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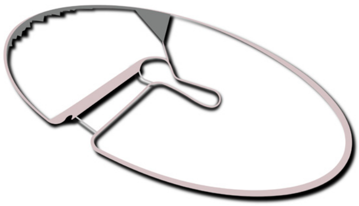

"Economical steel fibre reinforced sprayed concrete with low CO_2-footprint"

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ECONOMICAL STEEL FIBRE REINFORCED SPRAYED CONCRETE WITH LOW CO_2-FOOTPRINT

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Abstract

In addition to mechanical properties, durability, and economy, sprayed concrete mixes are increasingly focusing on ecology. To fulfil all requirements, it is important that the materials used are well matched to each other and also have the lowest possible CO_2-footprint.

The main focus of this article is to provide assistance in selecting the most technically suitable steel fibres for the respective sprayed concrete mix in order to achieve the required fresh and hardened concrete properties in a targeted and economical manner for the application. For this purpose, a parameter study is presented and carried out based on test results in which different fibre types - variation of length, diameter, and steel tensile strength - are used to select the optimum fibres. According to the available findings, this selection can reduce the fibre content by up to 45 %.

Furthermore, comparative calculations are used to show how high the CO_2-savings-potential is. On the one hand, the effect of reducing the dosing quantity is shown. On the other hand, an overview of the range of CO_2-footprints of standard fibres from different manufacturers with comparable dimensions and steel tensile strengths is provided.

Finally, case studies of real construction projects are presented to realistically estimate the savings potential. The information in this article shows that the best possible selection of a technically suitable steel fibre can make a significant contribution to reducing the environmental impact of sprayed concrete mixes and, at the same time, enable economic benefits.

Keywords: Sprayed concrete, steel fibres, Global Warming Potential, CO_2-saving

1 INTRODUCTION

The reduction of CO_2-emissions is becoming increasingly important worldwide. Norway has a pioneering role in this area, partly due to its history. Under the leadership of Norwegian Prime Minister Gro Harlem Brundlandt, the "Brundlandt Commission" developed the guiding principle "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" on behalf of the United Nations in 1987 [1].

This was the starting point for the work in Norway on sustainability, which is also being actively promoted by Norwegian industry in particular [1].

Consequently, the focus is also on sustainability in the field of tunnelling. This article takes a closer look at sustainability, particularly the CO_2-emissions (Global Warming Potential - GWP) of (steel fibre-reinforced) sprayed concrete and highlights the CO_2-savings potential.

There are two major levers for reducing the CO_2-footprint:

- Reduction of the concrete volume
- Use of raw materials with the lowest possible GWP

The following chapter will first show why the use of steel fibres for permanent sprayed concrete tunnel linings can help to reduce the concrete volume.

2 PERMANENT SPRAYED CONCRETE LININGS

2.1 General information

The use of steel fibre-reinforced sprayed concrete for the permanent lining of tunnels makes it possible to reduce the volume of concrete [2]. A comparison of Figures 1 and 2 and Table 1 shows that the Permanent Sprayed Concrete Lining(s) (PSCL) enables an overall thinner solution than a conventional solution as Double Shell Lining (DSL).

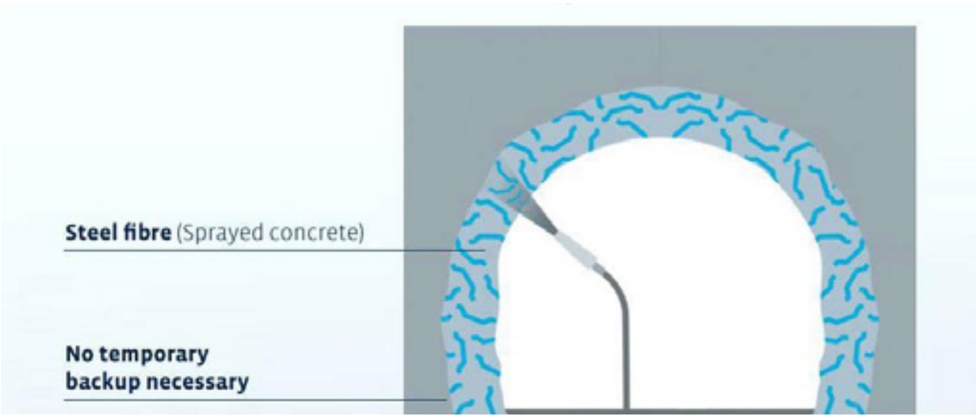

Figure 1 - Solution with steel fibre reinforced sprayed concrete [3]

Due to the ever-advancing development of the technology used, such as spraying robots, as well as constantly improving control and design methods, standards and guidelines, sprayed concrete is being used more and more frequently as a permanent lining method. In particular, the use of steel fibre-reinforced (see Figure 1) for (permanent) protection (final tunnel lining) is therefore increasing worldwide.

In Norway, the use of synthetic fibres has become rare and is not permitted for some applications for environmental reasons, as the fjords have been heavily polluted by floating plastic fibres [4]. The use of steel fibre-reinforced sprayed concrete offers numerous advantages:

1. Lower maintenance costs thanks to reduced cracking.
2. Concrete surface is much less sensitive to potential damage.
3. Faster completion of the tunnel through time- and cost-saving construction processes.
4. Simple handling: Only one step in the reinforcement process as the fibres are applied together with the concrete.
5. There is no need for temporary support because conventional reinforcement isn't installed, and the sprayed concrete can be applied directly as a finished layer.
6. Significantly increased service life thanks to the greater durability of fibre concrete.
7. High fire resistance when Polypropylene (PP) micro-fibre concrete is used.

Conventional lining (see Figure 2) has several disadvantages compared to the sprayed concrete solution:

1. The surface of the concrete is unprotected and susceptible to damage resulting from the greater spacing with classic reinforcement.
2. Installation of the steel bar reinforcement is considerably more time-consuming as the reinforcement is applied in a separate work step.
3. Very complex reinforcement situation with an irregular surface and holes.
4. Complex and close-mesh reinforcement can easily result in "spray shadows" (voids), which in turn can quickly lead to water ingress and further cracks.

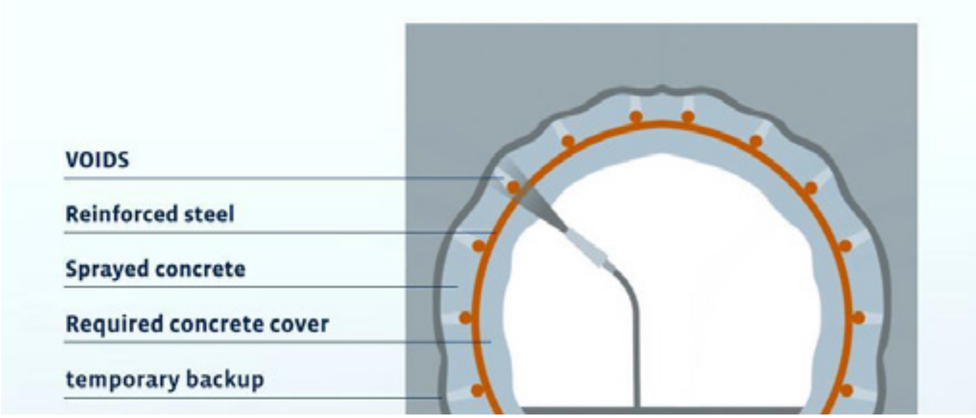

Figure 2 - Solution with conventional reinforced sprayed concrete [3]

The explanations described above are also discussed in detail in the ITA Report "Permanent Sprayed Concrete Linings" [2] and excerpted in the following chapter 2.2.

2.2 GLOBAL WARMING POTENTIAL OF PSCL

To obtain a valid basis of information for the life cycle assessment of a product, an Environmental Product Declaration (EPD) is often required to disclose the CO_2-balance of building products and thereby promote sustainable construction.

An EPD is a comprehensive, independently verified, and registered product passport. It contains life cycle information, characteristics of the life cycle analysis and test results for a detailed assessment of building materials and construction products. They are based on the international standard ISO 14025 [5]. Regarding the construction industry, EPDs are based on the EN 15804 standard [6] for construction products, services, and processes.

An EPD is ideal for communicating the environmental performance of building products and thus promoting sustainable construction. In the requirements for sustainable products, the focus today is primarily on the Global Warming Potential (GWP).

In the further course of the article, the GWP is illustrated using EPD.

Table 1 below shows the assumptions in [2]:

Table 1 - Key parameters for the comparison between PSCL and DSL carbon footprints [2]

Item	Hard rock PSCL	Hard Rock DSL
Primary lining concrete thickness (mm)	80	80
Primary fibre/bar (kg/m³)	40	40
	Steel fibre	Steel fibre
Membrane	40	0
	SAWM	PVC Sheet
Secondary lining concrete thickness (mm)	80	300
Secondary fibre/bar (kg/m³)	40	97
	Steel fibre	Steel bar

In [2], a sprayable waterproofing membrane (SAWM), which requires a regulating layer (a total thickness of 40 mm is assumed), is selected for waterproofing the PSCL option, and a conventional PVC waterproofing membrane is selected for the DSL options.

Sprayed concrete formulations usually have a higher cement content and therefore a higher GWP per cubic meter, but this is significantly reduced due to the low concrete volume (see chapter 2.1), resulting in a lower GWP overall (see Figure 3). The content of steel fibres is generally also significantly lower than the total amount of conventional reinforcement made of steel bars (see Table 1 and Figure 3).

The calculations show that a PSCL variant can result in GWP savings of approx. 20 to 50 % compared to the DSL variant (see Figure 3).

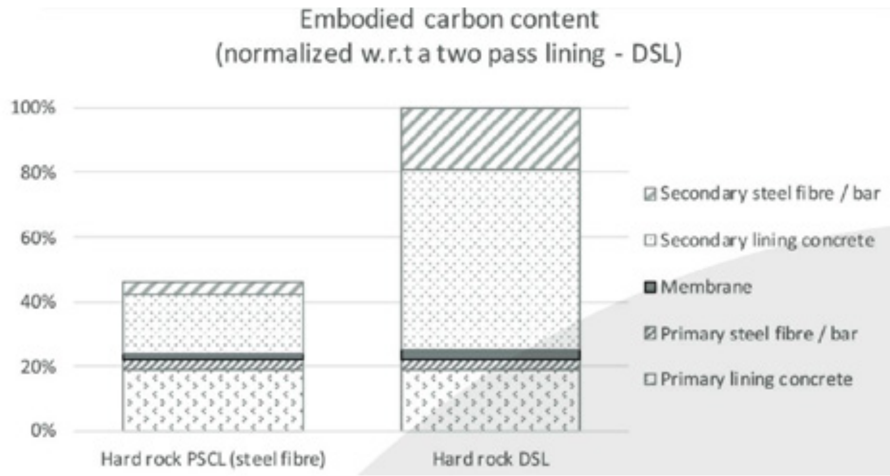

Figure 3 - Embodied carbon for hard rock tunnel linings (normalized w.r.t a two pass lining - DSL) [2]

In summary, it can be said that significant quantities of concrete can be saved, particularly with steel fibre-reinforced sprayed concrete.

3 CO_2 -SAVING AND RESPONSIBILITY

The main emitter of CO_2 from concrete is cement. The higher the proportion of clinker, the higher the CO_2-emissions. In the publication "Sustainability in Norwegian Tunnel" [1] reducing the proportion of clinker is identified as one option.

Unfortunately, practice has shown that the mixes have not changed significantly over the last decade. The reason for this is not a reluctance on the part of concrete manufacturers, construction companies or clients to use other cements, but rather the existing requirements for sprayed concrete. Both the required early strength and occupational safety still largely prevent the use of alternative cements.

This means that CO_2-savings can be achieved "only" through the other raw materials used, in addition to those already achieved through the steel fibre-reinforced construction method.

With our partner Mapei AS, we have therefore been endeavoring for over 10 years to find the most efficient sprayed concrete possible to reduce the dosing quantity as much as possible. In addition to a direct reduction in the CO_2-footprint of the formulation, CO_2-emissions during transport should also not be ignored, as significantly fewer journeys are required for the construction work.

The fibre producer takes the issue of responsibility very seriously, which is reflected in four areas:

- Consistent actions,
- fair and humane treatment,
- sustainability and
- reliability

As a manufacturer, we consume energy and impact the environment around us. However, it is important to us that we keep this impact as low as possible: since 2015 we only purchased 100 % green electricity from renewable energy, maintain short, low-emission delivery distances (90 % of the raw material is delivered by ship in an environmentally friendly way), ensure a high recycling rate of our products, and promote sustainable mobility and energy among our employees and in the company.

In the following, the development and the CO_2-saving-potential is shown based on real tunnels.

4 CASE STUDY

The case study compares two Norwegian tunnelling projects. Firstly, the Ryfast tunnel, which was built between 2015 and 2018, and the Rogfast tunnel, which has been under construction since 2023.

While the normal-strength fibre DE 35/0.55 N with a length of 35 mm and a diameter of 0.55 mm with a tensile strength of 1,250 N/mm² was used for the Ryfast tunnel, a 40 mm long fibre with a diameter of 0.55 m and a tensile strength of 1,800 N/mm² was used for the Rogfast tunnel.

Until around 2019, a fibre with a length of 35 mm and a diameter of 0.55 and a tensile strength in the range of approx. 1,200 to 1,300 N was commonly used worldwide for permanently applied sprayed concrete and is still frequently used today.

The main parameters of the two tunnels are summarized in Table 2.

Table 2: Parameter Ryfast and Rogfast tunnel

Parameter	Unit	Ryfast tunnel	Rogfast tunnel
Total length	m	28,600	51,000
Sprayed thickness	m	0.10	0.10
Sprayed concrete	m³/m	2.27	2.40
GWP concrete - A1 to A4[1)]	kg CO_2/m³	277.929	283.030
Fibre	-	DE 35/0.55 N	DE 40/0.55 M
Fibre dosage[2)]	kg/m³	28.00	21.75

1) Without fibres
2) ~ 75 % E700 and ~ 25 % E1,000

The concrete used for both tunnels had to fulfil the requirements of strength class B35 and durability class M40. As is generally known (see chapter 2.2), the cement content is somewhat higher in sprayed concrete mixes with steel fibres and is around 448 kg/m³ in this mix, which accounts for the majority of the GWP. The difference in GWP between the two tunnels per cubic meter of concrete is due to the slightly longer transport distances for Rogfast tunnels.

The detailed composition of the formulation is shown in the Table 3.

The steel fibre-reinforced sprayed concrete used in both tunnels had to meet the requirements for energy absorption class E700 for around 75 % of the areas and energy absorption class E1000 in accordance with EN 14887-1 [7] for the remaining approx. 25 %.

This results in an average dosage of 28 kg/m³ of DE 35/0.55 N for the Ryfast tunnel and 21.75 kg/m³ of DE 40/0.55 M for the Rogfast tunnel.

Table 3: Mix design for 1 m³ sprayed concrete B35 M40 D8 Spr 220 mm - E700 and E1000 [8]

Raw Material	Unit	Content
Air entrainer	kg/m³	1.00
Supplementary Cementitious Materials (SCM)		49.76
Cement		447.85
Superplasticizer		4.98
Aggregates		1,573.00
Water		188.00

By using the DE 40/0.55 M instead of the DE 35/0.55 N, a reduction in dosage of around 22 % was achieved in the Rogfast tunnel - with the same performance (see Figure 4, left).

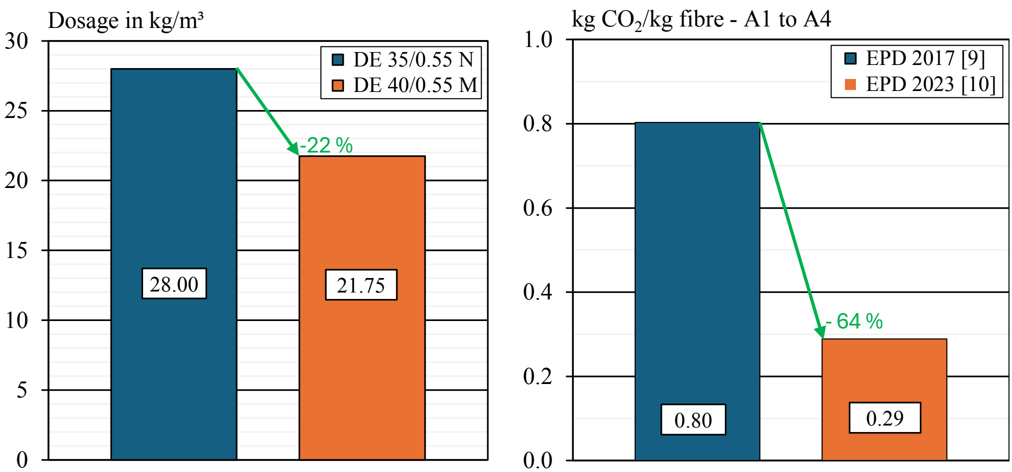

Figure 4 – Reducing the dosage (left) and reducing the GWP [9, 10] (right)

In addition to reducing the dosage, the GWP of the steel fibre has also been significantly reduced since 2017. While the value for the production stage (A1 to A3) in 2017 [9] was still around 0.771 kg CO_2 /kg fibre, this was significantly reduced to 0.257 kg CO_2/kg fibre by 2023 [10]. The share of transport A4 was simplified (basis [10]) to 0.032 kg CO_2/kg fibre. This value is used in the following to simplify the categorization of the results for the known range of GWP of comparable fibres and can be classified as very conservative for this.

Thanks to the progressive requirements and our customers and partners in Norway KrampeHarex has developed to the leading manufacturer for high performing steel fibres with the lowest GWP [10]. This was a long way which we continue mindful and persistent.

KrampeHarex has been sourcing 100 % of its electricity from renewable energy sources since 2015. The installed photovoltaic system produces more than 1.5 GW per year, which allows us to reduce our energy purchase by 15 %.

We also have established an energy management system according to ISO 50001 [11] what forces us to increasing efficiency constantly.

As a result of the measures described, the GWP was reduced by approx. 64 % (see Figure 4, right).
Table 4: Comparison of the GWP of different fibre types and possible CO_2-savings

Fibre typ	Dosage	GWP A1 to A4		CO_2-saving related to the reference
	kg/m³	kg CO_2/kg fibre	kg CO_2/m³	%
DE 35/0.55 N - reference	28.00	0.80 [9]	22.48	-
DE 40/0.55 M	21.75	0.29 [10]	6.29	72.04
Comparable fibre „low“	21.75	0.83	18.10	19.52
	7.56		6.29	72.04
Comparable fibre „high“	21.75	2.03	44.20	- 96.57
	3.09		6.29	72.04

Table 4 shows the GWP (A1 to A4) for the two fibres DE 35/0.55 N and DE 40/0.55 M as well as the range of known comparable fibres. Comparable fibre "low" represents the lower limit with a value of 0.83 kg CO_2 /kg fibres and comparable fibre "high" represents the upper limit with a value of 2.03 kg CO_2 /kg fibres. As explained above, a value of 0.032 kg CO_2/kg fibres was used for A4 for all four fibres, which is probably far too low for the comparable fibres.

In addition to the determined GWP values (A1 to A4) per cubic meter of concrete, the CO_2-savings-potential was also calculated in relation to the reference (DE 35/0.55 N, 28 kg/m³, EPD 2017 [9]). For the two limit values, a dosage of 21.75 kg/m³ was applied, as for DE 40/0.55 N. On the other hand, the content was calculated at which the same GWP is achieved as for DE 40/0.55 M with a dosage of 21.75 kg/m³.

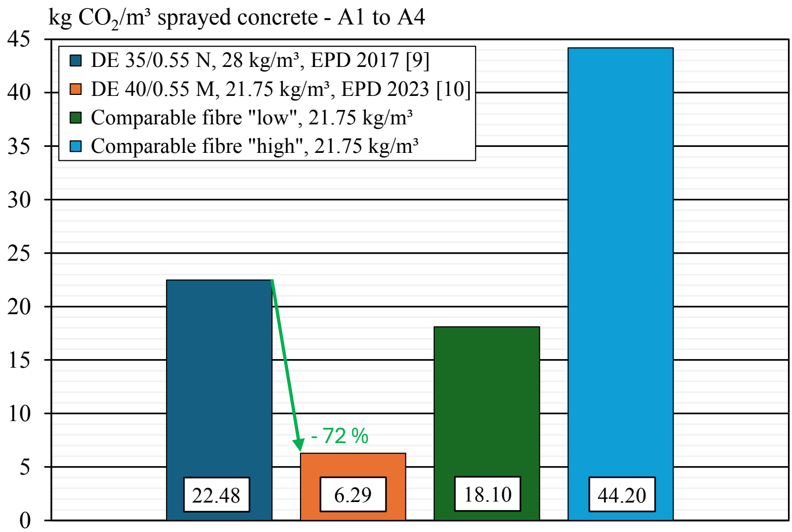

Figure 5 – Comparison of the GWP – A1 to A4 - in kg CO_2/m³ sprayed concrete of different fibres

Figure 5 shows that the low dosage of DE 40/0.55 M (21.75 kg/m³) in combination with the improved EPD results in a reduction in GWP of around 72 % for the fibres in the Rogfast tunnel compared to the Ryfast tunnel with DE 35/0.55 N and a dosage of 28 kg/m³. The comparison with the comparable fibres - dosage 21.75 kg/m³ - shows that with a low CO_2-footprint, there would only be a savings potential of just under 20 % and with a high CO_2-footprint almost double the CO_2-emissions compared to the Ryfast tunnel.

Furthermore, a comparison is made of the maximum dosing quantity that is possible to comply with the 6.29 kg CO_2/m^3 as with the DE 40/0.55 M in the Rogfast tunnel. The results are shown in Figure 6. With the DE 40/0.55 M, 288 % (comparable fibre "low") or 709 % (comparable fibre "high") more can be dosed than with the comparable fibres. Conversely, only 7.56 kg/m³ (comparable fibre "low") or 3.09 kg/m³ (comparable fibre "high") could be used to comply with the same CO_2-footprint.

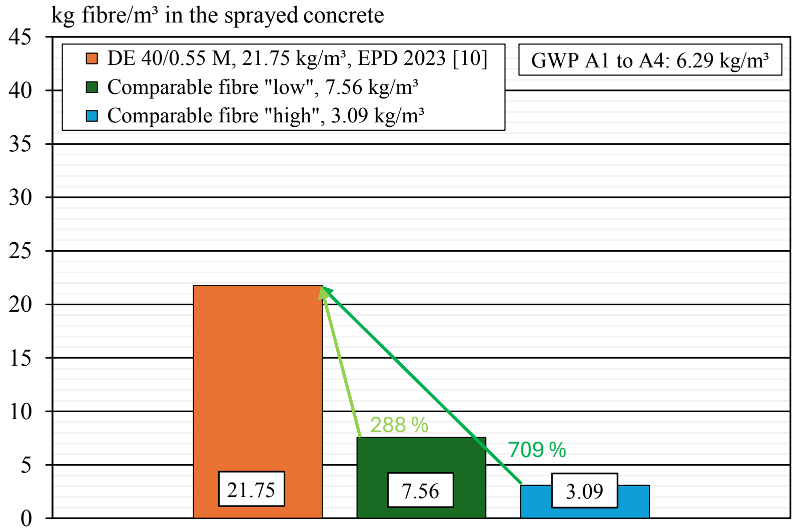

Figure 6 – Maximum dosage for reaching the same GWP A1 to A4 of 6.29 kg/m³ sprayed concrete

Chapters 2 and 3 have already explained that the use of steel fibre-reinforced sprayed concrete and a reduction in the proportion of clinker can make a considerable contribution to significantly reducing the GWP. According to [2], potential savings of 20 to 50 % are possible.

In this case study, the focus was "only" on the savings potential through the selection of the right fibres. Table 5 therefore only considers the effects of the fibre. The use of DE 40/0.55 M in the Rogfast tunnel resulted in CO_2-savings of approx. 3.7 % on the entire concrete, which corresponds to around 1,373 tons.

Table 5: GWP Tunnel with fibres

Parameter	Unit	Ryfast tunnel	Rogfast tunnel
Total length	m	28,600	51,000
Sprayed thickness	m	0.10	0.10
Sprayed concrete	m³/m	2.27	2.40
GWP concrete - A1 to A4[1)]	kg CO_2/m^3	277.93	283.03
Fibre	-	DE 35/0.55 N	DE 40/0.55 M
Fibre dosage[2)]	kg/m³	28.00	21.75
GWP fibre	kg CO_2/m^3	22.48	6.29
GWP concrete + fibres	kg CO_2/m^3	300.41	289.32
CO_2-savings	%	-	3.7
CO_2-savings	kg		1,373,385.60

1) Without fibres
2) ~ 75 % E700 and ~ 25 % E1,000

5 CONCLUSION AND OUTLOOK

Sustainability is becoming increasingly important in the construction industry and therefore also in tunnelling. Norway is playing a pioneering role here.

The use of steel fibre-reinforced sprayed concrete for permanent tunnel linings can make a major contribution here, as significantly less concrete is used, and less excavated material must be removed from the tunnel.

As the concrete formulas for sprayed concrete in Norway are currently not yet being changed significantly due to the requirements for early strength and occupational safety, a good selection of a high-performance fibre with a low CO_2-footprint can contribute to sustainability, especially in the raw materials.

As part of this article, the Ryfast and Rogfast tunnels were analyzed in a case study. It was shown that with the DE 40/0.55 M it was possible to reduce the dosage by approx. 22 % while maintaining the same performance requirements. In addition, the CO_2-footprint of the fibre has been significantly reduced in recent years thanks to a consistent selection of raw materials, production using green electricity and comparatively low-CO_2-emission transport by ship and rail to Norway, resulting in a reduction in GWP of around 72 %. Compared to comparable fibres, up to 700 % more fibres can be added with the same GWP.

It is known from other projects that potential savings of up to 45 % can be achieved in terms of fibre dosage with the DE 40/0.55 M, so that the CO_2-footprint can be further reduced in relative and absolute terms.

In addition to the CO_2-savings, the significantly lower dosages also result in considerable reductions in reinforcement costs, which will further promote the use of steel fibres in sprayed concrete construction in the coming years.

We would like to thank Ølen Betong AS and Mapei AS for their support with this article!

6 References

[1] Norwegian Tunnelling Society: Sustainability in Norwegian Tunnel, Publication no. 30, 2022

[2] ITAtech: ITA Report n°24 - Permanent Sprayed Concrete Linings - N°ISBN: 978-2-9701242-6-9, October 2020

[3] https://www.krampeharex.com, Retrieved on: 01.05.2024

[4] Myren, A. S.; Hagelia, P.; Bjøntegaard, Ø.: The ban of polymer fibre in FRSC in Norwegian road tunnels, Conference: 8th International Symposium on Sprayed Concrete, Trondheim, Norway, 11-14 June 2018

[5] DIN EN ISO 14025:2011-10: Environmental labels and declarations - Type III environmental declarations - Principles and procedures (ISO 14025:2006); German and English version EN ISO 14025:2011

[6] DIN EN 15804:2022-03: Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products; German version EN 15804:2012+A2:2019 + AC:2021

[7] DIN EN 14487-1:2023-03: Sprayed concrete - Part 1: Definitions, specifications and conformity; German version EN 14487-1:2022

[8] Ølen Betong AS: Environmental Product Declaration "B35 M40 D8 Spr 220mm A1-A4", NEPD-3204-1846-NO, EPD-Norge, valid until 02.10.2028

[9] Mapei AS: Environmental Product Declaration "Steelfibre (DE 35/0,55 DE 50/0,55 og DE 50/1,0)", NEPD-1383-447-NO, EPD-Norge, valid until 19.09.2022

[10] KrampeHarex GmbH & Co. KG: Environmental Product Declaration "Steel fibre with hooked ends", NEPD-4605-3859, EPD-Norge, valid until 18.01.2028

[11] DIN EN ISO 50001:2018-12: Energy management systems - Requirements with guidance for use (ISO 50001:2018); German version EN ISO 50001:2018

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