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Sprayed Concrete, a Modern and Versatile Construction Material, Is Well Covered by the New Austrian Sprayed Concrete Guideline †

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Abstract

Sprayed concrete, a highly versatile construction material, is an essential support material in underground work. When it was first introduced, it was deemed a temporary solution. However, over time, the material and its application evolved, boosting its durability. Additionally, concrete has faced criticism for its CO_2 emissions. Nonetheless, these technological improvements and environmental concerns were not fully incorporated into many standards. The Austrians have recently published an English version of the latest Austrian Sprayed Concrete Guideline, which covers most of the issues mentioned above. This paper outlines the main challenges and the support offered by the new Guideline.

Keywords: sprayed concrete; application requirements; permanent sprayed concrete; durability; CO_2 reduction; Austrian Sprayed Concrete Guideline

1. Introduction

Cement production, at its peak, accounted for approximately 8% of global human-made CO_2 emissions, measured as Global Warming Potential (GWP). Most construction emissions in new tunnel projects are directly related to cement consumption, with about two-thirds of the total CO_2 emissions traced back to cement and concrete. Therefore, it is essential to reappraise current tunnel construction methods [1].

Sprayed concrete is a highly versatile structural support option; however, it requires a higher cement (clinker) content compared to cast concrete due to its application requirements. This makes it a primary contributor to "gray carbon" at tunnel sites [1]. Reducing GWP necessitates a multi-faceted approach: one that involves efforts from owners, designers, and applicators, as well as a guiding standard that ensures both high technical quality and legal compliance.

The technical aspect includes minimizing material consumption through innovative design and enhancing structural longevity through optimized application, which is discussed in the first part of this paper. The "legal aspect," which pertains to the recently updated Sprayed Concrete Guideline from Austria [2], is explored further in the second part of this paper.

2. Design Strategies for Carbon Reduction

The volume of sprayed concrete used differs significantly from the design assumptions, and an overconsumption factor of about 2 may be a reasonable estimate. This overconsumption is also governed by geology and various design assumptions and rules, for example,

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the way the thickness of the freshly sprayed lining is measured. All factors contributing to this overconsumption should be reevaluated and adjusted to bring the total applied sprayed concrete volume closer to the design assumptions. However, following this line of thought would eliminate "hidden safety factors," as excessive thickness can be. The consequence must be to apply all sprayed concrete so that it meets all design assumptions in terms of long-term quality, so that occasional visible mistrust in durable sprayed concrete linings diminishes, and the structural integrity is maintained for a service life of 100 years or more.

2.1. GWP as a Decision Criterion

At the earliest possible project stage, owners and designers should consider establishing the tunnel's Global Warming Potential (GWP) as a primary decision criterion [3]. The focus must be on the "big contributors," such as concrete (cement clinker) and reinforcement, because carbon-saving decisions are most cost-effective at early project stages. Pragmatism is needed, as much of the required information is not available in full detail, such as specific cement EPDs (Environmental Product Declarations), and generic information must be used.

2.2. Permanent Sprayed Concrete

The most significant lever for CO_2 savings is the acceptance of sprayed concrete as permanent support. Moving away from traditional double-shell linings (a primary temporary sprayed shell plus a secondary cast shell) where possible, toward greater load sharing in general and, specifically, toward single-pass or composite linings, reduces total material volume. In hard rock environments, ensuring the long-term quality of the relatively thin sprayed concrete layer requires more adequate concrete mix designs and greater attention to the shrinkage potential of the rather unloaded linings.

2.3. Reinforcement and Waterproofing

In hard rock excavations, utilizing fiber reinforcement to replace mesh and bars allows the support to follow excavation contours precisely, eliminating the "over-spraying" required to cover exposed mesh. Additionally, spray-applied membranes should be evaluated as a method to optimize material use per linear tunnel meter, especially in complex geometries.

3. Application Excellence and Equipment

The final quality of sprayed concrete is determined by the mix design, the equipment performance (the concrete sprayers), the skill of the nozzle operator, and the post-application curing [1]. It is assumed that standard good application practices, such as preparing the substrate and ensuring a suitable application temperature, are in place.

3.1. Pulsation and Homogeneity

High-quality permanent linings require an uninterrupted concrete stream at the nozzle. Pulsation caused by the switchover of pump cylinders leads to structural layering and uneven accelerator distribution when the concrete flow is interrupted, while the accelerator flow remains constant, with a potential negative influence on the linings' long-term structural integrity. For durable structural linings, the pulsation rate should be as low as possible, and low-quality concrete sprayers should not be used. A skilled operator can always partly improve the application, for example, by reducing the pump throughput, thereby increasing the filling ratio in the pump cylinders and reducing pulsation.

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3.2. Rheology and Mix Design

The viscosity of the fresh mix directly influences pumpability. To ensure high quality, mix designs should be evaluated using the V-funnel test (EN 12350-9:2010-12) to assess yield stress and plastic viscosity; lower viscosity ensures better cylinder filling and lower pulsation. A combination of specialty plasticizers and hydration control admixtures is required to maintain this workability over the required project timeframes [1].

4. Durability and Shrinkage Control

Concrete layers applied in hard rock and/or as a final inner lining are mostly lightly loaded, if at all; they are highly susceptible to shrinkage due to water loss [4]. As shrinkage cracks are a "highway" for potentially damaging substances, they must be avoided or minimized. Adding special construction chemical admixtures further reduces water transport in these cracks [5].

To enhance durability, a dense, crack-free sprayed concrete layer is desired. As outlined above, equipment details and the operator's skill set contribute to this. Additionally, careful attention to mix design, including the selection of a plasticizer that ensures low viscosity, helps improve final quality.

Special attention should be paid to the largely overlooked positive contributions that small adjustments can make to minimize shrinkage cracks.

- The addition of anti-shrinkage admixtures and polymers helps reduce shrinkage potential and water transport [4,5].
- Fibers aid in distributing unavoidable shrinkage cracks, keeping widths below critical levels to ensure long-term durability [1,5,6].
- Curing is often the most underestimated factor. It must begin within hours of application. Redirecting ventilation away from fresh layers already helps, as high ventilation speeds promote rapid drying. In addition to internal curing admixtures that reduce the water transport within the concrete, adding water via water hoses or evaporation protection via spray-applied coatings that withstand a certain ventilation speed are essential to prevent premature water loss [1,4,6].

5. Interim Summary

Sprayed concrete began its career in the underground business as temporary support. Its quality improved over time as requirements for its long-term temporary properties increased. More recently, discussions about global warming highlighted the volume of concrete used per linear tunnel meter, leading to the recommendation that temporary support layers be avoided and that permanent sprayed concrete structures be preferred.

The quality of the sprayed concrete applied depends heavily on the application details. That's why a holistic approach is needed, covering design and application details, including machinery and operator qualifications.

6. Sprayed Concrete Guideline (April 2026)

To ensure a minimum level of quality and a level playing field, a standard was needed to achieve the desired quality and provide legal certainty. The Austrians decided to update their widely accepted and recognized Sprayed Concrete Guideline (German version dated 2009), resulting in a modern version available in both German and English, published in April 2026 (the German version published in 2025 is superseded by the April 2026 edition).

This Guideline is very likely the most comprehensive guideline worldwide, covering nearly all aspects of the use of sprayed concrete for underground and geotechnical use. It is built up of the following chapters:

1. Preliminary remarks
2. Area application
3. Definitions and abbreviations
4. Sustainability
5. Planning instructions and design specifications
6. Material
7. Execution
8. Testing
9. Test methods
10. Standards, guidelines, and literature

Annexes

The following explanations address only some specific aspects of more than 100 pages. There is no specific reference made to the discussed Guideline in the text below; it is considered covered by this sentence. Direct citations are marked with "quotation marks".

6.1. Sustainability

Sustainability got its own chapter, right at the beginning of this Guideline. "In the future, the Global Warming Potential (GWP) of key construction materials, such as concrete, sprayed concrete, and steel (including rock bolts), will become an essential criterion for assessing construction projects. By recognizing innovative, CO_2-reducing bidder proposals, the aim is to promote sustainability from the earliest stages of the planning process."

These two sentences are key to reducing CO_2 in modern, durable tunnel construction. They start with the owner's responsibility, which sets the rules, and this is now also covered by this Guideline.

A quite specific statement refers to permanent sprayed concrete: "In all practically feasible cases, sprayed concrete must be recognized as load-bearing throughout its service life".

Additional statements include: higher concrete strength preferred over additional thickness; assessing concrete strength after 56 or 90 days rather than 28 days; and the potential use of recycled excavation material.

Also, the potential for layer formation due to machine pulsation when spraying is addressed there, as it triggered an Austrian-funded research project, "Sprayed Optimised Concrete," whose findings have already been incorporated into this Guideline.

6.2. Design

Some design aspects are already dealt with under Sustainability above. One additional, and important, change was made regarding the old Guideline. The failure consequence classes were introduced. "They, along with the related reliability classes, serve as the primary criterion for distinguishing reliability. The failure consequence classes must be established during the planning stage".

6.2.1. Failure Consequence Classes

This introduction impacts all planning, testing, monitoring, manufacturing, quality control, and supervision measures (Table 1).

Because application quality affects the final lining properties, the spray mobile performance quality and the operator's specific qualification are also related to the failure consequence classes; see Table 2 below (Table 4.3 in the AT Guideline).

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Table 1. "Failure consequence classes as per draft ÖNORM EN 1990:2021 and their relation to monitoring measures in planning, execution, and the associated quality classes" (Table 4.1 in AT Guideline).

Failure Consequence Class	Design Monitoring	Inspection Level	Quality Class
CC 1	DSL 1	IL 1	Q1
CC 2	DSL 2	IL 2	Q2
CC 3	DSL 3	IL 3	Q3

Table 2. "Assignment of quality-related classification characteristics to quality classes". Note: The chapters refer to the AT Guideline chapters.

Quality Class	Inspection Category According to Chapter 7.5	Spraying Equipment Requirements According to Chapter 6.2	Staff Competence According to Chapter 6.3
Q1	ÜK 1	GA 1	PA 1
Q2	ÜK 2	GA 2	PA 2
Q3	ÜK 3	GA 3	PA 3

6.2.2. Fibers

Structural fibers, both steel and PP, are now more prominently featured in this Guideline, supporting a more sustainable tunnel lining approach when feasible. A statement sets the rules: "The dimensioning of the sprayed concrete lining is based on the results of the geotechnical design, in accordance with the ÖGG-Guideline "Geotechnische Planung von Untertagebauten Zyklischer und Kontinuierlicher Vortrieb"."

For sprayed concrete up to 10 cm thick, the reinforcement derived in the "Geotechnische Planung" can be directly converted into "EV Classes" (required energy absorption capacity); see Table 3 below (Table 4.5 in the AT Guideline). All samples must be sprayed, and the test age reflects the intended use, with 7 days permitted only for sealing layers.

Table 3. "Required energy absorption capacity".

	EV Classes	
Application/Function	Required energy absorption capacity	Assessment age
Sealing layer	EV > 500 J	7 days
Fiber-reinforced sprayed concrete as a replacement for sprayed concrete up to 10 cm thick and 1 layer of an AQ 50 mesh (3.08 kg/m^2)	EV > 700 J (28d)	28 days
Fiber-reinforced sprayed concrete as a replacement for sprayed concrete up to 10 cm thick and 1 layer > AQ 50 mesh	EV > 1000 J (28d)	28 days

Fiber-reinforced concrete layers over 10 cm in thickness are not covered in this Guideline.

6.3. Materials

Ongoing industry efforts to reduce the CO_2 footprint have required legal coverage under a standard. Therefore, Metakaolin (Table 4) and Ultra-fine Carbonates (FSM, Table 5) were introduced as new additions, neither of which is regulated in Austrian standards.

6.3.1. Metakaolin

"The quality of metakaolin must be verified through a preconstruction test, ongoing internal production control, and periodic external supervision. A clear distinction should

be made between the requirements for the preconstruction test and the parameters to be monitored continually".

"The amount of metakaolin added should be limited to 10% by mass of the total binder content".

Table 4. "Quality requirements for metakaolin" (Table 5.8 in AT Guideline).

Parameters	Limit Values	Test Procedure
Release of radioactivity	≤1	Index according to OiB Guideline 3
SiO_2	>25% by mass Reference value: 49 to 54% by mass	ÖNORM EN 196-2
Al_2O_3	≥30% by mass	ÖNORM EN 196-2
Chloride	<0.1% by mass	ÖNORM EN 196-2
SO_3	≤1.0% by mass	ÖNORM EN 196-2
Binding capacity	>700 mg $Ca(OH)_2$/g MK Reference value: 790 to 1530 mg	According to standard NF P 18-513 Annex A (Chapelle test, see Chapter 7.1.8)
Activity index	7d > 85% 28d > 90%	According to ÖNORM B 3309-1, Section 4.8 Test with mixing ratio: 405 g standardized cement and 45 g metakaolin

6.3.2. Ultra-Fine Carbonates

"The quality of the ultra-fine carbonates must be verified through a preconstruction test, ongoing internal production control, and periodic external supervision in accordance with ÖNORM EN 12620, considering Tables 5–9".

Table 5. "Quality requirements for ultra-fine carbonates" (Table 5.9 in AT Guideline).

Parameters	Limit Values	Test Procedure
d_{50}	≤3.0 µm	Laser granulometry according to ISO 13320, Test frequency: 1 × per production day
$CaCO_3$ $CaMg(CO_3)_2$ and mixtures thereof	>90%	ÖNORM B 4810 or ÖNORM EN 196-2, Test frequency according to the standard also applies to $CaMg(CO_3)_2$
Proportion of inactive minerals or methylene blue value	>98% ≤3 g/kg	ÖNORM B 4810, without pre-compaction and sieving of the sample; methylene blue ÖNORM EN 933-9
Organic carbon content	<0.20% by mass	ÖNORM EN 13639, Test frequency 2 × year
Water-soluble chlorides	≤0.01% by mass	ÖNORM EN 12620
Acid-soluble sulfate	Class AS0.8	ÖNORM EN 12620
Components affecting the setting and hardening behavior	passed	ÖNORM EN 1744-1

"The dosing level must be limited to a maximum of 15% of the total binder content, and, in cases of sulfate attack, to a maximum of 10% by mass".

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6.4. Execution

For health reasons, the Guideline defines that wet-sprayed concrete applications must be preferred over dry applications.

6.4.1. Equipment

Key in this chapter is that, for the first time ever, quality standards are established for spraying equipment and, consequently, are tied to the failure consequence classes (Table 6).

Table 6. "Device classes" (Table 6.1 in AT Guideline).

Device Class	Requirement
GA 1	Pulsation rate > 20% or no certification
GA 2	Pulsation rate $\leq$ 20%
GA 3	Pulsation rate $\leq$ 20% and liquid EB dosing accuracy within $\pm$10% by mass

6.4.2. Staff Competence

The required operators' competence is addressed and tied to the failure consequence classes.

6.4.3. Curing

A differentiation is made between curing needs at the face of a tunnel excavation and when placed outside tunnel headings.

For the tunnel face: "Because of favorable climatic conditions, no curing of the sprayed concrete is required in tunnel headings, regardless of the quality class, unless there are special external factors (e.g., severe drying due to ventilation). In such cases, the sprayed concrete surfaces must be kept moist for 7 days or adequately treated with a curing admixture, as per RVS 11.06.42".

For other applications: "Sprayed concrete outside tunnel headings, such as the subsequently applied inner linings of quality classes Q2 and Q3, must be cured to reduce early shrinkage and ensure adequate durability and bonding between the sprayed layers and the substrate. The curing process must not create a separating layer. Curing should begin immediately after application unless a subsequent layer of sprayed concrete is applied within 2 h".

7. Conclusions and Summary

It must be stated that the Sprayed Concrete Guideline from Austria (April 2026 version) addresses current industry challenges in a quite pragmatic way. It provides legal coverage and a level playing field, especially when quality is needed.

Promoting the GWP as a decision criterion and recognizing innovative, CO_2-reducing bidder proposals from the earliest stages of the planning process is guidance for a future we all will have to deal with.

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