Environmentally friendly, customised sprayed concrete

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ABSTRACT

The quality of structural shotcrete or sprayed concrete depends not only on the same factors as conventional structural concrete, but also on other placement-related issues such as pumping or spraying. Although today’s primarily prescriptive design and control tools guarantee quality to some extent, the results are uncertain and mix design procedures do not provide sound information, “a priori”, on mechanical properties or durability. Nor does this approach contribute to design or produce sprayed concrete with an improved environmental profile. This chapter shows how the use of a Performance-Based Approach (PBA) to structural sprayed concrete design and characterisation has led to greater homogeneity and increased efficiency while using less energy-intensive cements and almost any type of aggregate. Customised sprayed concrete is assessed on the grounds of performance indicators, some of which are fairly innovative. The results prove the feasibility of tailoring structural sprayed concrete design to specific needs while reducing its environmental impact. The application of PBA to the design and characterisation of sprayed concrete might also enhance the harmonisation of the specification and control stages.

20.1 INTRODUCTION

Concern about the environmental impact of the construction industry has been growing in recent years (Cardoso-Teixeira 2005; NCHRP, 2000; Anderson 2002). Such impact can be assessed on a number of grounds (Treloar et al. 2000; Ding 2005; CIB 2001), energy consumption and the associated CO₂ emissions among them. Other
environmental considerations include the shortage of suitable aggregates, reuse of excavation debris and structural service life (CIB 2001, Andrade et al. 2005). In addition to seeking longer service life for structures, underground engineering must develop customised solutions suitable for remote-controlled or automated on site processes, whose use continues to rise.

The selection of innovative concrete mix materials and design procedures can ensure economical, compatible and optimised concrete mixes in keeping with both sprayed concrete lining design and on site control. Such practices may also help define customised solutions, including concrete linings with an enhanced environmental profile.

General concrete codes and standards (ACI 506 2000; EN-14487-1, 2005; EN-14487-2, 2006; EFNARC 2002; Fernandez-Luco et al. 2006) contain provisions on sprayed concrete design and characterisation respecting:

- Mix design and proportions: maximum aggregate size or minimum cement content, type of aggregate, cement or fibres, water/cement or binder ratio and so on.
- Basic requirements for sprayed concrete linings: compressive strength, density, bond strength and similar, measured primarily on drilled panel samples.
- Requirements relating to the process parameters that determine construction quality: pumping capacity, rebound, the amount of sprayed concrete applied (i.e., difference between pumping capacity and rebound) and so forth.

These traditional specifications treat concrete as a commodity (Brasellon and Blair 2004), assuming that any given mix of components produces virtually identical performance, when in fact concrete – like most products – varies widely. Therefore prescriptive specifications are of little assistance when defining a robust mix suitable for fully automated processes or for including innovative components. Moreover, prescriptive specifications may result in the failure to meet performance requirements.

Although some existing standards claim to follow a performance-based approach (ACI 506 2000; EFNARC 2002) both their focus and methodology differ. Braselton and Blair, for instance, concluded that most concrete specifications “tend to be hybrids”. The present lack of clarity in the description of all the steps in such protocols leads to the partial application of PBA, in which performance and prescriptive specifications are combined. While this hybrid approach may initially appear to be wise, it may actually cause a variety of problems and generate confusion rather than contribute to better assessment of product fitness for use.

The demand for including more advanced sprayed concrete functionality-related parameters in current standards is growing in light of the need to better prevent adverse developments during the spraying process (Rodriguez et al. 2005). Of particular concern are problems around mix pumpability or sprayability (see Fig. 20.1), along with the pursuit of a fuller understanding of actual sprayed concrete mechanical properties and durability (Fernández-Luco et al. 2005, Río et al. 2006).

A number of proposals are at hand, based for instance on modelling mechanical behaviour (Hellmich et al. 2005; Pichler et al. 2008) or attack mechanisms (Tuuti 1982); or on the so called “performance” parameters (Berger 2002; Baroghel-Bouny 2002; CIB 2001; ACI506 2000); or on the use of “mechanical” (EFNARC 2002; Río 2009) or “durability” indicators (Andrade et al. 1987; Whiting 1981). Nonetheless,
their effective inclusion in standards is taking place rather slowly and a worldwide controversy has arisen over the definition of the best approach due to the lack of experience with these new proposals. Moreover, there appears to be a lack of accurate on site evaluation tools for establishing indicators other than mechanical strength. And in fact no standard method has been generally accepted, even for that basic parameter (Berger 2002; EN-14487-2, 2006).

In short, while the industry is theoretically moving toward performance-based specifications, few purely performance-based specifications have actually been written for concrete in general or for sprayed concrete in particular.

This chapter presents what is intended to be a comprehensive proposal in response to the demand for sprayed concrete performance parameters or indicators applicable to the design and characterisation of environmentally friendly customised sprayed concrete for tunnel linings. At the same time, it could be used to predict both sprayed starting mix- and (short- and long-term and structural) service life-related parameters (Rio et al. 2007; Andrade et al. 2005; Rodriguez et al. 2007). The parameters chosen are discussed briefly below, together with the proposal fundamentals that should enhance homogeneity and efficiency while allowing for the use of less energy-intensive cements and nearly any type of aggregate. The advantages are illustrated by a comparison of the traditional (according to EN standards) and new approaches based on certain selected mix proportioning parameters and shotcrete lining mechanical values.

20.2 PERFORMANCE-BASED APPROACH

The PB criterion is characterised by the importance attached to the actual performance of a given material or structure (CIB 2001). Performance requirements are closely related to industrial or technological needs or other technical or non-technical considerations (identification of goal or objective), but these needs must be expressed as quantitative values (definition of requirements and respective indicators) associated with specific test methods on standard samples. The general approach, therefore, calls for greater knowledge and most of the indicators and related tests are still under
development. Nonetheless, PB criteria accords designers considerable freedom, which in turn drives technological innovation.

These sampling and testing protocols are designed to be used for validation (verification of compliance to conformity criteria) and, depending on the values obtained, for acceptance or rejection of the material, structure or structural element (Andrade and Martínez 2005; Rio 2005).

Purely performance-based specifications provide all concerned with a fuller understanding of what is required of whom, while allowing for a wider range of methods to reach the desired results. A simplified overview of the requirements for tunnel linings is given in Fig. 20.2.

In the case of sprayed concrete linings, when identifying certain performance indicators, answers must also be given to questions such as:

- What is the purpose of the sprayed concrete?
- How will it be used, and by whom?
- What construction issues must be considered?
- How important are environmental and sustainability issues, and why?

![Figure 20.2 Summary of tunnel lining requirements.](image-url)
These questions are imperative because performance requirements focus on how the material is used rather than what it contains. Furthermore, owners’ needs may vary not only from site to site, but from one stage to the next within the same project. For instance, durability standards are not the same for temporary and permanent linings, nor are requirements or quality demands the same for manual and remote-controlled operations, and so on.

The parameters need not be assessed in terms of variables, as this criterion is flexible enough to allow for attributes as well. The PB approach meets the assessment needs not only of fresh and hardened sprayed concrete requirements (Rio et al. 2007), but also of spraying process operations. As a result, PBA is applicable to the various stages of sprayed concrete construction, including the selection of concrete mix components, mix proportioning, the process itself or the final sprayed concrete product as a whole. Quite clearly, owners need more comprehensive specifications, while specifiers’ and designers’ first responsibility should be a full understanding of the project.

Figure 20.3 shows the key performance indicators (PI) that characterise the different stages of concrete spraying and the requirements for each stage.

This discussion takes the points of view of the various stakeholders (suppliers, contractors and so on) and many other factors into consideration, in addition to mere cost-performance tradeoffs.

It is followed by a translation of owners’ expectations into measurable performance criteria. These were used to establish indicators, after smoothing over possible inconsistencies due to the variety of sources of information about requirements. For instance, producers would be allowed to use different proportions of any type of compliant aggregate available and/or supplementary binders to deliver high strength sprayed concrete while maintaining or improving concrete pumpability, lowering environmental impact and reducing overall costs.

Adoption of such a PBA might also make a substantial contribution to harmonizing the spec drafting and quality control stages, for both would be governed by

![Figure 20.3 Main stages of shotcrete production and application and respective indicators.](image-url)
the same criteria (Fernandez-Luco et al. 2005). The parameters need not be assessed in terms of variables, as this criterion is flexible enough to allow for attributes as well (Ríó et al. 2007; Rodríguez et al. 2007). Lastly, by focusing on results, PB specifications create incentives for quality and innovation, and encourage the use of higher-performing Portland blended and slag cements, the inclusion of new admixtures or the use of flaky or elongated particles wherever suitable. Furthermore, performance specifications encourage the proper use of mineral admixtures such as fly ash, taking ash quality and its consistency profile into consideration, along with aggregate packing density, to produce the most cost-efficient mixes. Specifications based on final product performance help create markets for new technologies, thereby furthering the manufacture of more effective and longer-lasting sprayed concrete.

20.3 INDICATORS CHOSEN AND THEIR MEANINGS

The holistic approach proposed here based on measuring performance indicators (see Fig. 20.3) makes use of a number of parameters chosen for their ability to comprehensively reflect any given property. Under this approach, moreover, process parameters are matched to a specific property of the material in question to define reliable indicators.

The differences between the proposed and traditional approaches may be illustrated with a property such as permeability. According to EFNARC (2006), for instance, when “water-tight sprayed concrete is required the maximum value of penetration in accordance with EN 7031 shall be 50 mm and the mean average value shall be less than 20 mm”. Permeability, however, depends on exposure conditions and structural design. Where sprayed concrete permeability is an issue, then, a need arises for a more comprehensive parameter denoting concrete microstructural behaviour, pore connectivity in particular, and therefore concrete resistance to penetration by liquid or gas (Andrade et al. 2005). Indeed, not all requirements are pertinent at any given time. Rather, their relevance depends on specific situations.

In this regard, the process parameters laid down in standards to determine the quality of workmanship (for instance, thickness of the sprayed concrete layer or pumping capacity) are exactly those process parameters, but not true indicators of shotcrete quality. To be a true performance indicator, the thickness of the layer of sprayed concrete, for instance, should be related to structural requirements (concrete strength, f, and/or the modulus of elasticity, E) and checked against process capabilities (min/max layer). This in turn entails establishing a method (such as proposed in Chapter 19) and determining the respective allowances. Similarly, concepts such as “pumping capacity” depend not only on the application and the equipment but also on mix pumpability, which is related to both. This called for the development of innovative testing methods (filed patent, 2007).

As a rule, the parameter used to specify sprayed concrete is early age and 28-day compressive strength. This may or may not be the most appropriate performance measure.
Flexural tensile strength or the modulus of elasticity, for instance, may be more relevant measures in some applications, even though their measurement is not included as a quality control procedure. Moreover, the early and very early age values of these parameters may be highly relevant, for they are used as such in lining design (Oreste 2003; Ansell 2007).

20.3.1 Constituent materials and mix proportions

The following discussion addresses only the main differences between the component materials and proportions in the three alternative mixes (SGr, SSf, SSC) used in this chapter to illustrate the advantages of the methodology proposed. The component materials and mix proportions in SRe (reference mix), a standard mix adopted in an actual tunnel, were established pursuant to European standard EN-14487-1 specifications.

Under the proposed approach the aggregate used in shotcrete must comply with the general requirements for conventional concrete aggregate, in addition to other features that ensure pumpability and sprayability. Where performance indicators are to be used, neither crushed fine aggregate nor flaky or elongated particles need be excluded (as specified in the existing standards) without proof of the unsuitability of the trial mix. The standard approach to mix design is based on optimizing the packing density of the coarse and fine aggregate. This criterion was also followed here because higher aggregate packing density requires less cementitious paste to fill the voids.

Less cement often leads to less shrinkage, improved durability, less heat of hydration, and importantly, lower total mix costs. Since dense packing might interfere with mix workability, in the proposed mixes other fine particles (binder or material passing through a 0.063-mm sieve) have been used in light of the key role they play in the starting mix (pumping and adhesion to substrate). Gunning distance, pump capacity and hose diameter are instrumental to pumping capacity and their specifications may vary depending on the circumstances (see Chapter 19 for further details).

The cement (actually the fines content) is the main binder in any concrete formulation but it is also the main lubricant for delivery of the sprayed concrete. The cement in sprayed concrete mixes acts as glue that binds and embeds the aggregate particles. Since very early age strength is an additional requirement, however, the cement in sprayed concrete must begin to set very soon after application. Setting behaviour depends on compatibility with the nozzle accelerator and as a rule the special admixtures needed for this purpose are more effective with cement type I than with blended formulations; thus, shotcrete formulations are usually made of CEM I 52.5 R (the type recommended by the existing standards). In light of the better sustainability profile of CEM II cements and their growing market share in the EU, CEM II 42.5 R (A-V) was chosen here for the shotcrete formulations after running laboratory compatibility trials with chemical admixtures.

Last but not least, active mineral additions are used to supplement the fines balance, improve the pore refinement effect (acting on durability) and increase mix stabilisation and pumpability, as well as to be able to use new admixtures such as developed by SIKA (see Chapter 21 for further information on such admixtures).
Concrete that contains admixtures and mineral additions is a complex multi-material system in which cross compatibility is essential to achieving good results. The importance of verifying the behaviour of chemical admixtures in the presence of other concrete components cannot be overstated. Mix water demand and accelerator dosing may be effectively controlled by the new prototypes developed by SIKA (see further information in Chapter 21). Although relatively high cement content and mineral additions were used in this exercise, since the volume of water needed was reasonably small, the water/binder ratios attained were likewise low (0.38). At the same time, the relatively small dose of accelerator reduced the heterogeneity of the sprayed concrete.

While different mix compositions (with and without mineral additions, fibres, crushed or natural siliceous and limestone aggregate and so on) and proportions were prepared by combining different requirements, only the mixes depicted in Fig. 20.4 are used here to illustrate the advantages of the methodology proposed. The results were compared to the findings for the standard mix, SRe.

The other three formulations were as follows: (SGr) was designed to increase the amount of primarily coarse aggregate while maintaining suitable pumpability and sprayability, and was tested by standard and non-standard methods such as a pumping rheometer (Río et al. 2007), whose reliability had been verified in full scale testing (see Chapter 19). The last two mixes contained mineral additions, silica fume in the case of mix SSf and colloidal silica fume in mix SSc and were tested as SGr on their fresh state. The proportions and aggregate grading were almost identical for the two, which contained higher amounts of paste and mortar than mix SGr.

Mixes SGr, SSf and SSc all contained the new chemical admixtures developed by SIKA for the TUNCONSTRUCT Project. CEM II 42.5 R (A-V) was used in all cases as a more sustainable alternative than CEM I 52.5 R, which is typically recommended by the existing standards. Consequently, CEM II 42.5 R (A-V) suitability was assessed by comparing the performance-based results to reported values for shotcrete mixes made with CEM I 52.5 R. Natural siliceous sand and crushed siliceous aggregate (for both fractions of coarse aggregate) were used throughout.

![Figure 20.4 Mix proportioning (relative volume).](image-url)
20.3.2 Full scale sample preparation and tests conducted

These four mixes were sprayed onto real walls and standard shotcrete panels (EN-14487, 2004) in the tunnel located at the Fundación Santa Bárbara facility in the Spanish province of León (see Fig. 20.5). The process was mechanized using a SIKA-Putzmeister shotcreting machine instrumented by AITEMIN and SIKA (see Chapters 19 and 21 for further information). Non-standard fibreboard panels were also sprayed, for in some cases the sensors had to be embedded or adapted to take NDT measurements.

The use of one or the other type was based on the tests or trials to be conducted on the shotcreted elements: extraction of drilled cores, or temperature, humidity,

Figure 20.5 Full scale testing conducted at the “Fundación Sta Bárbara” experimental tunnel: (a) full scale pumping rheometer trials to characterise mix pumpability; (b) standard slump characterisation; (c) pumping and (d) spraying stages; (e) on wall and panel samples; and respective (f) on site measurement sensors; (g) basic concrete specimens; and (h) drilled shotcrete core.
shrinkage or other continuous measurements. In addition, the starting mixes (basic concrete) were cast in cylindrical 150-mm \( \phi \) 300-mm steel or cardboard moulds as well as in prismatic wooden moulds to prepare sample specimens.

These specimens were cured as specified for the various tests. In addition to following standard curing recommendations, some panels were kept in a tunnel or similar environment to check differences. Two curing processes were therefore considered, under standard conditions and under tunnel or “natural” conditions. For the durability trials, however, the least favourable conditions were adopted.

All the fresh mixes were characterised with both standard trials and non-standard test procedures still under development: see Fig. 20.5 (Río et al. 2007, Rodriguez-Rio. 2007, Río et al. 2008, Chapter 19). Since the methodology focuses primarily on measuring actual performance, the use of NDT techniques was furthered by the development of new methodologies or testing equipment as necessary. Nonetheless, standards methods were also deployed for the purposes of calibration and standard evaluations were conducted. The tests run are listed in Table 20.1.

<table>
<thead>
<tr>
<th>Parameter measured</th>
<th>Method</th>
<th>Specimen type</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open porosity density</td>
<td>Archimedes</td>
<td>Drilled core</td>
<td>7–14 d</td>
</tr>
<tr>
<td>T over time</td>
<td>Vibrating wire and other sensors inside panel and manufacturer-recommended environment</td>
<td>Panel</td>
<td>Continuous</td>
</tr>
<tr>
<td>Dynamic modulus of elasticity</td>
<td>PUNDIT ultrasonic pulse velocity readings</td>
<td>Panels + Prisms</td>
<td>Continuous</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>Standard test on cylindrical cores</td>
<td>Drilled core and concrete sample</td>
<td>Since 72 h and over</td>
</tr>
<tr>
<td>Static modulus of E</td>
<td>Mechanic compressometer</td>
<td>Drilled core and concrete sample</td>
<td>72 h and over</td>
</tr>
<tr>
<td>Early age strength</td>
<td>Penetration needle and Bolt gun and pull out method</td>
<td>Standard shotcreted panel</td>
<td>According to equipment range</td>
</tr>
<tr>
<td>Shrinkage</td>
<td>Vibrating wire sensor</td>
<td>Special shotcreted panel</td>
<td>Continuous</td>
</tr>
<tr>
<td>Basic and coupled creep</td>
<td>Constant stress at 0.3 f'c, with and without drying</td>
<td>Drilled cores</td>
<td>14 to 130 d</td>
</tr>
<tr>
<td>Resistivity</td>
<td>4-probe Wenner technique and specific sensors inside panel</td>
<td>Drilled cores, samples and on site</td>
<td>Selected ages</td>
</tr>
<tr>
<td>Carbonation measurements</td>
<td>Phenolphthalein indicator (natural and accelerate conditions)</td>
<td>Drilled cores and samples</td>
<td></td>
</tr>
<tr>
<td>Chloride threshold methods</td>
<td>Migration accelerated and natural tests</td>
<td>Drilled cores, samples and discs</td>
<td></td>
</tr>
<tr>
<td>Other parameters</td>
<td>Humidity, water content, temperature (specifically developed sensors)</td>
<td>Panel and prisms</td>
<td></td>
</tr>
</tbody>
</table>
20.4 ADVANTAGES OF THE APPROACH: SELECTED RESULTS

The approach proposed can be successfully applied to assess both the components of the sprayed concrete and the respective starting mixes. Sustainability issues can be readily integrated into this PBA, for they can be considered as a primary requirement. As the findings in Fig. 20.6 show, CEM II 42.5 can be used instead of the cement usually recommended in the existing standards (CEM I 52.5), providing compatibility with the nozzle accelerator can be assured. The slightly lower position of the points for CEM II can be regarded to be insignificant, given the difference between the ambient temperatures (laboratory conditions, 20°C, for CEM I and actual conditions, 13°C, for CEM II). Vibrating-wire extensometer measurements of drying shrinkage in the shotcrete samples, taken at a constant temperature, showed that the behaviour of sprayed and ordinary concrete did not seem to differ significantly. Nevertheless, the peak (very early age) maximum temperature for the sprayed concrete appeared earlier than for the respective basic concrete and the initial slope was steeper. This finding can only be attributed to the effect of the accelerator.

The 28-day compressive strength ($f_c$) of the shotcrete formulations (see Fig. 20.7), measured from cores taken from standard panels after 3 days and over, as well as from the respective starting mix specimens, confirmed the design criteria proposed for each case. The $f_c$ attained lay in the upper strength range and all the formulations tested had higher 28-day strength values than the reference mix (SRe).

All the new mixes amply exceeded the minimum requirement for classification in the highest strength group defined by EFNARC (2002) and the strength was consistently smaller in the sample specimens than in the cores extracted from the wall (see Fig. 20.8).

![Early age results for SGr mix](image)

**Note:** ambient temperature 13°C cm for SGr mix. For all other mixes, $T=20$ °C

*Figure 20.6 Early-age strength results (log scale for time).*
The use of an innovative parameter, called overall efficiency (OE) in the proposal and defined as the ratio between the compressive strength of the shotcrete cores of sprayed concrete and the respective 30 × 15-cm basic concrete specimens, revealed the importance of using a lower percentage of accelerator and improved packing, with or without special admixtures (see Fig. 20.9, left).

This efficiency index can be used to compare the joint effect of components in different mixes, as well as mix design and execution. The overall efficiency of the shotcrete mixes tested averaged over 0.85, and for SSf and SSc the value climbed to 0.92. The coefficient of variation (CoV) found for core density (see the example in Fig. 20.9, right: CoV for SGr) on saturated, dry surfaces (SSD) denoted scant dispersion.

The findings evinced greater homogeneity (with a reduction of dispersion of from >20% to <8%) and enhanced efficiency (decline in losses from >40% to 12%), with a view to pursuing new, more cost-effective materials in the design stage.
Creep behaviour in the samples tested was as expected, while the results obtained for the modulus of elasticity showed that the actual values of this parameter should be used rather than values estimated from compressive strength.

Figure 20.10 shows the estimated depth of carbonation for the shotcrete solutions, assuming exposure to natural conditions over a service life of 50 and 100 years and applying the square root law (Andrade et al. 2006). While these findings should be treated with caution, for the results are subject to the conditions prevailing in each environment, for all the solutions proposed, a standard steel cover of 2 cm or less can be adopted even for a 100-year service life. The reference mix, however, would require a 4-cm cover.

![Figure 20.9 Overall efficiency of new shotcrete mixes (left) and distribution of the cylindrical core density (right).](image)

![Figure 20.10 Carbonation depth forecast for exposure to a conventional environment.](image)
20.5 FINAL REMARKS AND CONCLUSIONS

The need to improve the environmental profile of sprayed concrete by using less energy-intensive cements, nearly whatever type of aggregate is available, and new admixtures not yet on the market, along with the aspiration to enhance their engineering and durability, has driven the development of performance-based design and characterisation methodologies. While this approach is still subject to some limitations due to the lack of proven non-destructive methods to obtain actual performance indicators, it offers clear advantages.

The methodology presented here is based on the general performance-based approach. Sprayed concrete behaviour can be more reliably predicted if certain assumptions based on this approach are adopted for the design of the starting mixes and the products are tested using performance-based methodologies. Such procedures could prevent most of the adverse developments that arise at present and encourage innovation to surmount today's limitations.

Further to the case studies discussed in this chapter, the following conclusions can likewise be drawn:

- The performance-based approach can be successfully applied to assess both the components of the sprayed concrete and the respective starting mixes. Sustainability issues can be readily integrated into this PBA for they can be considered as a primary requirement.
- The use of blended cements, local aggregate and mineral additions improves the sustainability profile of basic and sprayed concrete, but their inclusion in the mix is only possible if PBA is applied.
- Efforts must be made to raise the overall efficiency parameter of shotcrete, as higher efficiency lowers the amount of cement consumed (lower CO₂ emissions) per effective MPa of sprayed concrete.

ABBREVIATIONS

\( f_{28} \) 28-day compressive strength
PBA Performance-based approach
PI Performance indicator
SCA Sprayed Concrete Association (UK)
SRe Shotcrete reference mix.
SGr Shotcrete mix with increasing aggregate content
SSF Shotcrete mix with silica fume
SSc Shotcrete mix with colloidal silica.

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