ENVIRONMENTAL FRIENDLY TAILOR-DESIGNED SHOTCRETE

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SUMMARY

Structural shotcrete can be designed and produced with an improved environmental profile when a performance-based approach (PBA) is addressed. The selection of suitable concrete constituents from a broad variety of alternatives can be ruled by the global environmental performance. Not only less energy intensive cement contribute to this objective but the use of locally available aggregates, a better efficiency and increased durability contribute as well.

This paper is aimed at highlighting a case study where the use of a PBA to structural shotcrete design and characterisation has lead to better homogeneity, increased efficiency while using less energy-intensive cements and almost any type of aggregate. The assessment of the tailored shotcrete is performed through the use of suitable performance indicators, some of them rather innovative. As a result, it can be stated that it is possible to design and produce a tailored designed structural shotcrete with an improved environmental profile. The application of PBA to the design and characterisation of shotcrete might lead also to a better harmonisation between specification and control stages.

1. INTRODUCTION

Since last years there has been an increasing concern on the environmental impact of construction industry. Its impact can be assessed from different approaches; energy consumption or CO_2 emissions associated being among them. Shortage of suitable aggregates and service life of built structures can also be regarded as environmental considerations.

The adoption of a PBA (CIB, 2001) to material selection or mix design might contribute to overcome the limitations imposed by present Standards and Codes (PrEN, 2004; EFNARC, 2002; ACI-506R, 2000), mainly prescriptive or deemed-to-satisfy-rules. But also to contribute to the development of most environmental friendly tailor-made solutions which fulfil functional needs at a time. PB criterion is characterised by the importance given to the actual behaviour of a given material or structure. The performance required is closely related to the industrial and technological needs but also other technical and not technical general considerations (*identification of goal or objective*), but these needs have to be expressed as quantitative value (*definition of requirements and corresponding indicators*) associated to specific testing methods on defined samples (Fig. 1).

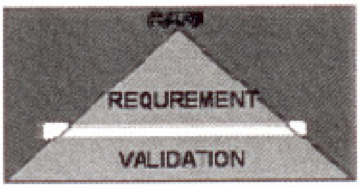

Fig. 1 Triangle of PB approach concept

These protocols for sampling and testing have to be used for validation (verification of compliance to conformity criteria) and then, according to the values obtained, to determine the acceptance or rejection of the material, structure or structural element (Andrade et al, 2005, Rio, 2005).

2. PB APPLIED TO SHOTCRETE

PB approach perfectly suits the needs of shotcrete or sprayed concrete (Rio et al., 2007) both fresh and hardened material related requirements but also process functionalities. As a consequence PBA can be applied to the different shotcrete stages: to the selection of concrete mix constituents, mix proportioning, shotcrete execution or, in a more integral manner, to the shotcrete or sprayed concrete material as final product.

The adoption of PBA might strongly contribute also to harmonize the specification and quality control stages, as both are ruled by the same concept (Fernandez-Luco et al, 2005). There is no need for the parameters to be assessed in terms of variables, as this criterion is flexible enough to allow for attributes as well. At present, Standards determine basic requirements for shotcrete, as well as for the parameters of the process which determine the quality of execution (Tab. 1. where both types of requirements according to EFNARC, are summarised as example) but for mix definition in general they still follows in principle a deemed-to-define-rules such maximum aggregate size, type of aggregate or type of cement, water/cement or binder relation, etc.

Tab. 1 Shotcrete Requirements

Shotcrete lining properties	Process parameters
Compressive strength and density	Pumping capacity
Flexural strength and residual strength	Rebound
Energy absorption class (plate test)	Applied shotcrete (as difference between pumping capacity and rebound)
Modulus of elasticity	Thickness of the shotcrete layer
Bond strength	Conveyor pressure
Permeability	Air consumption
Frost resistance	Air pressure
Determination of fiber content	Accelerator consumption
	Dust emission

The selection of constituent materials properties as well as its assessment and validation as part of the mix, by example, can be also based on PB approach. The advantages of using a performance criterion and its defined requirements (i.e. functional, environmental factors…), corresponding indicators (Structural stability- Safety, execution, etc. or health and sustainability..) and corresponding subindicators like (mechanical strength at different ages, or pumpability, projectability, mix efficiency or environmental effects, resources consume, etc.) are the freedom it gives to the designer and its triggering effect on technological innovations as we can see on the example described on this paper.

This attractive possibility pushed to extend the evaluation of the functions to the traditional standards but at the same time it has created confusion on the principles by mixing prescriptive and performance based methodologies and has contributed to the mistaking of definitions. PB subindicators and related tests as well are still under development for some of the cases.

3. SHOTCRETE MIXES SELECTED

The selection of most sustainable constituent materials for shotcrete can be based on a PBA, as mentioned in previous paragraph. For each of the constituents, main requirement have to be first identified and then, suitable performance indicators (PI) can be defined. Each of the performance indicators may lead to the use of convenient sub-indicators, which must be associated to specific sampling and testing procedures. The requirements considered in a PB approach must be seen as complementary of the ones set by Standards and Codes, which are mandatory and must be fulfilled. Under PBA, the assessment of concrete constituents and mix formulation may merge, as the performance is associated to both, constituent characteristic and mix proportions. Thus, four different formulations were prepared and tested following this criteria, as seen in Fig. 1.

One formulation, as it is used commonly, was tested as reference SRe. One formulation (SGr) was aimed at increasing the amount of aggregate, mainly the coarse, while maintaining suitable pumpability and projectability. Last two mixes are characterised for the inclusion of mineral additions, Silica fume for SSf mix and Coloidal Silica Fume for SSc mix. All mixes were projected using the same equipment onto real walls and standard shotcrete panel (PrEN, 2004). Panel cores were sampled at the age of 7d and standard cured until testing (28d).

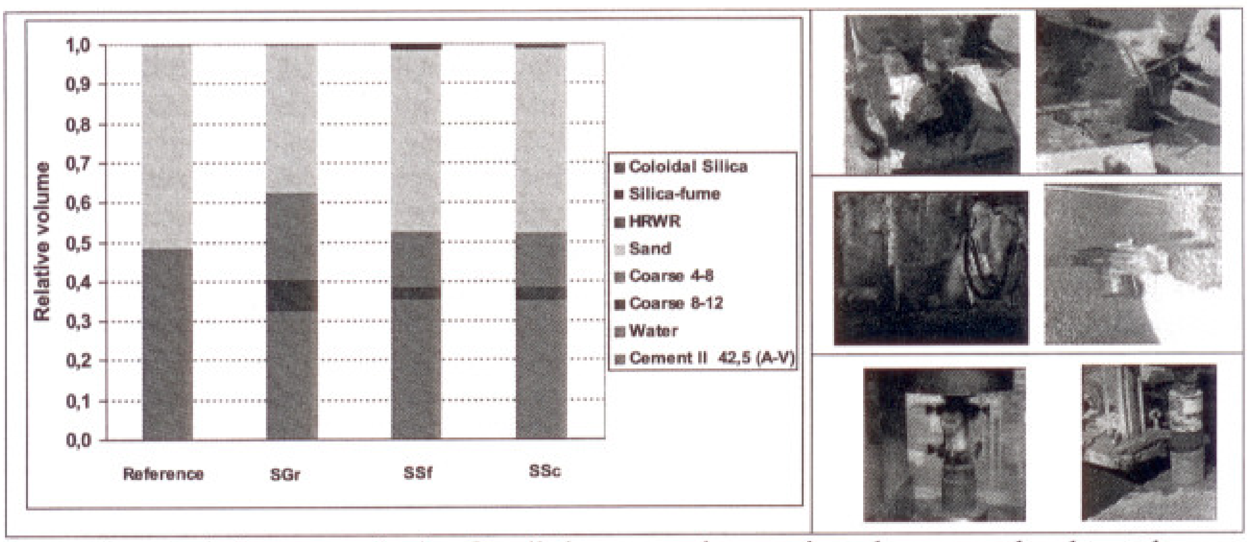

Fig. 1 Relative proportioning for all shotcrete mixes projected or sprayed and tested

3.1 Aggregates

Aggregates used for shotcrete must comply with the general requirements for aggregates for conventional concrete plus extra added features to assure *pumpability* and *projectability* (see table 1). Thus, grading, shape and texture are key issues as they have a significant influence on the properties of concrete at the fresh state. Present recommendations and standards prevent crushed fine aggregates and flaky or elongated particles to be used as aggregates for shotcrete, as they might interfere with pumping and projection.

Nevertheless, adequate proportioning (Fig. 2) and the use of suitable chemical admixture may reduce the effect flaky shapes and rough textures of aggregates have on the pumpability of a concrete mix. Distance of projection, pump capacity and hose diameter are a key issue in pumping capacity and thus, the requirement may vary according to any particular situation.

All mixes showed suitable pumpability, with low pressures at the pump. The amount of rebound was low, although it was not quantitatively measured but visually assessed. The homogeneity among samples was excellent and thus, grading and mix proportioning is good at achieving low dispersion, with a mean value of 2.23 kg/m^3 and a standard deviation of 0.02 kg/m^3, as well as high compacity. The reduction in density, taking the standard compacted basic concrete as a reference, was below 3 %. As a result, it can be said that the aggregate and the grading used fulfilled the performance requirements, as performance indicators show. Should additional requirements arise, such as very long pumping distances or limitations imposed by pumping equipment, conformity criteria should be adapted accordingly.

3.2 Cement

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. Very early age strength is an additional requirement, and thus, cement for sprayed concrete must always start to set extremely quickly to reach suitable very-early strength. Setting behaviour depends on the compatibility with nozzle accelerator and, as a general rule, these special admixtures work better with cement type I than with blended formulations; thus, shotcrete formulations are usually made of CEM I 52.5 R (also it is recommended by standards).

Based on the better sustainability profile of CEM II type cements and their increasing share in the European market (over 65 % in 2002 according to CEMBUREAU), a CEM II 42.5 R (A-V) was selected and tested for above shotcrete formulations after laboratory trials showed a good compatibility with chemical admixtures used. Regarding real scale testings on panels and on site fast setting was achieved at standard dosage of nozzle accelerator and early-age strength (tested according PrEN 14487 proposed methods) was only 15 % lower than the corresponding strength for a CEM I 52.5 R at the same age. Low temperatures, between 8-12 ºC may have prevented the mix to achieve higher strength. Compressive strength (f_c) of shotcrete formulations at 28-days (Fig. 3), was measured from cores taken from standard panels at 7d. The f_c achieved lies in the upper range of strength classes and in any case, all formulations tested have higher 28d strength than the reference mix (SRe). Moreover, they can all be classed as the highest group according to (EFNARC, 2002).

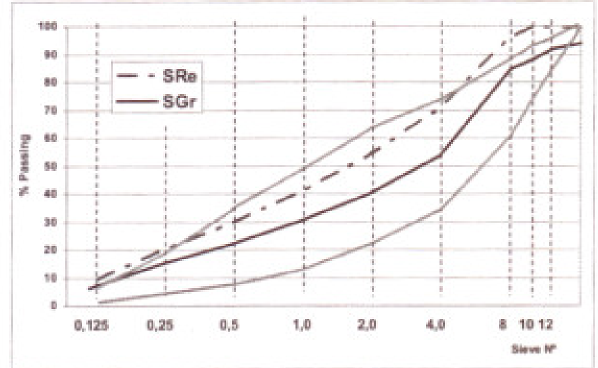

Fig. 2 SRe and SGr aggregate grading compared with SCA limits (orange)

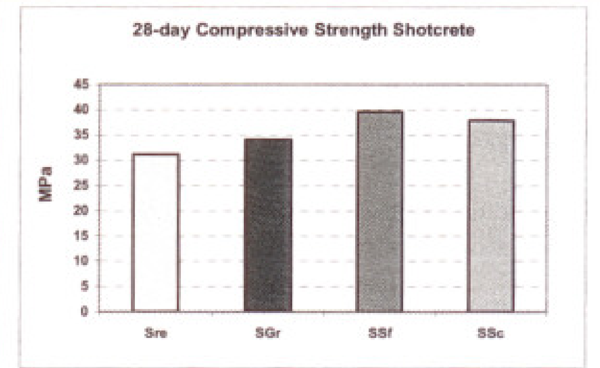

Fig. 3 28d compressive strength of different shotcrete formulations tested

3.3 Mineral admixtures

The use of mineral additions contributes to the sustainability profile of any concrete. They can be used to improve fresh-state properties and/or hardened state properties. These additions may be active (like silica fume, slag and fly ash) or almost inert (mineral filler), depending on the performance requirements. Their contribution to long-term properties is well documented yet they might reduce the strength evolution at early age. Their compatibility with other shotcrete constituents should be verified in lab tests and confirmed with real scale trials, as the presence of mineral additions might interfere with the nozzle accelerator.

Real-scale trials showed that water demand for both mineral additions mixes (SSf and SSc) evaluated (Fig. 1) was increased as compared to no-addition mixes, although the difference was kept relatively low and the compressive strength at all ages was better than the corresponding for no-addition mixes, as can be seen from Fig. 3. From the results obtained, it can be stated that the mineral additions tested improved the properties of shotcrete mix.

3.4 Chemical admixtures

Concrete admixtures and mineral additions make concrete a complex multi-material system and the crossed compatibility becomes a key issue in achieving good results. It cannot be overemphasised that chemical admixtures should be verified jointly with other concrete constituents. A new superplasticizer (prototype under development by SIKA which feasibility has been proven on lab) was used on real scale trials. This new prototype presents a high potential for controlling water demand of the mix. Although relatively high cement content and mineral additions were used, water was kept reasonably low thus allowing for low water/binder ratios (0.38) to be achieved. Slump-loss was negligible during 1.5 hours and thus, cement used and the superplasticizer are compatible.

The fast-setting behaviour and the low reduction of shotcrete f_c as compared to basic concrete f_c confirm the very good performance of this product not available on market yet as well as the possibilities of the PBA as a way of ensuring quality while encouraging *innovation*.

3.5 Mix efficiency

Among the innovative proposals presented in this paper, it is worth to mention the definition of "overall efficiency" (OE) of shotcrete, which can be defined as the ratio between the compressive strength of the shotcrete samples (panel cores of projected concrete) and their basic 30x15 cm concrete samples (no projected concrete). This efficiency index is very important because it can be used to compare different mixes. Overall efficiency value represents the joint effect of constituents, mix design and execution. It cannot be overemphasised that the overall efficiency for the shotcrete mix tested averaged more than 0.85 (Fig. 3) and, for mixes SSf and SSc, it reached 0.92.

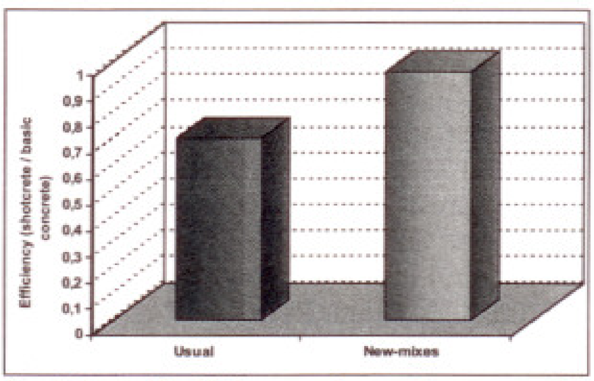

Fig. 4 Overall efficiency of new shotcrete mixes

4. CONCLUSIONS

From the results shown above, the following conclusions can be stated:

1. Performance-based approach can be successfully applied to the assessment of shotcrete constituents as well of shotcrete mixes. Sustainability issues can be easily integrated in this PBA for they can be considered as primary requirements.

2. The use of blended cements, local aggregates and mineral additions contribute to the improvement of the sustainability profile of concrete and shotcrete and its inclusion as part of the mix is only possible if a PBA is applied.

3. Efforts must be forwarded to improve the overall efficiency parameter as better efficiency means less consumption of cement (less CO_2 emissions) per effective MPa in the shotcrete.

5. NOTATIONS

f_{c28}	Compressive Strength at 28 days
PBA	Performance Based Approach
PI	Performance Indicator
SRe	Shotcrete **Re**ference mix.
SGr	**S**hotcrete mix with increasing amount of ag**gr**egates
SSf	**S**hotcrete mix with **S**ilica **f**ume
SSc	**S**hotcrete mix with **S**ilica **c**oloidal.

6. ACKNOWLEDGEMENTS

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