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Reducing CO_2 emissions from grouting in hard rock tunnelling

H. Strømsvik
SINTEF Community, Trondheim, Norway
helene.stromsvik@sintef.no

Abstract

Cement-based pre-excavation grouting represents a significant portion of the total CO_2 emissions from hard rock tunnelling, particularly in urban projects. This paper presents strategies to reduce these emissions through; 1) optimisation of grouting strategies using real-time on-site monitoring, and 2) the use of grouts with lower CO_2 emissions. An example is presented, demonstrating how real-time monitoring with decision support, combined with adaptive procedures, can enhance grouting efficiency, reduce grout consumption, and minimise the environmental impact of PEG operations, achieving up to a 30–40% reduction in grout consumption. Additionally, the study presents two alternative grout materials: 1) Silica Green Stone (SiGS) as a cement replacement, and 2) alkali-activated grout utilising mining tailings, with no cement. The potential emissions reductions for these innovative grouts are 29% and 62%, respectively, compared to traditional cement-based grouts. The study also highlights the potential to use industrial byproducts, further enhancing the sustainability of PEG.

Keywords

Rock Mass Grouting, CO_2 emissions, Tunnelling

1 Introduction

Pre-Excavation Grouting (PEG) of rock mass during underground construction is a complex process dependent of many factors, as shown in Table 1.

Table 1 Overview relevant factors for PEG.

Execution	Grout	Site conditions	Factors of success
Procedures	Type of grout material	Joint characteristics	Is the LRIR[1] met?
Stop criteria	Rheology/flow properties	Number of joints	Time and cost
Grouting pressure	Material fineness	Overburden	CO_2 emissions
Number of holes	Early setting time	Rock Stress	
Length of holes	Bleeding	Groundwater pressure	
Contract	Filtration stability	Rock type	
Equipment	Penetrability	Limit Residual Inflow Rate (LRIR)	
Worker qualification	Additives	Surroundings	
	Temperature		

[1] LRIR= Limit residual inflow rate

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The factors in the first two columns of Table 1, *Execution* and *Grout*, can be categorised as controllable variables that can be adjusted to achieve a satisfactory grouting outcome. Conversely, the factors associated with *Site Conditions* are considered uncontrollable, forming the framework within which grouting activities must be tailored. In many cases, the site conditions have the most significant influence on the Residual Inflow Rate (RIR), as well as the resources required, such as time and materials, which directly impact costs. However, substantial potential exists to reduce resource consumption through optimisation of execution-related factors and the selection of grout materials.

The CO_2 emissions associated with pre-excavation grouting (PEG) are directly tied to the quantity and type of materials used. This paper explores how specific factors can significantly reduce material consumption and presents a study on innovative alternative grout materials aimed at minimising CO_2 emissions from PEG.

One of the most challenging aspects of rock mass grouting is the inherent variability of geological conditions; no two sites are identical, and there is no universal method that suits all ground conditions and objectives. Furthermore, each borehole in a grout round presents unique characteristics, requiring individualised handling to achieve effective grouting. This underscores the importance of on-site monitoring and the implementation of robust procedures, enabling the full application of expertise and craftsmanship to ensure successful outcomes.

1.1 Grout consumption in Norwegian tunnelling projects

Grout consumption for pre-excavation grouting (PEG) varies significantly across different tunnelling projects. Fig. 1 illustrates the average grout consumption per grouting round in four recently excavated tunnels in Norway, encompassing both railway and road tunnels in rural and urban settings, including one subsea tunnel. The data, sourced from the Logic Grouting project, reveal large standard deviations in consumption, with particularly high levels in Tunnel 3. Tunnels 2 and 4 align with the findings of Strømsvik (2019), who analysed grout consumption in six Norwegian tunnels.

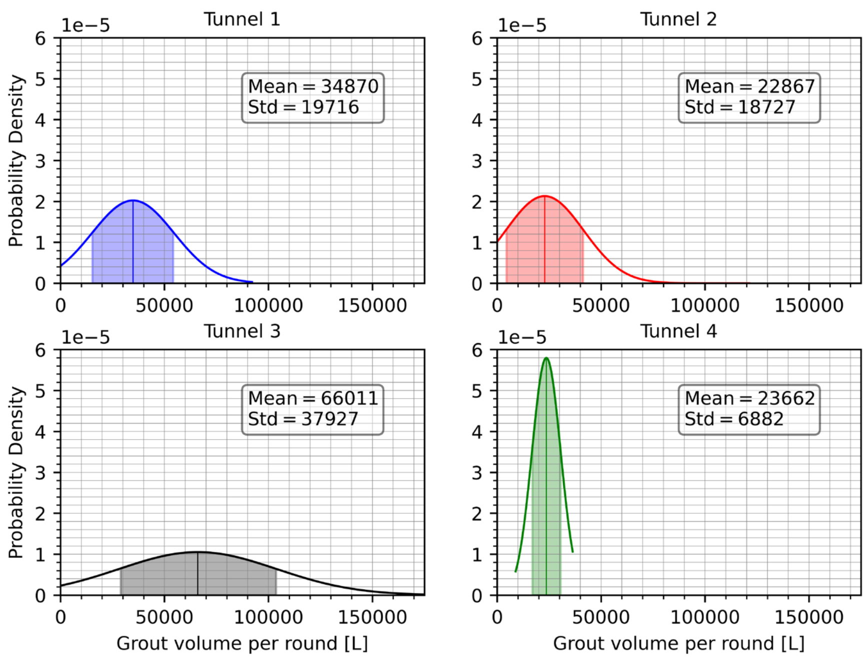

Fig. 1 Grout consumption per round of PEG in four Norwegian tunnels.

Despite substantial variations in overall grout consumption, both within individual projects and between different tunnels, the distribution of grout within the holes in a single PEG round follows a similar pattern. This pattern is depicted in Fig. 2, where grout consumption across holes in one round of PEG is analysed. When the holes are ranked from highest to lowest consumption, it becomes evident that approximately 20% of the holes (those with the highest consumption) account for 55–65% of the total grout consumption. Conversely, 30% of the holes (those with the lowest consumption) require only minimal grout, primarily for hole filling.

Based on these observations, three categories of grout consumption are defined:

1. High grout consumption: The 20% of holes with the highest consumption, labelled "grout loss" with red background in Fig. 2.
2. Intermediate consumption: The 50% of holes with moderate consumption, labelled "effective local grouting" with green background in Fig. 2.
3. Hole filling: The 30% of holes with the lowest consumption, labelled "hole filling" with yellow background in Fig. 2.

These categories are specific to the data used in this study and may not be directly applicable to other projects. The grouting procedures used in the analysed projects align with the traditional Norwegian practice, as described in Strømsvik and Grøv (2023).

This study leverages Categories 1 and 2 to elucidate fundamental principles of grouting and to explore strategies for reducing grout consumption.

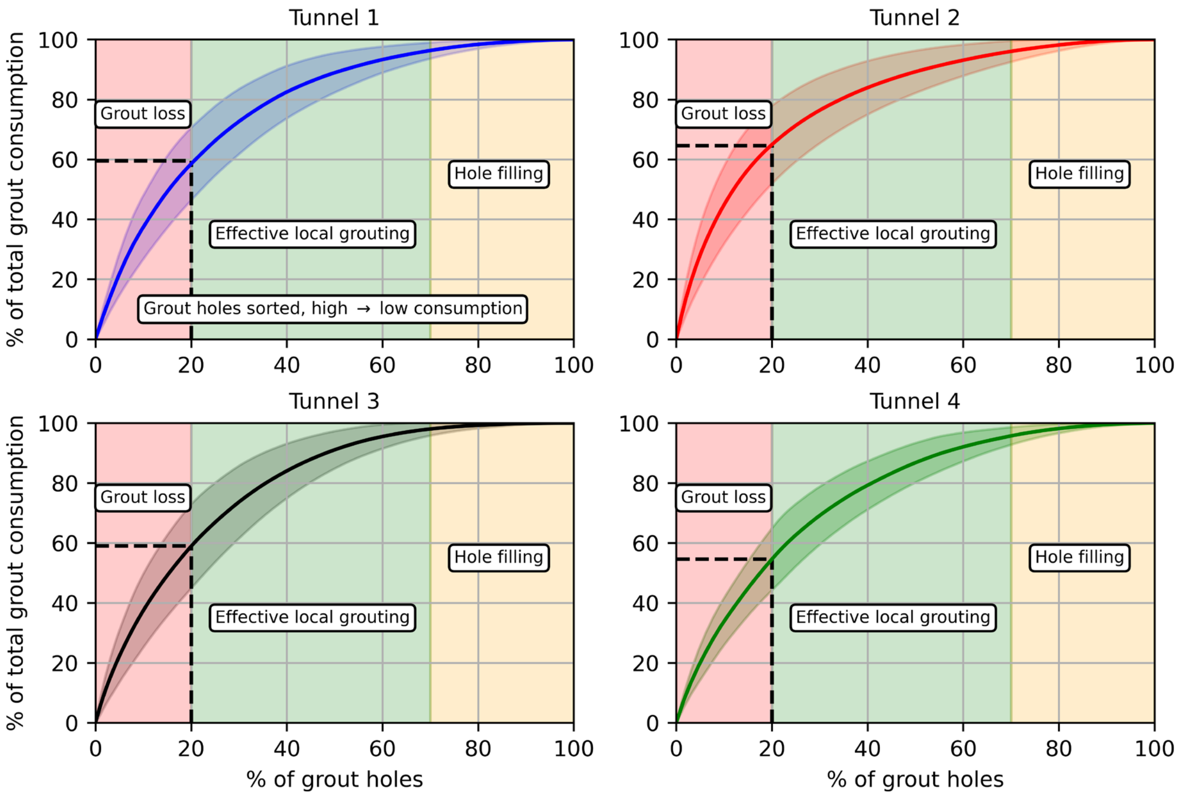

Fig. 2 Gout holes in one round of PEG, sorted from high to low grout consumption, showing the accumulative percentage of the total grout consumption in one round of PEG. The background colours, red, green and yellow, represents respectively category 1, 2 and 3.

Fig. 3 illustrates the volume of grout consumption for all analysed grout holes for the four tunnel projects, arranged in ascending order of grout usage. It is observed that approximately 48% to 60% of the total grout is utilised in holes where 1000 Litres already is grouted.

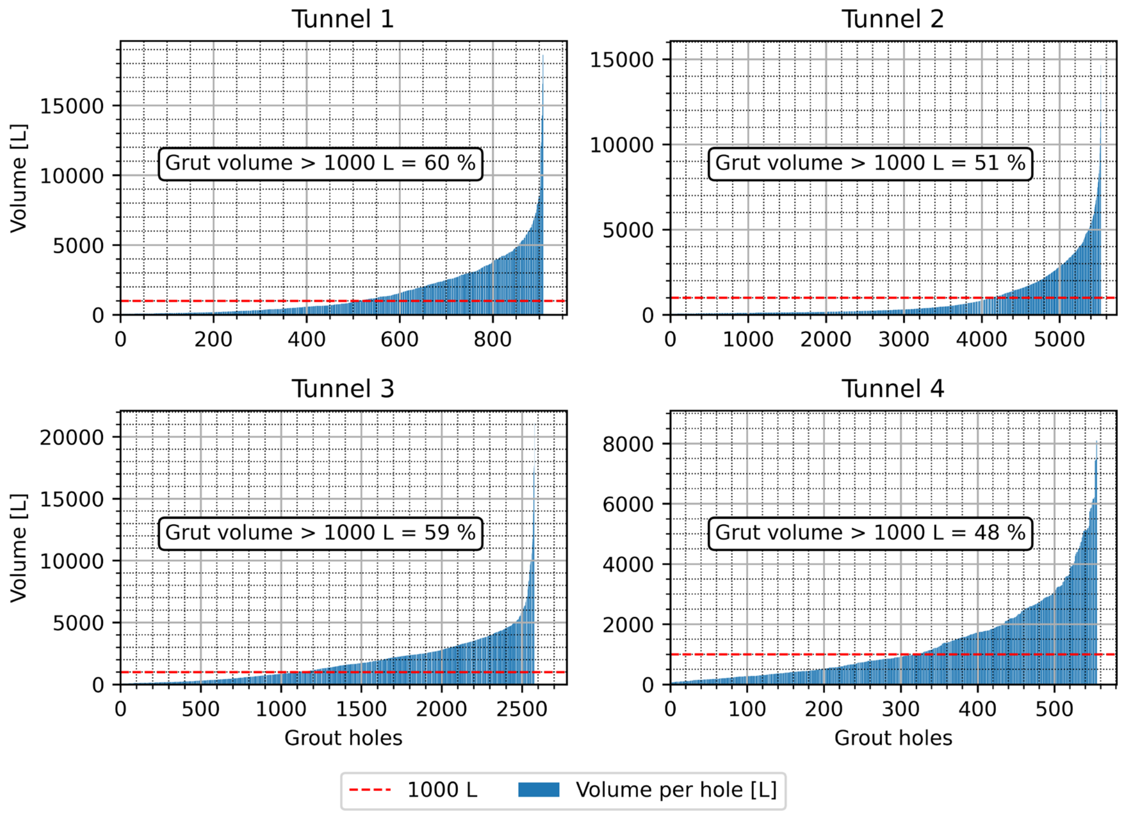

Fig. 3 Grout consumption for all the grout holes for each of the four tunnel projects, sorted from low to high grout consumption.

The presented data reflect a typical scenario encountered in many Norwegian tunnelling projects, thereby underscoring the importance of discussing resource optimisation strategies. Optimising the use of resources in this context can lead to significant reductions in both costs and CO_2 emissions.

1.1.1 Holes with high grout consumption (Category 1)

In open fractures that readily accept grout material, the grout typically flows through channelled pathways. The grout follows the path of least resistance within these channels, often moving upward toward the surface and areas of lower groundwater pressure. Under such conditions, the grouting does not contribute significantly to the filling of entire fracture planes within larger fractures in close proximity of the tunnel, or infiltrating finer fractures. The grout disperses with channelised flow through the open fractures, while finer fractures receive little or no grout.

This forms the basis for the following considerations for grouting of holes in category 1:

- *Prolonged grouting without intervention is inefficient,* as it has minimal impact on the intended target areas, namely the fractures near the tunnel profile.
- *Grouting with a low water-cement (w/c) ratio intensifies channel flow*; low-viscosity grout creates thinner channels, further concentrating the flow.
- *Distributing grout effectively across both open and finer fractures is highly resource-intensive*, with a high risk of unsuccessful grouting.

The result is often an unnecessary overuse of grout, a high risk of hydraulic fracturing in open fractures, and a substantial chance of inadequate sealing. Hydraulic fracturing exacerbates these issues by increasing grout flow into open fractures, while pressure loss can further deteriorate conditions for the grouting of finer fractures.

1.1.2 Holes with intermediate grout consumption (Category 2)

The grouting of holes with intermediate grout consumption is often finished by reaching the refusal criterion, which means close to zero flow at a given pressure. In such situation the grout does not run off from the intended focus area of grouting. And the grouting conditions can be considered as optimal for the grouting of fractures in the proximity of the tunnel. The grouting results depend on the grout properties, such as penetrability, bleeding and rheology. In such holes, the use of low-viscosity grouts could give unsuccessful grouting as this could significantly reduce the penetrability of the grout.

2 Optimisation of grouting strategy and the use of real-time on-site monitoring

As outlined in Section 1.1, the optimal grouting strategy for PEG varies based on the specific characteristics of each borehole within a grouting round:

1. High grout consumption (Category 1): Actions are required to control and minimise grout loss.
2. Intermediate grout consumption (Category 2): Grout materials should be optimised to ensure adequate penetrability in fine fractures.

The challenge lies in identifying the category of a grout hole as early as possible during the grouting process. Real-time on-site monitoring and adaptive procedures are key to achieving this, enabling adjustments to in-situ conditions during PEG for improved results and reduced material and resource usage.

In the Logic Grouting project, a real-time monitoring system was developed and tested through a cooperation between SINEF and Bever Control, with contribution from the industry from Bane NOR, AMV, Skanska, Veidekke and MossIA. This system provides decision support by offering filtered visualisations of grouting data, with notifications of:

- Risk of high grout consumption: the grout consumption is expected to be very high in a hole (Fig. 4 b).
- Signs of hydraulic jacking: Allowing for immediate adjustments of grouting pressure (Fig. 4 a, b).

The system enables dynamic adaptation of grouting strategies for individual grout holes as soon as possible.

The practical application of the monitoring system has demonstrated that grout hole categorisation can often be determined after 150–200 litres of grout. This early evaluation allows operators to:

- Decide whether to continue with the current grout recipe, or switch to a low-viscosity grout
- Adjust grout properties to reduce grout loss in high-consumption holes (Category 1).
- Respond to notifications of potential hydraulic jacking by pausing grouting and reducing pressure for the subsequent grouting, further mitigating grout loss and material overuse.

This continuous monitoring and adaptive approach improve grouting efficiency, minimises unnecessary material consumption, and reduces the environmental impact of PEG operations.

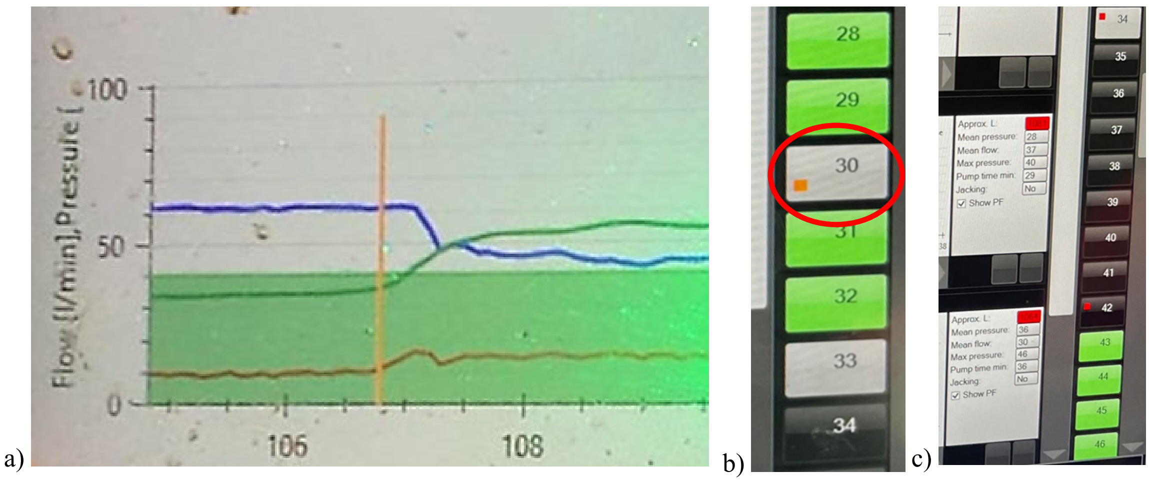

Fig. 4 Pictures of the display during real-time on-site monitoring with notifications; a) potential hydraulic jacking in orange, b) each hole with potential hydraulic jacking, and c) risk of high grout consumption shown in red.

Based on grout consumption data from traditional Norwegian grouting projects, as shown in Fig. 1, Fig. 2 and Fig. 3, implementing adaptive procedures guided by decision support from an on-site real-time monitoring system could realistically achieve a 30–40% reduction in grout consumption. This reduction would lead to significant savings in time, materials, and costs, while also lowering CO_2 emissions associated with pre-excavation grouting (PEG). If only the production of the materials (cradle-to-gate) is considered, the reduction in CO_2 emissions would be reduced by 30-40%. It is challenging to provide specific numbers for potential reduction CO_2 emissions and time, as some strategies of conservative grout consumption might lead to secondary rounds of grouting.

Each tunnelling project presents unique site conditions. The procedures and actions should be carefully planned to suit the specific project conditions, considering surroundings, overburden, LRIR, groundwater and other relevant conditions. Each project should prepare a toolbox for grouting, including materials and strategies, to adjust to the site conditions. As previously discussed, no two sites are alike, and a single method cannot address all ground conditions or project goals. By combining real-time data analysis, adaptive strategies, and a well-prepared grouting toolbox, projects can achieve improved efficiency and sustainability, aligning with both economic and environmental objectives.

3 Grout with reduced CO_2 emissions

In the Norwegian research project "Sustainable value chain and use of materials in road construction", the aim is to find novel ways of reducing environmental impacts of road infrastructure through recycling and reuse of waste materials. This includes performing full-scale pilots of new and sustainable solutions for roads, including tunnels and constructions along the road. In this project, two new materials were introduced as potential products for PEG: 1) SiGS (Silica Green Stone) as cement replacer, 2) Alkali-activated grout with the use of mining tailings, with no cement. The purpose of this study was to investigate if the two innovative grouts can adequately replace standard grout, and to have a baseline understanding of their climate reduction potential. A detailed description of this study can be found in Strømsvik & O'Born (2025).

The laboratory research on grout properties will not be presented in this context, but the main findings was as following; For tests on early setting time, bleeding, marsh funnel and mini-slump, all the results were comparable to standard cement-based grout recipes for both 1) SiGS as cement replacer in cement-based grout and 2) alkali-activated grout. The findings indicated that both can be potential future products for rock mass grouting in tunnels.

3.1 SiGS (Silica Green Stone) as cement replacer

SiGS (Silica Green Stone) is a byproduct waste from SiMn (Silico Manganese) production, produced by the company Eramet. SiGS is low in heavy metals, has no organic compounds and is inert to leaching in water, or in reaction to air. SiGS is also a zero-emission product, as it is a waste byproduct of the silicon manganese production process (Eramet, 2024). SiGS has during recent years been of interest in the concrete industry and is in the final stages of a standardisation for use as cement replacer in concrete. This is the first study where SiGS has been tested as cement replacer in cement-based grout.

For the test as grout, SiGS was ground down to a fineness of $D_{95} < 25$ µm, to be comparable to the grain size of "Injeksjonsement 25", delivered by Norwegian producer Heidelberg (Heidelberg Materials, 2024).

The approach with SiGS as cement replacer is the most developed technology, and SIGS has been thoroughly assessed as a material for cement replacement in concrete. Within the project "Sustainable value chain and use of materials in road construction", a full-scale PEG pilot will be conducted in a Norwegian tunnel under construction in 2025.

3.2 Alkali-activated grout with no cement

The Norwegian company Cemonite has developed a technology that uses mine tailings and other types of waste as raw materials to produce cement binders completely without Portland cement. The chemical process during hardening is alkali-activation (Cemonite, 2024). In this project this technology was used to produce alkali-activated grout. The alkali-activated grout was composed of

Norite, a co-binder and an activator. The Norite is mine tailings from the Tellnes mine (Titania AS), ground down to a fineness of D_{95} < 25 µm. The co-binder and activator are currently confidential. This technology is still in an experimental stage, and further development and research is needed.

3.3 LCA of innovative grouts with reduced CO_2 emissions

In Strømsvik & O'Born (2025), the assessment of CO_2 emissions was performed by using life cycle assessment methods (LCA) and the main findings are summarised in the following. Two innovative grout mixes were compared to the standard Heidelberg "Injeksjonsement 25" to find a baseline CO_2 profile. The LCA standard ISO 14040:2006 was followed for the analysis, which comprises four main parts: 1) Goal and scope, 2) Inventory analysis, 3) Impact assessment, and 4) Interpretation. The goal of this study was to compare the grout needed for a functional unit of 1 meter tunnel length for three different material mixes. The scope of this study is cradle-to-gate with the tunnel being designed under Norwegian conditions.

The material production is assumed to be carried out under Norwegian conditions with a Norwegian energy mix and normal local materials. It was assumed that each meter tunnel length would comprise 900 kg of grout and that the lifetime and mechanical properties of each grout were assumed to be identical based on the laboratory testing. The data collected for the life cycle inventory (LCI) came from meetings and internal documents with Cemonite and Eramet while the LCI of the base case scenario for ordinary micro cement comes from the recipe for the Heidelberg "Injeksjonsement 25". The analysis was carried out using SimaPro version 9.5.0.1 with the ReCiPe 2016 (midpoint, hierarchist perspective) impact assessment method chosen. The ecoinvent 3.9.1 (unit process) database was used, with some modifications to processes to account for Norwegian conditions, as described in Strømsvik & O'Born (2025).

Table 2 Life cycle inventory of the cement mixes, in percentages (Strømsvik & O'Born, 2025)

Mix	Water	CEM I	SiGS	Rheobuild	X-Seed	Activator	Norite	Co-binder
18	49%	50%	-	0,5%	0,5%	-	-	-
5	49%	35%	15%	0,5%	0,5%	-	-	-
4*	30.8%	-	-	-	-	19.25%	29.97%	19.98%

The results presented in Fig. 5, shows that the potential emissions reduction of using SiGS as cement replacement is 29%, compared to a traditional cement-based grout. The potential reduction for alkali-activated grout with the use of mining tailings is 62%, compared to a traditional cement-based grout. For alkali-activated grout the activator is the main contributor of CO_2 emissions, and the composition of the activator and thus the CO_2 emission for this type of grout is only an approximation based on current knowledge.

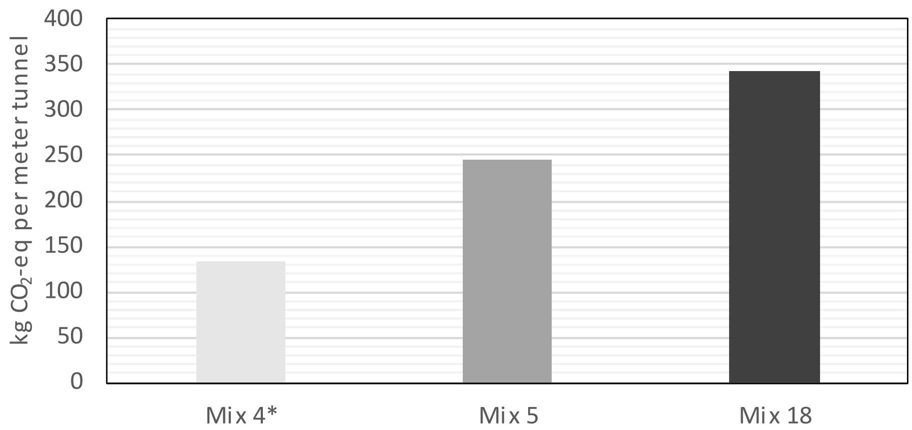

Fig. 5 Comparative CO_2-emissions between three grout mixes, per 1 m tunnel with 900 kg of grout (Strømsvik & O'Born, 2025)

4 Conclusions

Two different approaches for reducing CO_2 emissions from the process of PEG has been assessed and the potential for CO_2 emissions is shown in Table 3, where the potential reduction in CO_2 emissions for methods that is on the market (real-time on-site monitoring) and very close to the market (cement replacement with 30% SiGS) are presented.

Table 3. Potential reduction in CO_2 emissions for PEG with real-time on-site monitoring and cement replacement with 30%

Operation	**Reduction in CO_2 [%]**
Real-time on-site monitoring with optimised procedures	30-40
Grout with 30% cement replacement (SiGS)	29
Total	59-69

The results indicate the potential to significantly reduce the CO_2 emissions from PEG by both optimising the grouting process and using alternative materials as cement replacement. In addition to this, the costs can be reduced for both approaches. Real-time on-site monitoring and optimised procedures could reduce the use of time and materials, thus costs. For grout with SiGS as cement replacement the current market price for SiGS is significantly lower than for cement. It also shows that it is possible to use byproducts from other industries further improving the sustainability of PEG.

5 Acknowledgement

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