

Designing low carbon two-component grout in the tender process: Oslo E6 Clean Water Tunnel

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ABSTRACT: The necessary work that the civil engineering sector must undertake to improve the sustainability of infrastructures cannot overlook a more conscientious and attentive design with regard to the various impacts of the project. In mechanized tunnelling, the annular gap formed outside the tunnel lining is filled with mortar. Even though the mortar contains much less cement than concrete, it is usually injected in very large quantities and therefore has a significant environmental impact in terms of CO₂ emissions. These emissions can and should be reduced. Furthermore, the backfilling is usually in contact with the surrounding groundwater, which could be affected by the release of alkaline compounds from cement hydration. The tender documents for the E6 Clear Water Tunnel, part of the New Water Supply Oslo project, are an exemplary case where the technical specifications for the backfill grout were provided based on both the physical-mechanical properties of the fresh and hardened grout and its environmental profile in terms of carbon footprint and pH. This paper presents the research conducted by GEEG on behalf of Ghella to meet these requirements. The main objective was to identify possible mix designs for a backfill grout that would achieve high performance in terms of strength, low carbon footprint and low leachate pH. Keeping these targets in mind, the experimental activity was designed and carried out by applying innovative products and alternative solutions. Several mix designs were tested using cement-free binders or alternative cement and binder mixtures to investigate the effectiveness of additional cementitious materials such as slag and silica fume. All proposed solutions were able to achieve satisfactory performances in terms of strength and pH values of the sample leach water. The carbon footprint of each tested mix shows low CO₂ emissions both by completely and partially replacing cement with other binders.

1 INTRODUCTION

In mechanized tunneling, filling the annular void between the precast concrete lining and the surrounding soil is crucial. This operation can be done with the two-component grout system, consisting of a base component and an accelerator that are mixed to create a fast-setting mortar. Incremental improvements and innovations have been made over the past fifteen years, by companies and research institutions, to meet the evolving needs of the construction industry.

As tunneling technology advances, the specifications for backfill grout are increasingly demanding, leading to specific research activities and the development of innovative mix designs. These specifications now require not only better mechanical performance, but also the use of more sustainable materials. With the aim of reducing CO₂ emissions, the design phase of a tunnel takes on a more important role than in the past. Indeed, it is important to quantify carbon dioxide emissions at an early stage of project planning and work to reduce them by evaluating the use of innovative low-carbon materials as a total or partial replacement for Portland cement. This paper presents a study aimed at identifying potential mix designs for a backfill grout that meets the requirements specified in the tender documents for the E6 Clear Water Tunnel, part of the Project New Water Supply Oslo. For this project, technical specifications addressed both the physical-mechanical

properties of the fresh and hardened grout and awarded points for different solutions based on their environmental profile in terms of pH and carbon footprint. This emphasis on sustainability prompted the exploration of more environmentally friendly materials from the early stages of the project. The following sections describe the environmental aspects of the backfill grout considered in this case and the experimental work carried out to support Ghella in proposing mix designs for the tender. The results presented in this paper show that it is possible to evaluate different grout solutions in advance by using alternative materials, totally or partially replacing cement, which meet mechanical and environmental requirements at the same time.

2 ENVIRONMENTAL PROFILE OF BACKFILL GROUT

The evaluation of the environmental profile of a two-component backfill grout should quantify the impacts associated with each stage of the grout's life cycle. A full assessment should consider the impact of sourcing materials such as binder and any other compound used in the formulation, the energy consumption, water usage and waste related to the production, potential leaching of contaminants into the environment and the durability of the grout once in place. Eventually, the biodegradability of materials and the energy or resources required for recycling or disposal should be accounted for.

In this study, the focus was on the two aspects required by the tender documents, namely CO₂ emissions and the alteration of groundwater caused by alkaline compounds released from the mortar.

2.1 *Carbon footprint*

The concrete industry and particularly the cement production are responsible of about 5-8% of the total global carbon dioxide emissions (Nehdi et al., 2024). More than half of the gross CO₂ emissions for a ton of cement are due to the chemical reaction producing clinker, while the remnant is due to the fuel and energy used to run the production plants.

The carbon footprint of a product is expressed by the GWP (Global Warming Potential) in kgCO₂e/ton, which is one of the indicators in a LCA (Life Cycle Assessment). The full LCA of cementitious materials as concrete and mortar entails the analysis of their impact from “cradle to grave”, i.e. from resource extraction to use and disposal phase, but, at an early stage of the project when a lot of information about the suppliers and the plants are still unknown, a rather simple comparison between design solutions can be made based on the GWP values of the single components of each mix design estimated in the system boundary “cradle to gate”, A1 – A3, provided by the manufacturer in the Environmental Product Declaration (EPD), thus not considering a specific jobsite.

The Intergovernmental Panel on Climate Change (IPCC) has identified the substitution of current concrete binders with high fly-ash and slag content binders or geopolymers as a realistic option for reducing CO₂ emissions. In fact, cement may be partially replaced with supplementary cementitious materials (SCMs) obtaining satisfying compressive strength and improved durability, fillers may be introduced enhancing the strength, geopolymers or cement-free binders may be used as cement substitutes. The range of possible solutions for reducing the carbon footprint of the backfill grout depends on the technical requirements in terms of workability of component A, of gel time and of compressive strength at early stage and at 28 days of curing that the grout should meet. Each option comes with possible shortcomings that can be prevented adjusting the mix accordingly.

2.2 *Release of alkaline compounds*

Two-component backfill grout may alter the pH of the surrounding groundwater due to the release of alkaline compounds from both cement hydration and unreacted accelerant.

One of the main products of cement hydration, besides calcium silicate hydrate (C-S-H), is portlandite (CH), responsible of the high pH values initially exhibited by cement pastes, that are usually around 12.5 (Kim et al. 2011). According to literature studies (Karim et al., 2014; Lothenbach et al., 2011), alternative binders as silica fume and slag could effectively reduce the amount

of alkaline compounds leaching from the grout, because they react with portlandite to create more C-S-H and also C-A-S-H. Besides consuming portlandite with pozzolanic reactions, these binders have the important advantage of enhancing the long-term mechanical performances of the mortars, due to the higher content of calcium silicate hydrates that can be reached with respect to traditional cement mortars.

3 EXPERIMENTAL ACTIVITY

3.1 Objectives

The experimental activity was designed to find one or more mix designs that would meet the technical specifications listed in the tender documents (Table 1) while limiting as much as possible the equivalent CO₂ emissions per cubic meter of grout and the pH of the leaching water.

Table 1. Technical requirements.

| Parameter | acceptable range |
|--|------------------|
| Flow time for the Marsh cone test maintaining the workability 72 hours | 30 – 45 s |
| Bleeding | <5% |
| Gel formation time | 10 – 18 s |
| UCS 4 hours | ≥0.3 MPa |
| UCS 28 days | ≥10 MPa |

3.2 Materials and mix design

Producing a low carbon grout mainly consists of substituting part or all the cement with alternative binders, which in this case seemed the best way to achieve both technical and environmental purposes. In fact, secondary cementitious materials are known to improve the strength of cement-based mortars (Lothenbach et al., 2011) allowing to reach values of UCS at 28 days that in a two-component grout made with only cement would require water/cement ratios too low to be feasible for backfilling applications, especially regarding the pumpability of the grout. As previously said, SCMs consume the portlandite produced by the hydration of cement creating a denser matrix, thus reducing porosity and enhancing strength, while causing lower CO₂ emissions than those associated with cement production. Furthermore, in recent years the industry has started to put on the market alternative binders completely devoid of cement, AAMs (alkali activated materials) and geopolymers, which are not yet widely used in engineering practice.

When applied to two-component backfilling grout, all these materials may have unwanted effects on key parameters such as viscosity, gel time and early strength, which require adjustments of the mix design (Di Giulio et al., 2020).

The experimental activity explored a few solutions that included an innovative cement-free binder as well as secondary cementitious materials. Table 2 reports the mix designs selected after preliminary testing on the fresh grout, working on the water/binder ratio and on the dosage of accelerator to keep the gel time in the acceptable range and to conjugate the necessity to have a good fluidity at the Marsh cone maintaining the bleeding low. Mix B1 is based on the cement-free binder and has been proposed by the product supplier. Since this binder is a patented product, its composition is not known but it can be assumed that it belongs to the wide category of AAMs which reactivity depends on the activator, that in this case is composed of 50 – 75 % calcium hydroxide. Mix B2 was obtained modifying B1 to increase the strength. In Mix CS the binder is made by equal parts of cement and slag, while in Mix CS+SF by 35% cement, 35% slag and 30% silica fume.

3.3 Mechanical performance

Laboratory tests here described were performed on both fresh and hardened mortar, obtaining the results presented in Table 3. To assess the workability and pumpability of the mixture in the fresh state, the Marsh cone test (UNI 11152-13) was carried out at 0 and 72 hours after mixing the components and bleeding (UNI 7122). The gel time was measured using a commonly practiced

method, although not standardized: the two components were joined in a beaker and then transferred from one beaker to another until the formation of a gel was observed, recording the time in seconds required for the mixture to become too thick to be poured.

Table 2. Mix design considered in the study.

| Products | B1 | B2 | CS | CS+SF |
|--------------------|-------------------|-------------------|-------------------|-------------------|
| | kg/m ³ | kg/m ³ | kg/m ³ | kg/m ³ |
| CEM II/A 42.5 | | | 261 | 174 |
| Cement free binder | 321 | 426 | | |
| Activator | 71 | 96 | | |
| GGBFS | | | 261 | 174 |
| Water | 773 | 670 | 724 | 715 |
| Silica fume | | | | 149 |
| Bentonite | 22 | 19 | 19 | 24 |
| Retarder | | | 5 | 5 |
| Accelerator | 92 | 165 | 111 | 108 |
| Water/binder | 2.0 | 1.3 | 1.3 | 1.4 |

Table 3. Properties of the fresh and hardened mortar obtained for each mix design.

| | B1 | B2 | CS | CS+SF |
|---------------------|------|------|------|-------|
| density | 1.25 | 1.28 | 1.32 | 1.35 |
| flow time | 38 | 38 | 40 | 37 |
| flow time @72 hours | 41 | 50 | 31 | 36 |
| bleeding @3 hours | <5 | <5 | <5 | <5 |
| bleeding @24 hours | 24 | 7 | 10 | 6 |
| gel time | 11 | 13 | 13 | 17 |
| UCS 4 hours | 0.1 | 0.3 | 0.6 | 0.5 |
| UCS 28 days | 6.5 | 10.2 | 12.5 | 9.4 |

The unconfined compression strength (UCS) test was performed according to UNI EN 196-1. UCS tests were conducted on cubic specimens (40x40x40 mm) after 4 hours and 1, 7 and 28 days of curing in water at 20°C. The evolution of the UCS over 28 days is presented in Figure 1 where the lines indicate the average resistance values obtained.

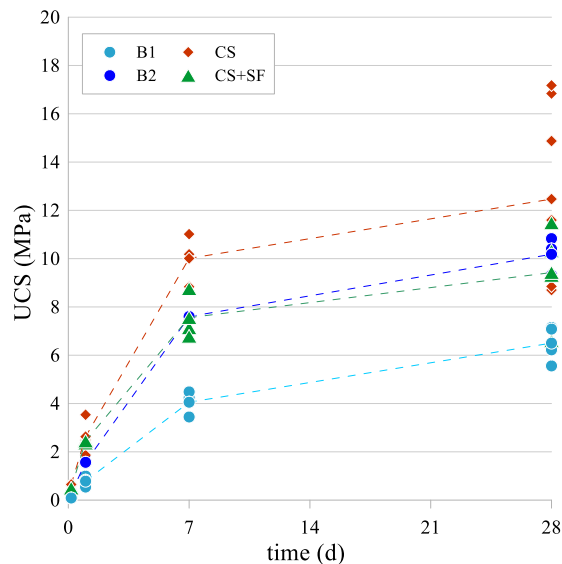


Figure 1. UCS evolution over time.

All the results obtained on the fresh mixtures are in the ranges specified in Table 1, while only Mix B2 and Mix CS achieve the required strength at 28 days. At this stage of the project, these results were deemed sufficient to compare solutions and steer further optimization.

3.4 Embodied carbon

The carbon footprint of each mix was assessed calculating the global warming potential in kilograms of CO₂eq for one cubic meter of grout, considering mix recipes and equivalent kilograms of CO₂eq for one kilogram of every material in them. The estimates in Table 4 allow to compare emissions in the system boundary A1-A3, i.e. cradle to gate.

Table 4. Equivalent CO₂ emission of each mix for unit volume of grout (A1-A3 frame).

| Products | GWP | B1 | B2 | CS | CS+SF |
|---|-------------------------|-------------------|-------------------|-------------------|-------------------|
| | kg CO ₂ e/kg | kg/m ³ | kg/m ³ | kg/m ³ | kg/m ³ |
| CEM II/A 42.5 | 0.811 | | | 261 | 174 |
| Cement free binder | 0.077 | 321 | 426 | | |
| Activator | 0.498 | 71 | 96 | | |
| GGBFS | 0.143 | | | 261 | 174 |
| Water | 0 | 773 | 670 | 724 | 715 |
| Silica fume | 0.480 | | | | 149 |
| Bentonite | 0.483 | 22 | 19 | 19 | 24 |
| Retarder | 0.935 | | | 5 | 5 |
| Accelerator | 0.741 | 92 | 165 | 111 | 108 |
| total GWP (kg CO ₂ /m ³) | | 139 | 212 | 345 | 333 |

The GWP of each product was taken from the relevant EPD provided by the manufacturer when available (as it was for cement free binder, activator, silica fume, retarder and accelerator) while other emissions were derived by literature ranges. In detail, the average OPC has a GWP of 0.820 – 0.840 kgCO₂/kg (Cement Industry Energy and CO₂ Performance. Getting the Numbers Right, 2016; Ouellet-Plamondon et al., 2014; Blast Furnace Slag Cements & Aggregates: Enhancing Sustainability, 2012) while blended cements as CEM II have less clinker and therefore lower GWP values depending on the composition. The slag is considered a recovered resource material, with emissions related mainly to the manufacturing and in the range 0.10 – 0.2 kgCO₂/kg (Ouellet-Plamondon et al., 2014; Blast Furnace Slag Cements & Aggregates: Enhancing Sustainability, 2012). Regarding the bentonite, there are few information in the literature on its GWP. In this study, it was assumed in the range 0.4-0.5 kgCO₂/kg (Ouellet-Plamondon et al., 2014; Specifying Sustainable Concrete, 2020). Being the bentonite a secondary component of these mixes in terms of quantity, below 2% of the total weight, this choice doesn't significantly affect the comparison between mixes nor the overall estimate.

Cement-slag mixes have more than 300 kgCO₂eq/m³, values that are similar to those of concrete (ITAtch Activity Group. Low Carbon Concrete Linings 2024), notwithstanding the higher water/binder ratio. This is due to the accelerator, that accounts almost as cement emission-wise.

Figure 2 reports a comparison between mechanical and environmental performance, clearly showing that Mix B1 e Mix B2 have the best ratio between GWP and compressive strength at 28 days.

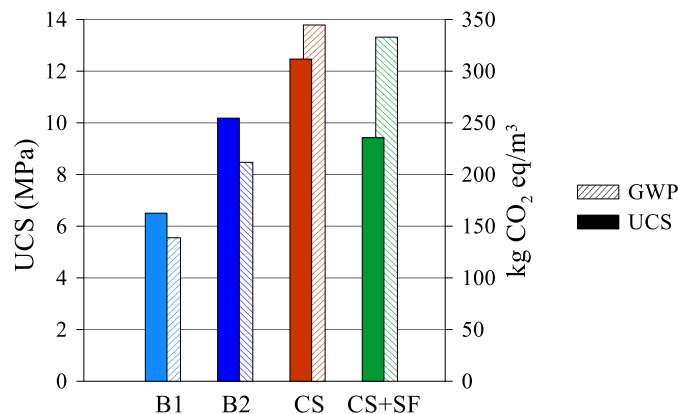


Figure 2. GWP and UCS_{28days} for each mix.

3.5 Evolution over time of the pH

Simulating in the laboratory what happens to the groundwater at contact with the backfilling ground is not an easy task, mainly due to the very different scale of the problem in terms of water volume and flow conditions, which are often unknown at an early design stage but have a great influence on the concentration of ions released by the grout in the surrounding body.

In this study, it was decided to subject the samples to standard curing and, at fixed times, to transfer them in distilled water to leach, measuring the pH of the leachate after 24 hours. The curves in Figure 3 show the pH records over a period of about 70 days.

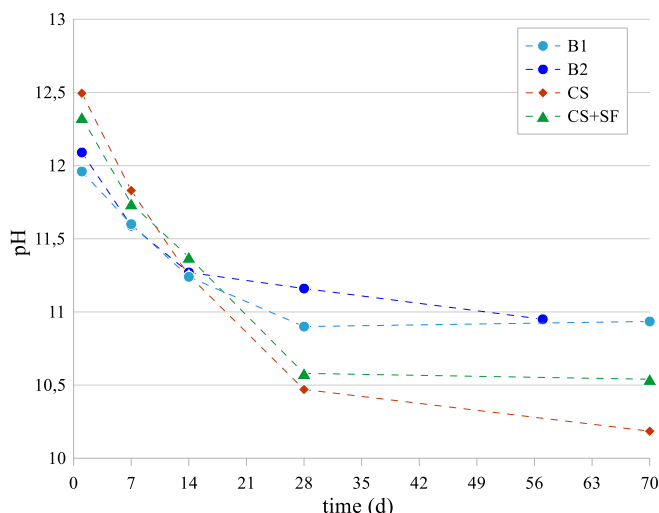


Figure 3. Evolution of pH over time.

It can be noted that the most significant drop in pH occurred within the first 14 days for the cement-free binder and within the first 28 days for the cement-slag mixes. The cement free binder has the lowest pH at the beginning, while the mixes CS and CS+SF have values comparable to those reported in literature for cement mixes (Kim et al., 2011). At the end of the monitoring period all mixes reach values below 11, with the cement-slag mixes providing the greatest reduction. This can be due to the different reactions that take place during the hardening process. The portlandite from cement hydration is quickly consumed by the sodium silicate, which is the main responsible of the observed alkalinity, while the pH values after 14 days observed for the cement-free binder can be due to the presence of reaction products more alkaline or more soluble in water than those of the cement-based mixes, beside sodium silicate.

4 CONCLUSIONS

The case study here presented demonstrates how it is possible to evaluate in advance various backfilling grout solutions that meet both mechanical and environmental performance criteria. This allows the consortium participating in the tender to submit proposals that have already been vetted in terms of material supply and costs. Making changes to a project becomes more difficult and expensive as it progresses, and declaring environmental performance requirements that assign a score to “greener” proposals is certainly a way to promote the adoption of innovative and sustainable solutions very early on the project timeline.

The research activity considered different types of binders: cement-free, cement and slag, silica fume, with which four mix designs were prepared. All mixes could meet the requirements for fresh and hardened mix properties, or could do so following minor adjustments, and could provide a more or less marked reduction in the release of alkaline compounds responsible for the pH of the leachate water. pH values below 11 were observed for all the mixes at the end of the observation period, while the most significant drop in these values occurred within the first 14 days for the cement-free binder and within the first 28 days for the cement-slag mixes. Considering the GWP values of the mixes in a cradle-to-gate reference system, it was also possible to evaluate the

environmental impact of each mix. The values obtained fall within the range 139-333 kgCO₂eq/m³, where the cement-free binder showed the best performance in terms of ratio between emissions and strength achieved at 28 days.

These estimates can serve as a useful tool in selecting the most convenient mix design and material suppliers but should be refined also including the emissions associated with transporting these materials to the site. Complete LCAs should in fact consider the impacts of materials from the cradle up to disposal, which could not be calculated in this research. The adoption of innovative materials may require some modifications to the usual plants or impose different consumption levels, considering, for example, the higher viscosity of some cement-free mixes compared to pumping mortar from the plant to the shield of the TBM.

Finally, it must be emphasized that CO₂ emissions are not the only indicator of LCAs, although certainly the most important one. Materials such as two-component grout involve the use of large volumes of water and chemicals that can also impact other indicators (ozone depletion, acidification of soil and water and eutrophication potentials, etc.). In this sense, the industry is making efforts to produce increasingly comprehensive EPDs, enabling designers and companies to develop more detailed LCAs, promoting the adoption of design solutions that effectively favor sustainability.

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