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Mix proportioning of sprayed concrete: A systematic literature review

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ABSTRACT

The widespread use of sprayed concrete for structural and non-structural applications. The high performance required demands solid mix proportioning guidelines and procedures that consider the peculiarities of this material with respect to conventional concrete. This review synthesizes current practices defined on standards, guidelines, and scientific literature in a format focused on allowing quick comparison and understanding of the current scenario of sprayed concrete proportioning to specifiers, sprayed concrete technologists, and ready-mix producers. The review highlights a reasonable consensus of standards and guidelines on the mix design approach based on the definition of recommended ranges and requirements on materials and dosages. These are deliberately flexible to account for the different sprayed concrete applications and specificities of work conditions. Based on the systematic literature review, a discussion on major areas holding significant potential to improve current practices is presented and practical recommendations are provided to advance towards more direct and optimized methods.

1. Introduction

Sprayed concrete is a construction technique widely used as a structural support method for tunnels and mines, slope stabilization, and rehabilitation of structures (Bernard and Thomas, 2020). It is not simply a material but a unique process that combines the application and the consolidation of the matrix in a single step, without formwork and external vibration (Austin, 2019). Well-proportioned and adequately installed by experienced applicators, sprayed concrete provides a versatile and feasible solution, both technically and economically, compared to conventional concrete (Galan et al., 2019).

Although sprayed concrete is accepted worldwide and several procedures have been developed for its application ((CEN, 2005); (AuSS, 2020); (EFNARC, 1996); (ÖBV, 2013); (AENOR, 2014); (ACI, 2016); (ABNT, 2012)), the knowledge acquired about this technology is mainly based on particular experiences derived from specific projects. Consequently, the influence of several variables associated with materials and the application process on the mechanical performance of sprayed concrete is not well defined. Furthermore, unlike conventional concrete, no widely accepted procedure has been established to select admixtures and mix proportioning of sprayed concrete.

Mix proportioning aims to minimize voids in the placed concrete by using a combined grading of the different solid particles (aggregates, cement, and mineral additions) while complying with the rheological behavior required for pumping and spraying. Fig. 1 shows a general scheme of the traditional mix design process, which comprises several iterative stages. First, it is initiated with the specification of sprayed concrete, which describes the requirements for materials, proportioning, and application.

According to EN 14487–1:2005 (CEN, 2005), sprayed concrete should be specified either as designed or as prescribed concrete, whose basic requirements are presented in Fig. 1. Designed mixtures should only be adopted for inspection categories II and III. In contrast, prescribed concrete can be used when the particular inspection category I is adopted (Tables A.1, A.2, A.3, and A.4 in (CEN, 2005) provide descriptions and examples of inspection categories). However, this specification method is not very common in sprayed concrete applications due to the wide range of conditioning factors affecting the spraying process and the specific features of each project.

The typical approach for prescribed mixes defines the complete

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composition based on preliminary tests or past experiences with similar sprayed concrete applications. By doing so, the specifier must prescribe the mix proportions required, whose conformity criteria are based solely on the specified composition and not on any performance requirement intended due to the strong influence of the application process. As a result, this approach discourages innovation by constraining a contractor's ability to use new technologies and application methods to achieve the required result more effectively. It may also promote poor practices by omitting the requirement to prove that the performance of the placed sprayed concrete is satisfactory (AuSS, 2020).

For designed mixtures, the specifier only describes the required performance of both fresh and hardened concrete. The properties required are related to consistency ranges, strength evolution, maximum aggregate size, and durability criteria. Additionally, it is common to define the minimum cement content, grading curves of the aggregates, and a maximum w/c ratio. However, a specific mix proportion is not defined (this could be considered a hybrid version, combining the designed and prescribed-based specification). Nowadays, this is the preferred method in sprayed concrete applications due to its flexibility, allowing adaptation to the specific conditions of each project.

At this point, one should ask the following question: "When the specifier only defines the performance required, who defines the materials and initial proportioning of sprayed concrete prior to preconstruction trials?" Usually, the ready-mix producer is responsible for providing a mix design that complies with the required properties. This practice has its logic, as the supplier has information on the local aggregates and the teams working in the area, so they might have some previous practical experience. However, occasionally, the user's technical staff (company using fresh concrete in the execution of the construction) faces the challenge of sprayed concrete proportioning. This latter case occurs more often within large construction companies doing design and building, who might accumulate an extensive record of previous experiences. In either case, in most projects, initial sprayed concrete proportioning is primarily based on past experiences. However, due to the large number of variables involved in each sprayed concrete application, the initial proportioning established often differs significantly from the optimum, leading to repeated and costly preconstruction trials.

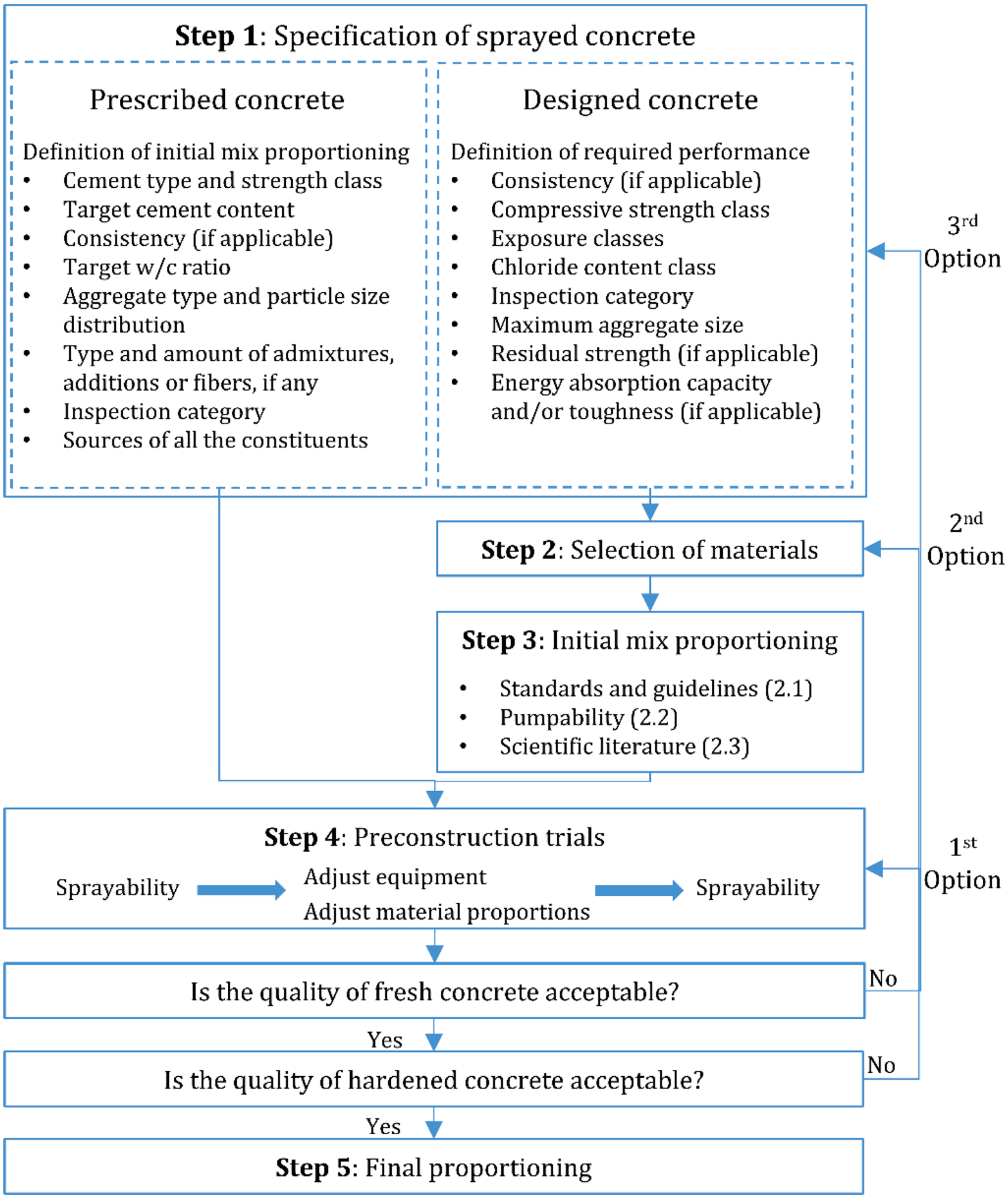

Fig. 1. The general process for the mix proportioning of sprayed concrete.

Alternatively, during the last decades, different institutions have developed standards and guidelines which include sprayed concrete proportioning procedures (ACI (ACI, 2016), AENOR (AENOR, 2014), AFTES (AFTES, 2000), ASCE (ASCE, 1995), CEN (CEN, 2005), DIN (DIN, 2014), EFNARC (EFNARC, 1996), ICH (ICH, 2014), JSCE (JSCE, 2007, 2016), MITMA (MITMA, 2021), NB (NB, 2011), ÖBV (ÖBV, 2013), etc.). In general, these only offer a series of guidelines and requirements on the material components and the mixture based on empirical criteria. In many cases, it is explicitly stated that the concrete supplier's expertise and capabilities are being relied upon for proper mix design. Some regulations contemplate the proportioning of wet mix sprayed concrete based on the existing methodology for conventional concrete that includes pumping applications (ACI 506R-16 (ACI, 2016). Finally, some authors have published different purely empirical proportioning methods, especially in the early 1990 s (Prudêncio, 1993; Rodriguez, 1997; García et al., 2001), without any of these being widely adopted by the industry.

The objective of this paper is to present a systematic review of the different sprayed concrete mix design methods available up to date, as no similar documents have been found in the literature. Additionally, areas with significant potential to improve sprayed concrete mix design and advance towards more direct and informative proportioning methods are identified and discussed.

2. Review of common practices on sprayed concrete proportioning

2.1. According to different standards and guidelines

During the last decades, different institutions have developed standards and guidelines that include some sort of sprayed concrete proportioning procedures, requirements, or recommendations. Table 1 summarizes the primary documents of interest that address aspects related to the proportioning of sprayed concrete developed by standardization bodies and professional associations grouped by region. Applying the codes and prescriptions established in the technical guides is, in general, voluntary. Only the regulations reflected in the legislation are mandatory. However, both the standards developed by standardization bodies and the guides published by prestigious professional associations establish technical specifications that are considered appropriate or sufficient to meet the technical requirements of national legislation.

The only documents developed by standardization bodies that address aspects related to sprayed concrete mix design are those that regulate the European (EN 14,487 series), North American (ACI 506R-16 and ASTM C1436-13), Chinese (JGJ/T 372–2016), and Brazilian (ABNT NBR 14026:2012) framework. These documents are currently widely recognized, being used internationally due to the high technical level and the economic importance of the markets for which they were initially elaborated. In addition, it should be noted that some national standardization organizations in European countries have developed their own specifications that complement or clarify the European regulatory framework.

All the other documents included in Table 1 are technical guides prepared by different professional associations on a transnational or national basis. Prior to the development and harmonization of the European regulatory framework (EN 14,487 series), the technical guides developed by professional associations were, in many countries, the reference documents that regulated the use of this material in practice. At that time, the specification of the European Federation of Producers and Applicators of Specialist Products for Structures (EFNARC) and the Austrian guidelines of the Austrian Society for Construction Technology (ÖBV) were widely recognized internationally. Currently, some aspects of these documents might have become obsolete, but they continue to be of great interest for knowledge. However, whenever possible, it is recommended to refer to current regulations, either European or North American, as these follow a constant review process. Nowadays, professional associations continue to produce advanced technical documents to respond to specific needs of the sector.

Table 1
List of standards and technical guides referring to sprayed concrete proportioning.

Europe	
E.U.	European Committee for Standardization (CEN): UNE-EN 14487–1:2005 Sprayed concrete – Part 1: Definitions, specifications and conformity (CEN, 2005).
	European Federation of Producers and Applicators of Specialist Products for Structures (EFNARC): European Specification for Sprayed Concrete. Guidelines (EFNARC, 1996).
Germany	German Institute for standardization: DIN 18,551 Sprayed concrete - National application rules for series DIN EN 14,487 and rules for the design of sprayed concrete constructions (DIN, 2014).
Austria	Austrian Society for Construction Technology (ÖBV): ÖBV Guideline Sprayed Concrete (ÖBV, 2013).
Spain	Asociación Española de Normalización y Certificación (AENOR): UNE 83607:2014 IN Hormigón proyectado. Recomendaciones de utilización (AENOR, 2014).
	Ministerio de Transportes, Movilidad y Agenda Urbana (MITMA): Código Estructural 2021 Anejo 9 (MITMA, 2021).
	Asociación Española de Túneles y Obras Subterráneas (AETOS): Diseño, Fabricación y Puesta en Obra del hormigón proyectado en Obras Subterráneas (AETOS, 2015).
France	Association Française des Travaux en Souterrains (AFTES): AFTES recommendations for the design of sprayed concrete for underground support (AFTES, 2000).
Norway	Norwegian Concrete Association (NB): Sprayed Concrete for Rock Support (NB, 2011).
Other regions	
North-America	American Concrete Institute (ACI): ACI 506R-16 - Guide to Sprayed concrete (ACI, 2016).
	American Society for Testing Materials (ASTM): ASTM C1436-13: Standard Specification for Materials for Shotcrete (ASTM, 2013).
China	Ministry of Housing and Urban-Rural Development of PRC (JGJ): JGJ/T 372–2016, Technical Specification for Application of Sprayed Concrete (JGJ, 2016).
Chile	Instituto del Cemento y del Hormigón de Chile (ICH): SPRAYED CONCRETE-Guía chilena de hormigón proyectado (Ed. 2) (ICH, 2014).
Brazil	Brazilian Association for Technical Standards: ABNT NBR 14026:2012. Shotcrete Specification (ABNT, 2012).
Australia	Concrete Institute of Australia: Shotcreting in Australia. Recommended practice (Ed. 3) (AuSS, 2020).
	Transport for New South Wales: B82-Shotcrete Work (TfNSW, 2020).
Japan	Japan Society of Civil Engineers (JSCE): Standard specification for concrete structures–2007 “Materials and Construction” (CH 8) (JSCE, 2007).
	Japan Society of Civil Engineers (JSCE): Standard Specification for Tunneling-2016 (JSCE, 2016).

2.1.1. Aggregates

Most of the regulations propose maximum aggregate sizes to comply with the restraints imposed by the spraying equipment, layer thickness, and minimize the rebound. According to the Concrete Institute of Australia (AuSS, 2020), rebound increases significantly when the maximum aggregate size exceeds 14 mm, and dry mortar content is below 60% in mass. Standards and technical guides propose maximum sizes between 8 mm and 10 mm for sprayed gunite and between 11 mm and 20 mm for sprayed concrete. In the Spanish regulation (AENOR, 2014), it is recommended to set these limits at 8 mm for sprayed gunite and between 12 and 16 mm for sprayed concrete. In addition, the maximum particle size should be 3–5 times smaller than the internal diameter of the spray hose and nozzle.

Along with the limitation of the maximum particle size, many regulations offer previously proven combined grading limits to adjust the granulometric curve of the aggregates and shorten the design process of the optimal mixture (Table 2). Gradings outside the ranges may be used if either preconstruction testing or past uses proved satisfactory results.

Table 2

Recommended combined aggregate grading. % passing for specification.

Sieve size		ACI 506R 2016 (ACI, 2016) ASTM C1436 2013 (ASTM, 2013)		UNE 83607 2014 IN (AENOR, 2014)		CE 2021 (MITMA, 2021)	ÖBV 2013 (ÖBV, 2013)	AFTES 2000 (AFTES, 2000)	TfNSW B82 2020 (TfNSW, 2020)	EFNARC 1996 (EFNARC, 1996)	ABNT 14026 2012 (ABNT, 2012)		JGJ/T 372 2016 (JGJ, 2016)	
ASTM	ISO (mm)	G1	G2	0–8	0–15	0–12	0–11	0–20	0–13	0–16	0–4.75	4.75–12.5	0–10	0–12
No. 230	0.063						2–6							
No. 120	0.125					4–12				4–12				
No. 100	0.15	2–10	2–10	0–12	0–8			7–12	2–10		5–10		5–7	4–8
No. 60	0.25					8–26	8–15			11–26				
No. 50	0.30	10–30	8–20	5–19	3–15			10–20	8–20		15–35		10–15	5–22
No. 35	0.50					18–50	18–25			22–50				
No. 30	0.60	25–60	20–35	12–27	9–25			20–35	20–40		45–65		17–22	13–31
No. 18	1.0					30–72	30–40			37–72				
No. 16	1.20	50–85	35–55	22–42	19–38			30–45	35–55		70–80		23–31	18–41
No. 10	2.0					45–90	45–55			55–90				
No. 8	2.40	80–98	50–70	42–62	28–54			45–60	50–70		80–90	0–5	35–43	26–54
No. 5	4.0					65–100	65–75			73–100				
No. 4	4.75	95–100	70–85	74–85	40–72			60–75	70–85		95–100	0–20	50–60	40–70
1/4 in.	6.3											35–60		
5/16 in.	7.9			100		85–100	85–95			90				
3/8 in.	9.5	100	90–100		76–89			85–95	90–100			85–98	82–73	62–90
7/16 in.	11.1						95–100							
1/2 in.	12.5		100		90–96	95–100						95–100		
0.53 in.	13.4								100					
5/8 in.	15.9				99–100	100				100			100	100
3/4 in.	19.0							100						

Adjusting to the corresponding combined aggregate gradings is especially important in structural applications, not in those where an aesthetic component prevails.

Table 2 highlights differences in the recommended combined aggregate gradings for similar maximum aggregate sizes. EFNARC establishes the widest gradation range, covering finer regions than other guidelines. The Spanish standard UNE 83607:2014 IN promotes larger aggregate sizes, with 11–24% of the aggregate blend above 10 mm. The other standards and guidelines reviewed in Table 2 recommend intermediate gradings, being the recommendations provided by the American Concrete Institute (ACI 506R G2) and the Transport for NSW (TfNSW B82) nearly identical.

On the other hand, a great alignment with two fundamental aspects of this empirical approach is observed. The first is the importance of introducing sufficient fines to lubricate the pumping lines, and the second is the sand fineness modulus. UNE 83607:2014 IN recommends a minimum of 2 % of sand particles smaller than 0.08 mm and from 8 to 12 % of particles below 0.25 mm. ACI 506R-16 (ACI, 2016) establishes that fine aggregate should have a fineness modulus of 2.5–2.9 while the Spanish UNE 83607:2014 IN sets this range to 2.4–3.2. Similar values are provided by the Chinese JGJ/T 372–2016 (2.5–3.2). Furthermore, according to ACI 506R-16 (ACI, 2016), it is not advisable to incorporate>30% coarse aggregate as a percentage of the total aggregate in the mixture, which is further reduced during spraying due to rebound. Other regulations, such as the Japanese JSCE (JSCE, 2007), set this limit between 30 and 45%.

2.1.2. Binder

The binder type and content should be selected to meet the specified requirements for concrete pumpability, strength at early ages, durability, and proper compatibility with admixtures. Consequently, guidelines and standards do not exclude specific cement types for sprayed concrete use as long as these comply with general concrete prescriptions included in current regulations. Any material proposed as a binder not included in regulations must comply with the minimum requirements for traditional cement and be assessed for suitability through full-scale tests.

Generally, sprayed concrete is produced with CEM I and CEM II Portland cement (ACI 506R-16 (ACI, 2016), UNE 83607:2014 IN (AENOR, 2014); CE 2021 (MITMA, 2021) or equivalent classifications used in different regions, such as General Purpose Portland – GP, General Purpose Blended – GB or Shrinkable Limited SL (AuSS (AuSS, 2020), TfNSW B82 (TfNSW, 2020). CEM I 52.5R might be preferably adopted for applications where high strength at early ages is required, while in general applications, the preferred cement is a CEM II/A-L 42.5R or equivalent. Although CEM I 52.5R SR (C_3A content below 5%) is usually recommended for tunnel lining applications, spraying concretes with low C_3A contents might be troublesome for the build-up of layers in overhead areas especially in cold climates (below 5 °C).

Standards and technical guidelines prescribe minimum cement (binder) content and, in some cases, recommended ranges depending on the spraying method (dry or wet), material (mortar or concrete), and target compressive strength. In any case, it must always comply with the minimum content requirements set by current regulations for particular environmental exposure classification.

The European regulation EN 14487 (CEN, 2005) only establishes a minimum cement content of 300 kg/m^3. ACI 506R-16 (ACI, 2016) recommends a cement content between 385 and 415 kg/m^3 for most wet applications; while the Spanish standard UNE 83607:2014 IN (AENOR, 2014) sets this range between 350 and 400 kg/m^3. Indicative values reported in ÖBV range between 400 and 500 kg/m^3 (ÖBV, 2013). The early guidelines from EFNARC state that cement content should typically be between 350 and 450 kg/m^3 for the dry process and 400 and 500 kg/m^3 for the wet spraying process (EFNARC, 1996). Nowadays; the recommended content for wet mixes is usually slightly lower than in dry mixes. Recommendations from other bodies range between 300 kg/m^3 and 500 kg/m^3. These quantities are effectively increased in placed sprayed concrete due to the higher rebound of coarse aggregates during spraying.

The wide ranges defined respond to the different applications (mining, civil engineering, etc.), placement method (manual or robotic and dry or wet), and structural requirements of the sprayed concrete. However, most standards and guidelines do not define specific ranges depending on either the cement grade (fineness) used or the target strength of the sprayed concrete. The only guides directly referring to this aspect are the Japanese standard specification from JSCE (JSCE, 2007) and the Spanish sprayed concrete guide from AETOS (AETOS, 2015).

The first document states that unit cement content is about 360 kg/m^3 for normal strength and commonly 400–500 kg/m^3 for high strength sprayed concrete or where liquid accelerators are used. AETOS proposes several indicative ranges of cement content depending on the strengths required: 380–425 kg/m^3 for f_{ck} 25–30 MPa, 400–450 kg/m^3 for f_{ck} 30–35 MPa, 425–475 kg/m^3 for f_{ck} 35–40 MPa and above 450 kg/m^3 for $f_{ck} > 40$ MPa.

Despite the ranges defined by the standards, regular practices in sprayed concrete structural applications rarely report cement content values below 400 kg/m^3. In addition, no direct correlation between cement content and f_{ck} must be assumed since the spraying process significantly influences the mechanical properties of the matrix. The cement content adopted in many cases might be influenced by the availability and cost of fines, as additional content might be introduced in the mixture solely to reduce rebound, dust, and improve pumping.

The most commonly used mineral additions are fly ash, silica fume, and limestone filler (AENOR, 2014). Despite presenting the initial disadvantage of requiring supplementary silos in the concrete plants, the incorporation of these mineral additions is becoming more common, especially in tunnel linings, with combinations such as 290 kg/m^3 of cement, 80 kg/m^3 of fly ash (20 %) and 30 kg/m^3 of silica fume (7.5 %) (total: 400 kg/m^3). These additions effectively reduce permeability and rebound and improve the consistency and workability of fresh concrete (Bindiganavile and Banthia, 2001; Bin et al., 2014; Galan et al., 2019). Depending on the type and amount of supplementary cementitious materials, strength at early ages may be reduced. However, the strength development continues for a more extended period when compared to an all-cement mixture, resulting in an improvement of mechanical properties of the placed sprayed concrete.

Standards and guidelines propose maximum dosages of silica fume between 12 and 15 % by cement weight (% bcw). In the case of HPY-III (sprayed concrete for permanent structural application), the Spanish recommendation prescribes a maximum silica fume content below 10 % bcw, which should only be used with CEM I. Regarding fly ash, UNE 83607:2014 IN (AENOR, 2014) indicates maximum contents below 15 % bcw for CEM II or 20 % bcw for CEM I. For permanent structural applications, fly ash should only be used with CEM I. Other guidelines adopt similar values. Recommendations on limestone filler dosages are not included in the reviewed documents. Thus, contents should be selected according to standard national specifications on CEM II/A-L or equivalent.

2.1.3. Water

Water quality must comply with the requirements defined in local regulations. The amount of water is addressed in guidelines and standards based on the prescription of maximum values and recommended ranges. As with conventional concrete, the moisture content of the aggregates and water contained in admixtures should be considered when determining the water demand of the sprayed concrete mix. In addition, the water/cement (w/c) ratio of the base mix must conform to the requirements associated with the exposure classification.

Some regulations prescribe very wide w/c ranges (0.3–0.6) as these do not differentiate between neither the dry and wet method nor the type of application (UNE 83607:2014 IN (AENOR, 2014). Even those regulations that differentiate between dry and wet methods, the recommended ranges are still very broad. For the wet method, w/c values reported are generally in the range between 0.35 and 0.60. The lower values are usually adopted for civil and underground applications (0.35–0.45), while the higher values correspond to non or low-demanding structural uses, such as swimming pools. For the dry method, values oscillate from 0.30 and 0.55, but these can vary widely as the sprayer controls the consistency of the mix to reach adequate adhesion to the substrate and the build-up of layers with sufficient thickness.

Alternatively, the Chinese guide JGJ/T 372–2016 (JGJ, 2016) provides a direct empirical method to estimate the water/binder ratio of the sprayed concrete mix for those cases where concrete supplier's expertise and capabilities cannot be relied upon.

2.1.4. *Accelerators*

Accelerators are used mainly in wet-mix sprayed concrete to promote fast strength development, enhance the maximum layer thickness and reduce the incidence of early material fallouts. Currently, the two most common families of chemical accelerators are those based on alkaline aluminates and aluminum sulfate (alkali-free). The latter is the most used worldwide, especially in closed tunnel-type environments without large presence of underground water. In contrast, the use of the first is reduced to specific regions where economic criterion prevails. Alkaline accelerators usually significantly reduce long-term strength and present health issues for workers (Prudencio, 1998; Galobardes, 2013; Galobardes et al., 2014; Salvador et al., 2017). The Spanish regulation UNE 83607:2014 IN (AENOR, 2014) quantifies the decrease in final strength at 28 days associated with different types of accelerators compared to a reference sprayed concrete without accelerators (Table 3).

The optimal dosage varies with spraying method, sprayed concrete mix, cement type and content, spraying position, type of backing material, and presence of water in the substrate. Consequently, most standards and guidelines do not include recommended contents and only prescribe dosage rates below the maximum recommended by the manufacturer or the maximum dosage established during preconstruction tests. Overdosing might delay strength development and compromise durability. Therefore, the manufacturer's recommendations should be followed.

UNE 83607:2014 IN (AENOR, 2014) includes estimated dosages for accelerators: between 2 and 8 % bcw in powder admixtures (maximum 10 %), between 2 and 6 % bcw for aluminate-based accelerators, and between 3.5 and 10 % bcw for alkali-free accelerators. The Australian sprayed concrete guideline reports usual dosage rates between 3 and 8 % bcw for alkali-free accelerators (AuSS, 2020). All the alkaline accelerators have been effectively banned in several countries, such as Australia, Austria, and Germany.

Accelerator dosages are commonly calculated based on the total content of the binder (cement + addition). However, since additions are less reactive than cement, the adequate accelerator dosages for concretes produced with compound cement must be determined in field trials. By doing so, accelerator dosages may be adjusted according to the performance requirements of the sprayed concrete.

2.1.5. *Fibers*

Fibers have become a common component for dry and wet-mix sprayed concrete in many applications. Structural fibers (steel and macro-synthetic) improve the mechanical performance (flexural behavior and post-crack bearing capacity), impact resistance, and limit crack propagation. Non-structural micro-synthetic fibers are generally used to control plastic shrinkage cracking, reduce rebound and mitigate the risk of spalling of sprayed concrete when subjected to high-intensity hydrocarbon-fuelled fires. Even though steel and synthetic fibers are commonly used with sprayed concrete, most current regulations do not exclude any material, shape, or section as long as these reach the required performance during preconstruction trials.

Fiber content depends on project requirements, application method, the expected rebound, and the fiber characteristics. Therefore, fiber dosage should always be based on the reinforced concrete performance, determined by residual tensile strength/energy absorption tests required in the design. However, some guidelines and standards still provide general recommended ranges for different fiber types. For example, ACI 506R-16 (ACI, 2016) recommends dosage rates for steel fibers from 12 to 47 kg/m^3 for wet-mix sprayed concrete, while for dry-mix sprayed concrete, quantities might be increased up to 1 % in volume (approximately 78 kg/m^3). In the case of synthetic macrofibers, the usual contents fall within 3 and 7 kg/m^3, while for synthetic microfibers, the usual dosage is in the range from 0.6 to 1.2 kg/m^3. The Australian guideline (AuSS, 2020) recommends dosage rates of micro-synthetic fibers from 1 to 2 kg/m^3, and maximum steel fiber dosages for dry-mix sprayed concrete of 30 kg/m^3, which can be up to 50 kg/m^3 with special equipment. ÖBV (ÖBV, 2013) prescribes a minimum steel fiber content of 30 kg/m^3 and a minimum dosage of micro and macro-synthetic fibers of 1.5 kg/m^3 and 4.0 kg/m^3, respectively. Finally, TfNSW B82 (TfNSW, 2020) prescribes between 1 and 2 kg/m^3 of fine micro polypropylene monofilament fibers to mitigate the effects of spalling during fire exposure.

Some regulations also recommend maximum lengths of the steel fibers (30, 35, and 36 mm according to UNE 83607:2014 IN (AENOR, 2014), JSCE (JSCE, 2007) and ACI 506R-16 (ACI, 2016), respectively) and prescribe a minimum compressive strength of the concrete to ensure the necessary bonding of the fibers to the matrix (about 20 MPa according to UNE 83607:2014 IN (AENOR, 2014) and ÖBV (ÖBV, 2013). Additionally, the Spanish association of tunnels and underground structures (AETOS) (AETOS, 2015) relates the recommended fiber length with the internal diameter of the pumping line and nozzle. Fiber length should be smaller than 80% of the internal diameter of the hose and 50% of the diameter of the nozzle. In addition, the length of structural fibers should be between 2.5 and 3 times larger than the maximum aggregate size. Similar considerations are included in the AFTES (AFTES, 2000) recommendations as the steel fiber length is limited to values below 0.7 times the diameter of the nozzle, or else tests should be conducted to assess the risk of pipe blockage. Adding fibers to a sprayed concrete mixture may require adjustment to the mix design. Fiber content should be checked at regular intervals, as the amount of fibers contained in the placed sprayed concrete might be lower than in the base mix due to rebound.

2.1.6. *Summary*

Tables 4 and 5 summarize the main sprayed concrete mix design recommendations included in the standards and guidelines examined, respectively. These aim to provide specifiers, sprayed concrete technologists and ready-mix producers a quick comparative overview of the current recommended practices on sprayed concrete proportioning across the globe.

2.2. *According to methodologies for pumpable concrete*

When dosing conventional concrete, both the hardened and fresh state performance must be considered. This duality becomes critical when pumping is considered a boundary condition in the mix design.

The pumpability conditions are associated with the mix consistency, density, and cohesion. These properties are defined by the quantity and

Table 3
Strength loss at 28 d associated with accelerators, UNE 83607:2014 IN (AENOR, 2014).

Type of set accelerators	Strength loss (%)
Powder (dry-mix)	30–40 (max. 45)
Alkaline aluminates (solution)	20–25 (max. 30)
Aluminum sulfate (solution)	4–8

Table 4
Main sprayed concrete proportioning recommendations included in standards.

Main variables	ACI 506R 2016 (ACI, 2016)	EN 14487 2005 (CEN, 2005)	UNE 83607 2014:IN (AENOR, 2014)	CE 2021 (MITMA, 2021)	JGJ/T 372 2016 (JGJ, 2016)
Cement Type and Grade	I or II	–	I or II 32.5R or 42.5R	I or IIa	≥42.5 for permanent applications
Cement content (kg/m^3)	385–415	>300	350–400	–	General: >300 With steel fibers: >400 High strength: >450
Silica fume content (% bcw)	5–12	–	5–10 (<15)	–	OPC: <10 PC: <12
Fly ash content (% bcw)	10–25	–	CEM I: <20 CEM II: <15	–	OPC: <20 PC: <30
Max. aggregate size (mm)	12	–	16	12	12
Fines content	–	–	2 % <0.08 mm 8–12% <0.25 mm	500–550 kg/m^3 < 0.063 mm (Fines + Cem)	–
Sand fineness modulus	2.5–2.9	–	2.4–3.2	–	2.5–3.2
w/c ratio Dry–mix	–	0.35–0.5	0.3–0.6	–	High strength: <0.45
Wet–mix	0.35–0.45				
Cement/agg. ratio (dry mix)	1:4	–	–	–	–
Accelerator dosage (% bcw)	–	–	Silicates: 10–15 Others: 2–8	Silicates:12–15 Alkali–free:4–8 Alkaline:3–7	–
Fiber dosage (kg/m^3)	Steel: wet–mix 12–47 Steel: dry–mix < 78 Macro synthetic: 3–7 Micro synthetic: 0.6–1.2	–	–	–	Steel: 30–80
Fiber length (mm)	Steel: < 36	–	Steel: < 30	Steel: 30–40 Synthetic: <65	Steel: 20–35 $< 0.7\cdot\phi_{nozzle}$ Synthetic: 12–25
Slump (cm)	5–10	–	–	–	–

Table 5
Main sprayed concrete proportioning recommendations included in guidelines.

Main variables	EFNARC 1996 (EFNARC, 1996)	AFTES 2000 (AFTES, 2000)	AuSS 2010 (AuSS, 2020)	ÖBV 2013 (ÖBV, 2013)	AETOS 2014 (AETOS, 2015)	JSCE 2016 (JSCE, 2016)
Cement Type and Grade	–	–	–	–	I or II > 42.5 R	–
Cement content (kg/m^3)	Dry–mix: 350–450 Wet–mix: 400–500	–	–	380–450	350–500	360–500
Silica fume content (% bcw)	3–8	–	5–10	< 11	–	5–10
Fly ash content (% bcw)	–	–	10–25	15	–	–
Max. aggregate size (mm)	16	16		4–11	12	10–15
Fines content	–	17% <0.01 mm (Fines + Cem)	–	–	–	–
Sand fineness modulus	–	–	–	–	–	–
w/c ratio Dry–mix	0.3–0.5	–	–	0.35–0.5	≤ 0.45	0.4–0.65
Wet–mix	0.55					
Accelerator dosage (% bcw)	Alkali–free Powder:4–8 Liquid:4–10 Alkaline Powder:4–8 Liquid:4–12	–	3–8	–	–	Powder calcium sulfoaluminate 10 %
Fiber dosage (kg/m^3)	–	–	Steel: dry–mix < 50 Synthetic micro: 1–2	Steel: >30 Synthetic macro: >4 micro: >1.5	–	–
Steel fiber length (mm)	25–35 < 0.50	$< 0.7\cdot\phi_{nozzle}$	–	–	$< 0.5\cdot\phi_{nozzle}$ $< 0.8\cdot\phi_{hose}$	< 35
Slump (cm)	8–20	10–15	8–18	8–14	16–22	–

quality of the mortar present in the concrete and allow proper pumping with no segregation. Therefore, large amounts of fines and plasticizers are incorporated, simultaneously reducing the maximum aggregate size and adopting granulometric gradings in which the fine fraction takes on particular importance.

In the wet spraying process, the mixture is prepared with the mixing water and pumped until the spraying nozzle. As in conventional concrete, the transportation of the mixture constitutes a critical condition in wet sprayed concrete, and the criteria established for the dosage of conventional pumpable concretes may be used for its design.

This option is contemplated in some regulations. For example, ACI 506R-16 (ACI, 2016), within their specifications regarding the dosage of wet mix sprayed concrete/mortar, states that proportioning can be done according to ACI 211.1 (ACI, 1991) with an aggregate content correction for pumpable concrete. This correction consists in reducing the estimated coarse aggregate content for normal weight concrete by 10 %. According to ACI 506R-16 (ACI, 2016), in some situations, the resulting coarse aggregate content might still be high after its reduction. It is thus advised to ensure that the resulting slump, water/cement ratio and strength properties of the concrete are consistent with placing constraints and meet project specification requirements.

2.3. According to different authors

Several studies have been conducted on sprayed concrete in which the mix design is discussed. Most authors acknowledge that the basis of the design of sprayed concrete mixtures is unclear, especially the empirical approach of the dry mix spraying. As in the existing regulations, most authors limit their contribution to a series of recommendations and considerations regarding the composition of the initial concrete (Galan et al., 2019; Austin and Robins, 1995; Jolin and Beaupré, 2003; Thomas, 2020; Chapman et al., 2010; Hemphill, 2012; Banthia, 2019). Instructions on mix proportioning and the typical mix designs provided are in line with the recommendations described in Section 2.1, as in many cases, the same authors have participated in the preparation of the guidelines and standards reviewed.

Mahar et al. (Mahar et al., 1975) consider that the composition of wet sprayed concrete can be determined by applying ordinary concrete dosage methods, suitably selecting parameters such as the water/cement ratio, the cement content, and the aggregate granulometry to obtain a pumpable mixture. Likewise, Fernández Cánovas (Cánovas, 1990) proposes that the dosing of wet mix sprayed concrete should be performed by using the procedures used in conventional concretes with specific requirements on its workability.

A recent review focused on the durability of sprayed concrete for underground support (Galan et al., 2019) includes the range of variability of standard sprayed concrete components. Although this work aims to give an overview of the most important agents and impacts on durability, it also provides typical superplasticizer and retarder dosages. Notice that these components are not referred to in the standards and guidelines reviewed in Section 2.1. Superplasticizers are usually required in wet mix applications to provide adequate workability and pumpability. Common dosages fall within 0.50 and 1.5 % bcw (Galan et al., 2019) and may vary according to cement composition (Salvador et al., 2019). Depending on the distance from the concrete manufacturing plant to the spraying site and on the concrete open time required, retarders may also be employed, in dosages up to 0.50 % by cement weight (Galan et al., 2019).

Marc Jolin and coworkers (Jolin and Beaupré, 2000; Jolin et al., 2009, 2006) have performed some of the most fundamental research conducted on the pumping of concrete and the effects of mixture design (total paste content and entrained air) on pumping pressure. Their findings highlight the importance of providing a sufficient amount of paste to cover aggregates and lubricate the inner wall of the hoses. In addition, they demonstrate that there is a threshold value for the actual paste content below which pumping is not possible. For the particular aggregate and internal diameter of the hose used, authors determined the paste content of 35.1 % as a minimum value below which a mixture is not pumpable.

Prudêncio (Prudêncio, 1993) is one of the first authors that differs from the common indirect approach of guidelines and regulations and proposes a semi-empirical dosage methodology for dry and wet mix applications. In both cases, a previous testing campaign is required to determine concrete composition. The proposal evaluates the unique parameters of each spraying system: compressive strength and consolidation in the dry-mix and workability and compressive strength in the wet-mix.

Years later, this work inspires Rodríguez (Rodriguez, 1997) and other authors (García et al., 2001) on the development of a complete wet/dry sprayed concrete dosage methodology. Such method considers the existing differences between the starting and the placed concrete due to the change in composition caused by rebound and air incorporation. Based on this principle, it is considered that the characteristics of the placed concrete will be those corresponding to the starting concrete modified by the placement procedure.

This proposal was structured in four main phases (García et al., 2001). The first stage evaluates the modifications introduced during the application, quantified by different rebound coefficients relative to the spraying concrete crew, the characteristics of the backing material, and the starting concrete composition based on different studies (Ward and Hills, 1977; Teichert et al., 1991). Afterward, cement and water contents of the starting concrete are defined based on recommended ranges (345–450 kg/m^3 and 360–500 kg/m^3 for dry and wet mixes, respectively) and a modified Feret formulation (Feret, 1892, 1896; Duriez and Arambide, 1961; De Larrard, 1990, 1999). In the third stage, the amounts of aggregates in the placed concrete are determined to fit an ideal granulometry. Finally, in the fourth stage, the complete composition of the starting concrete and the placed concrete are determined, considering the rebound effect and the different densities of the starting material and the one finally placed.

3. Discussion and future directions

The review of the different standards and guidelines addressing sprayed concrete proportioning procedures highlights a common approach based on the definition of recommended ranges and requirements on the material components and the mixture. Similarly, most scientific studies addressing this topic assume this indirect approach and limit their contribution to a series of recommendations and empirical considerations based on past experiences. The restraints and ranges provided are deliberately flexible to account for the different sprayed concrete applications and specificities of work conditions. Despite this being a reasonable approach to cover a wide range of scenarios, it diminishes the usefulness of these tools for initial sprayed concrete proportioning and explains the current struggle of sprayed concrete specifiers and ready-mix producers to set optimized mixes that effectively minimize the cost associated with preconstruction trials.

On the other hand, full sprayed concrete proportioning methods (Prudêncio, 1993; Rodriguez, 1997; García et al., 2001) are scarce and have not been widely accepted amongst practitioners. These tend to be overly complicated for daily practice since these are based on a blend of disassociated empirical relations. Moreover, the results obtained have not proved to be more precise than other current methods. Although current proposals might not attain the required precision and practicality, these point to interesting directions by which to improve sprayed concrete proportioning. The following sections discuss major key aspects holding significant potential to progress sprayed concrete mix design.

3.1. Rebound

Rebound is a well-known phenomenon that accounts for the part of the sprayed concrete lost due to the impact on the surface during spraying. The reduction of rebound losses has become a fundamental goal for the industry due to the negative impact on cost and in-place material properties (Armelin and Banthia, 1998; Jolin and Beaupré, 2004; Kaufmann et al., 2013). Moreover, nowadays its reduction is also important from the environmental standpoint, to avoid leaching and contamination of groundwaters. The Spanish standard UNE 83607–2014 IN (AENOR, 2014) estimates the relationship placed concrete-to-starting concrete at 1–1.35 for the dry mixes and 1–1.21 for the wet mixes. The ACI regulation (ACI, 2016) indicates that a starting dry-mix concrete with a 1:3 cementitious material-to-aggregate ratio entering a gun may result in a 1:2 concrete in place.

Several standards and authors acknowledge the importance of rebound on mix proportioning and encourage the consideration of its effects on the in-place material (Jolin et al., 2001; Pfeuffer and W., 2001; Ginouse and Jolin, 2016). However, current practices target starting concrete to comply with all the performance requirements. Therefore, it makes sense that those requirements related to facilitating pumping and the spraying process are applied to fresh concrete proportioning, but aspects such as the required strength or durability should target the mix design of the concrete in place.

Therefore, the ideal cement content and the ideal granulometric curve of the aggregates should be defined upon the placed concrete, not the initial wet mix, as rebound will modify the effective contents of the granular skeleton during placement. It must be borne in mind that the rebound percentage is not the same for all components of the mixture, as it increases with the particle size. For example, certain very fine materials, such as undensified silica fume, blast-furnace slag, and ultra-fine limestone filler, improve the rheological behavior of the concrete and help reduce rebound. The work presented by (Rodriguez, 1997; García et al., 2001) is in line with this approach and adjusts the content of constituents for the placed concrete, which in the case of sprayed concrete can differ significantly from the starting concrete.

3.2. *Cement content and strength*

In all standards examined, recommended ranges are provided for cement content regardless of the cement type and grade. For example, it is well established that a type I cement is expected to develop compressive strength at a higher rate than a type II cement, as it contains a higher percentage of clinker. Similarly, a grade increase is associated with a strength gain due to a higher specific surface area and changes in the composition.

Table 6 presents some recommendations on the binder quantities based on cement type, strength grade, and the specified $f_{ck,28}$ of the placed concrete. The values provided are derived from the regular practice of the authors in structural sprayed concrete applications and research projects within Spain. Notice that values indicated in Table 6 refer to the binder content of the placed concrete. These should be modified based on the expected rebound to set the binder content on the initial mix. It is essential to mention that most of these results were derived from direct axial compressive tests of concrete cores (diameter: 75 mm; height: 150 mm) extracted from trapezoidal panels designed according to UNE EN 14488–2 (AENOR, 2007). Concrete was produced with a maximum aggregate size of 12.5 mm and an alkali-free accelerator at 6.0% by cement weight. Spraying was conducted in a piece of spraying equipment with a flow rate equal to 8 m^3/h, coupled to a 28-bar air compressor and a 60 mm nozzle.

Table 6 is of practical interest as a first approximation in construction projects with sprayed concrete mixes. If additions are introduced, these can be considered in the binder content and water/binder ratio with an efficiency coefficient multiplying the added content.

At early ages, mechanical strength development is governed by the interaction between cement and accelerator (Salvador et al., 2017). Therefore, in applications where a fast rate of strength development at early ages is required due to safety reasons, it is crucial to follow the classification J1, J2 and J3 described in the Austrian guideline (ÖBV, 2013). To achieve concretes that belong to classes J2 and J3, CEM I contents around 400 kg/m^3 and alkali-free accelerator dosages around 5–8 % bcw are usually employed (Galobardes et al., 2014, 2015).

Early strength must be considered to determine the safe re-entry times for newly sprayed linings. Mechanical strength development at early ages results from the combination of several factors related to mix composition, application method, and microstructure of the matrix. In addition, the temperature during curing significantly influences the rate of strength gain and should be considered in cold climate applications.

Table 6
Recommended binder content (kg/m^3) based on type, grade, and $f_{ck,28}$.

Cement	Characteristic compressive strength [MPa]					
	25	30	35	40	45	50
I52.5	–	400	410	420	430	440
I42.5	400	410	420	430	440	450
II52.5	400	410	420	430	440	450
II42.5	410	420	430	440	450	–

3.3. *Water*

The amount of water or the water/cement ratio (w/c) is addressed in guidelines and standards based on the prescription of maximum values and broad recommended ranges with limited value to the specifier or producers. The amount of water needed in the mix is strongly influenced by the type, quality and fineness modulus of the aggregates, the cement-aggregate ratio, and the effectiveness of admixtures used. Unfortunately, current regulations and guidelines do not provide tools to quantify these phenomena to any extent during sprayed concrete mix design.

Conventional concrete proportioning methods could be adapted for modern sprayed concrete applications to set the amount of water in the fresh mix. The Fuller method provides reference water contents for different aggregate types (rolled or crushed) and maximum sizes (Fuller and Thompson, 1907; Cánovas, 2013). These values were initially proposed based on experimental tests for aggregates of medium granulometry, with a w/c ratio of 0.57 and a slump of 76 mm. Therefore, these values should be modified for sprayed concrete applications to comply with the desired slump.

Suitable slump ranges vary significantly for different applications and spraying equipment. In fact, the main sprayed concrete standards do not provide slump limits, as shown in Table 4. In general, lower slump mixes (60–80 mm) are more suited in applications without set accelerators, while higher slumps (80–180 mm) are more suited to applications in which set accelerators are used. In this case, the slump should be further optimized for operational requirements (AuSS, 2020).

Fuller proposed a ± 3% variation of water content to increase or decrease the slump by 2.5 cm (Fuller and Thompson, 1907; Cánovas, 2013). The effects of water-reducing agents on the amount of water in the initial mix could be considered by incorporating a reduction coefficient based on admixture type. Although suppliers usually determine the efficiency of water-reducing agents, authors propose the following reduction coefficients based on manufacturers' recommendations and experience: −5, −15, and − 25 % for low (lignosulfonates), medium (melamine or naphthalene sulfonate-based chemicals), and high (polycarboxylates) range water-reducing admixtures.

3.4. *Accelerators*

As a recommendation, the selection of materials for an adequate evolution of mechanical strength should be based on the chemical composition of cement and accelerators. To achieve a balance between short- and long-term properties, aluminum content added to the matrix, controlled by Al^{3+} concentration or accelerator dosage, should be the minimum necessary for an adequate spraying and consolidation consistency (Al^{3+} amount should be in the range between 324 and 428 g for 100 kg cement). Furthermore, the Al_2O_3/SO_4^{2-} molar ratio in the accelerator should be similar to that of ettringite (0.33) so that the sulfate balance of cement is not negatively altered. The adequate final C_3A/SO_3 ratio in the accelerated matrix is the one to obtain properly sulfated systems (Salvador et al., 2017, 2016). Authors recommend requiring those pieces of information to accelerator manufacturers.

Since in wet-mix spraying applications accelerators are required, alkaline accelerators based on sodium and potassium aluminate solutions should be avoided. For dry-mix applications, sprayed concrete may be produced without accelerators. By doing so, concretes may be more resistant to sulfate attack.

3.5. Durability and use of sulfate-resisting cement

The increasing interest in permanent sprayed concrete structures has raised attention on the durability of sprayed concrete. Currently, durability during sprayed concrete mix design is addressed in standards and most technical guides in the same way as conventional cast concrete. Durability generally involves compliance with material components selection, minimum binder contents, and limitation on the water/binder ratio tailored to the particular exposure risks of each project. Similarly to conventional concrete, these actions aim to produce concrete as impermeable and stable as possible. Although aspects related particularly to the durability of sprayed concrete have been discussed in Section 2, an in-depth description of durability requirements is out of the scope of this work and may be found elsewhere (Galan et al., 2019; ITA Report, 2020).

Particular attention should address sulfate resistance since this is one of the most common forms of matrix degradation. The use of sulfate-resisting cement in sprayed concretes containing accelerators is not enough to limit the aluminate content in the matrix and provide proper durability against sulfate attack. Limitations regarding the aluminate content should be defined for the total amount of potentially expansive aluminates (cement + accelerator) per volume of concrete. The common practice found in guidelines and projects that rely mainly on sulfate-resisting cement represents a critical gap in current specifications. Therefore, it should be revised to adopt the C_3A/SO_3 ratio as the main parameter that governs concrete durability (Herrera-Mesen et al., 2020; Salvador et al., 2020). Such parameter may be calculated following the results obtained in previous works from the research group (Salvador et al., 2017, 2016).

3.6. Field trials

Although several recommendations were proposed in this paper, mix proportioning of sprayed concrete should always be verified with pre-construction trials. Field trials are crucial to confirm that the mix design fulfills the requirements of specific projects because the spraying equipment and the ability of the nozzlemen may significantly affect the evolution of properties. The main parameters to be determined in field trials and the associated laboratory testing are pumpability, sprayability, layers, mechanical strength development at early and late ages, porosity, and susceptibility to chemical attacks. In the case of fiber-reinforced sprayed concrete, the determination of residual strength and toughness is necessary.

3.7. Mix design and sustainability

There is an increasing trend towards incorporating sustainability assessment into engineering projects. The high Portland cement content of usual sprayed mixtures place this technology in the spotlight regarding its carbon footprint. However, a fair assessment of the sprayed concrete sustainability should comprise several factors, such as concrete composition, the volume of concrete used, equipment, and the structure's service life. Comparisons have demonstrated that even though sprayed concrete has a higher embodied carbon content than cast concrete per cubic meter due to its higher cement content, the need for less material in sprayed concrete tunnels can result in a lower carbon footprint of the project as a whole (ITA Report, 2020).

Focusing on sprayed concrete material components, the carbon embodied arises from their production, transportation, and application, where cement and steel reinforcement are the main contributors. Despite cement replacements being widely used, the percentage of additions typically incorporated remains low compared to cast concrete. This fact is mainly associated with the high early strength required in most sprayed concrete applications for safety and its economic impact on production rates (e.g. thickness of layers) (Thomas, 2020). Further research is needed to boost the performance of set accelerators with binary or tertiary blends as cement replacements do not hydrate as fast as Portland cement.

Regarding steel reinforcement, progress has been made in many industrialized countries to replace traditional steel mesh by fibers. Despite a kilogram of steel fibers has a higher embodied carbon content than a kilogram of plain reinforcing steel bars, the mass of fibers needed is lower, effectively reducing the embodied carbon content (ITA Report, 2020). The use of macrosynthetic fibers (if applicable) could further improve the material's sustainability. However, its use in underground projects is often compromised by potential contamination of nearby water sources with plastic fibers.

A couple practical examples are presented here to show administrations and clients possible frameworks in which these types of evaluations might be articulated. Kodymova et al. (Kodymova et al., 2017) used the life-cycle assessment method defined in ISO 14044:2006 to evaluate the environmental impact of rock bolts in tunnel projects. The life-cycle stages of a rock bolt considered in this study includes the production phase, product transport, installation, and maintenance of the product. The Polytechnic University of Catalonia worked with BASF Spain to create a sustainability index for sprayed concrete mixtures (Interempresas, 2021). The approach used to evaluate the sustainability of each alternative was based on the MIVES multicriteria method (Pardo-Bosch and Aguado, 2015; de la Fuente et al., 2017). This model is specifically designed to discriminate between accelerators types and justify the ban of alkaline accelerators for given set of economic (during execution and service), social (health and safety) and environmental requirements (use of non-renewable materials, CO_2, amongst others).

4. Conclusions

This paper provides a general overview of the different existing approaches for sprayed concrete proportioning published in standards, technical guides and scientific documents and discusses major areas holding the significant potential to improve current practices. The information is presented as a practical guide to assist sprayed concrete specifiers, technologists and ready-mix producers in producing quality initial mixes that minimize the number and cost of current pre-construction trials. From this work, the following outlines can be concluded:

- The review highlights a widespread agreement of standards and guidelines on the mix design approach and recommendations on material components and the mixture. These are deliberately flexible to account for the different sprayed concrete applications and specificities of work conditions. Currently, these documents represent the most updated guide on sprayed concrete mix design.
- There is a lack of modern direct sprayed concrete proportioning methodologies to establish optimized initial mixes. However, these approaches, taken broadly, might provide rational methods for mix design without heavily relying on past experiences of the concrete supplier.
- Practical recommendations on material components and the mixture are provided to advance towards more direct sprayed concrete proportioning methods.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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