly used.

Case study

The city of Oslo is building a reserve water supply system to secure the long-term water supply for Norway's growing capital [4, 5].

The joint venture between the Norwegian engineering and construction company "AF Gruppen" and the Italian tunnelling specialist Ghella is currently building a new water supply tunnel as part of the E6 Rentvannstunnel project, which will enable the additional supply of clean drinking water from the new water treatment plant at Huseby, west in Oslo and an underground sewage treatment plant in Huseby for around 1 million inhabitants [4, 5].

The water distribution network will be built between Huseby, Oset and Stubberud in Oslo (see Fig. 1). The tunnel will be bored over a length of around 11 km using a double-shield

Fig. 1: Planned new water supply for the city of Oslo [5]

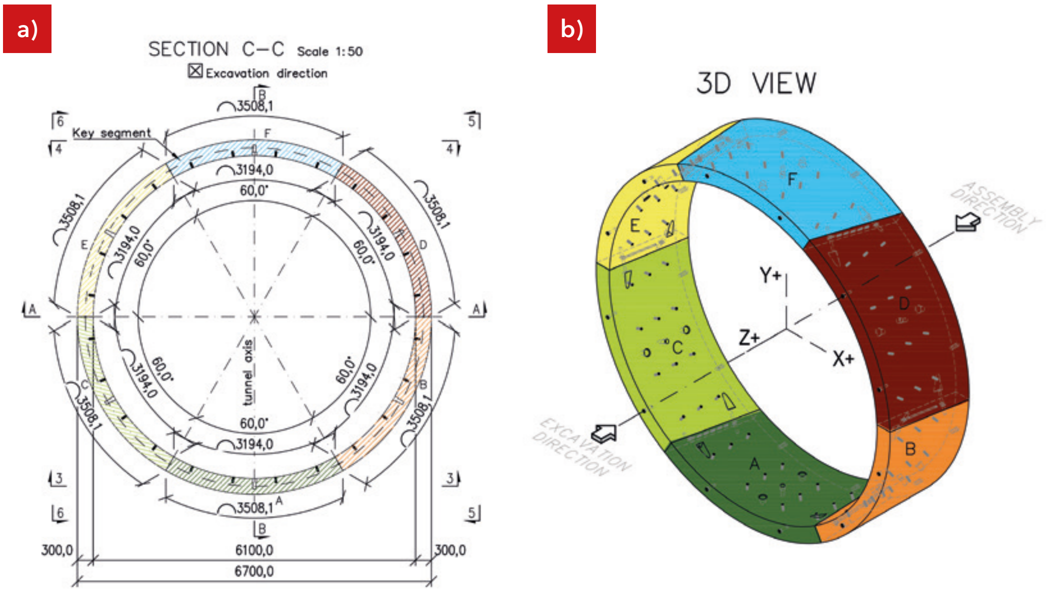

Fig. 2: Segment rings, dimensions of the segments, detail (a), 3D model (b) [7]

TBM (Tunnel Boring Machine) in hard rock and 7 km will be driven by drill and blast. The work is scheduled for completion in November 2027 [4, 5].

Planning of the lining

Tunnelling is carried out by mechanical excavation using a TBM and the installation of a prefabricated segmental lining with an internal diameter of 6.1 m. The tunnel lining consists of six prefabricated reinforced concrete segments with a thickness of 300 mm (see Fig. 2), which are assembled into a ring by the TBM immediately after excavation. Around 6,000 rings will be produced for the tunnel. The outer diameter of the ring is 6.70 meters, each of which is 1.80 meters long. A total of over 65,000 cubic meters of concrete will be needed to produce the segments.

Two different concrete mixes are used, one a concrete of the Norwegian concrete compressive strength class B45 ($f_{ck,cylinder}$ 45 N/mm^2) and the other a concrete of the Norwegian concrete compressive strength class B65 ($f_{ck,cylinder}$ 65 N/mm^2). With regard to the post-cracking flexural strength, the *fib*-Model Code Class 4C [6] must be achieved for both concretes. This means that the characteristic post-cracking flexural strength f_{R1k} must be greater than 4.0 N/mm^2. In addition, the ratio of f_{R3k}/f_{R1k} must be between 0.9 and 1.1.

The design life of the tunnel is 100 years and the following requirements must be met:

1. Concrete Durability Class M40 (exposure classes XD2, XD3, XS2, XS3, XA3, XSA, minimum air content 4 % by volume)

2. Sulphate resistance class should be SuR2 (XA2, XA3 and risk of alum shale (pyrite form) exists). According to NS-EN 206-1 pt. 5.2.8/NA.5.2.8 [8] and NS-EN 1992-1-1 pt. NA.4.4.1.2 [9]

3. Chloride class, according to. NS-EN 206-1 pt. 5.2.8/NA.5.2.8 [8] and NS-EN 1992-1-1 pt. NA.4.4.1.2 [9] for all reinforced concrete structures shall be chloride class Cl 0.10.

CO_2 savings in the project

Transport

The segments are manufactured in Mukran/Sassnitz in Germany and transported directly to Oslo by rail in special wagons.

Binder

Particular emphasis was placed on a low clinker content in the mix design, which was achieved on the one hand by substituting a high proportion of Portland cement with granulated blast furnace slag. A pozzolan was also added to ensure that the requirements for early strength and durability were met.

Steel fibres

On the other hand, the use of steel fibres DE 60/0.9 H from KrampeHarex with a particularly low GWP of 0.257 kg CO_2 eq [10] and the reduction of the total steel content significantly reduced the GWP.

Calculations

In the calculations, the CO_2 emissions from the manufacturing process – cradle to gate (A1 to A3) – are used and compared with each other.

The use of Portland cement leads to a GWP of 406 kg CO_2/m³ segment, assumption [11]. By using a blast furnace slag cement, the value can be reduced to 167.8 kg CO_2/m³ segment (B45) or 191.1 kg CO_2/m³ segment (B65). The use of pozzolan produces 3.0 kg CO_2/m³ of segment in the binder area for the B45 and 3.4 kg CO_2/m³ of segment for the B65.

The steel fibres result in a GWP total of 10.8 kg CO_2/m³ of segments (B45) and 9.0 kg CO_2/m³ of segments (B65). With a GWP total of 0.500 kg CO_2 eq [12] for the conventional steel bar reinforcement, this results in a CO_2 content of 18.5 kg CO_2/m³ segment for the B45 and 24.0 kg CO_2/m³ segment for the B65 concrete type.

Compared with a conventional reinforcement content in segments of 150 kg/m³ and a GWP total of 0.500 kg CO_2 eq [12] for the steel bar, this results in a CO_2 content of 75 kg/m³ segment.

Figure 3 shows the GWP for one cubic meter of segment for a standard mix design commonly used in tunnel construction as well as the B45 and B65.

Table 1 shows the calculation of the CO_2 savings potential of concrete types B45 and B65 compared to a standard mix design.

With a total concrete volume of 66,352 m³ and assuming that approx. 2/3 of the concrete is produced with B45 concrete and approx. 1/3 with B65 concrete, the hybrid reinforcement with KrampeHarex fibre DE 60/0.9 H and steel bars instead of conventional steel bar reinforcement results in CO_2 savings of around 2,950 tonnes. The CO_2 footprint of the binding agent is reduced by almost 15,100 tonnes. This results in a total CO_2 saving of over 18,000 tonnes.

Table 1: CO_2 savings potential of concrete types B45 and B65 compared to the standard mix design

Raw Material/ Parameter	Standard mix design	B45	CO_2 savings potential	B65	CO_2 savings potential
	% by mass		–	% by mass	–
Cement	20.7$^{1)}$	14.5$^{2)}$	–	16.0$^{2)}$	–
Puzzolan	–	2.3		2.6	
Rebar	6.25	1.5		1.9	
Steel fibres	–	1.7		1.4	
–	kg/CO_2/m³ Segment		%	kg/CO_2/m³ Segment	%
Binder	406.0	170.8	57.9	194.5	52.1
Reinforcement	75.0	29.3	60.9	33.0	56.0
Total	481.0	200.1	58.4	227.5	52.7

$^{1)}$ OPC $^{2)}$ Blast furnace slag cement

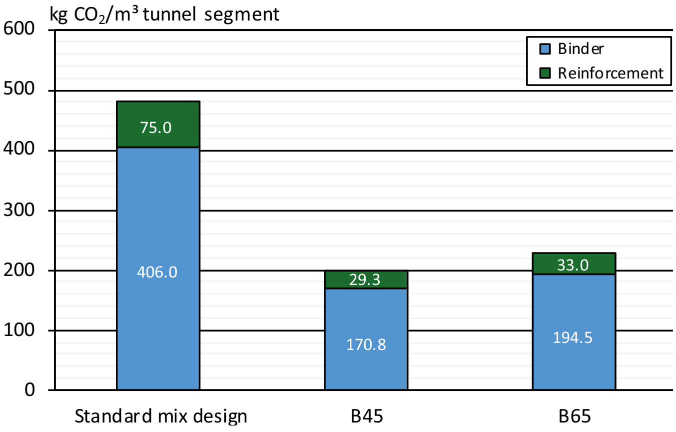

Fig. 3: Comparison of the GWP (A1 to A3) for the binder and reinforcement of the standard mix design and the two types of concrete used, B45 and B65, in kg CO_2 per cubic meter of segment

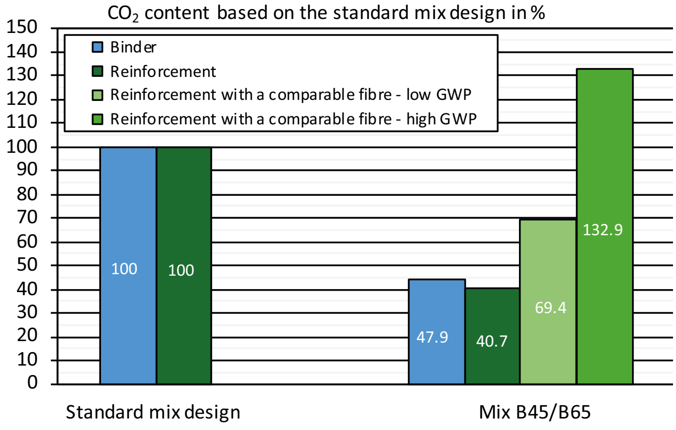

Fig. 4: Comparison of the GWP (A1 to A3) for the binder and the reinforcement of the standard mix design and the mix of concrete types B45 and B65, CO_2 content in relation to the standard mix design

Figure 4 shows the CO_2 emissions for the standard mix design and the B45/B65 mix for both the binder and the reinforcement.

Compared to the conventionally reinforced standard mix design, the B45/B65 mix with the hybrid reinforcement has CO_2 emissions of only around 48% for the binder and around 41% for the reinforcement. With a comparable steel fibre with a low GWP of 0.80 kg CO_2/kg fibre, the CO_2 content would be 69 % of the standard mix design, but 70 % higher than with the DE 60/0.9 H. If comparable fibres with a high GWP of 2.0 kg CO_2/kg fibre were used, the CO_2 content of the hybrid reinforcement would be 133 %, even higher than with the standard mix design, and would be 325 % in relation to the DE 60/0.9 H.

Conclusion

In the E6 Rentvannstunnel water tunnel project, both concrete types B45 and B65 used must achieve a post-cracking flexural strength class 4c in accordance with MC 2010. The use of reinforced steel fibre concrete segments can save considerable amounts of CO_2. On the one hand, this is achieved by using a blast furnace slag cement and, on the other hand, by reducing the overall reinforcement content in conjunction with a very low GWP for the steel fibres DE 60/0.9 H. Savings of up to 60 % can be achieved for both the binder and the reinforcement compared to a conventionally reinforced standard mix design. ■

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