Performance vs Prescription Based Shotcrete Specifications

There are two general approaches to preparing specifications for shotcrete: *prescription-based* and *performance-based.*

by D.R. "Rusty" Morgan, Ph.D

In *prescription-based* specifications the engineer will typically set out in detail all requirements for the materials and shotcrete mixture proportioning as well as the type of equipment required for batching, mixing, supply, and application of shotcrete. In *performance-based* specifications the engineer will specify the required performance characteristics for the shotcrete and let the contractor select the materials, mixture proportions, type of equipment and application procedures to be used. In general, *performance-based* specifications are preferred to *prescription-based* specifications in that they encourage innovation and introduction of new technology and generally result in lowest cost to the owner. Let us examine in some detail the differences between these two different methods of specifying shotcrete.

Prescription Based Specifications

In *prescription-based* specifications the engineer will typically specify (in kg/m^3 or lb/cu yd, or mass to volume ratios):

- The type and quantity of cement to be used (sometimes even specifying a particular brand name of cement).
- The type and quantity of supplementary cementing materials, such as fly ash, silica fume, blast furnace slag, or metakaolin, etc. to be used.
- The source of supply, gradation and quantity of coarse and fine aggregates to be used.
- The type (often including name brand) and dosage of all chemical admixtures to be used, e.g. water reducers, retarders, accelerators, superplasticizers, and air entraining admixtures for wet-mix shotcrete, or accelerators and dust supressants for dry-mix shotcretes.
- The type (often including name brand), length, aspect ratio (length to equivalent diameter), and addition rate of steel or synthetic fibers to be added to the shotcrete, if required.

Alternatively, the engineer may specify that the contractor use a particular proprietary dry-bagged shotcrete mixture. Conceptually, both these *prescription-based* methods are acceptable, provided the contractor demonstrates proper mixing, batching, supply, application, and curing methodology and the engineer/owner is prepared to accept the resulting performance (in terms of com-

Table 1: Shotcrete Performance Specification Stave Falls, BC Hydroelectric Project

Property	Age, Days	Specified Limits
Maximum Water/Cement Ratio		0.45
Air Content-As Shot, % CSA A23.2-4C		4 + 1%
Slump, mm, CSA A23.2-5C		80 + 30
Minimum Compressive Strength, MPa CSA A23.2-14C	7 28	30 40
Maximum Boiled Absorption % Max. Volume of Permeable Voids % ASTM C642	7 7	8 17
Minimum Flexural Strength, MPa Min. Flexural Toughness ASTM C1018 & Ref 1	7 7	4.0 Toughness Performance Level III
Shotcrete Core Grade ACI 506.2-95		Mean <2.5 Individual <3

pressive strength and other physical properties achieved) with these prescription mixes. What is unfair, however, is if the engineer requires the contractor to use a given *prescription-based* mixture formulation, and also meet certain performance specifications, e.g. meet compressive strength, flexural strength, toughness, shrinkage, etc. values. Unfortunately, from time to time, one still finds such specifications in bid documents. The contractor should be alerted to this and raise the issue with the specifying engineer prior to bid submittal in order to avoid being placed in a compromised position, should a *prescription-based* mix design fail to meet imposed performance requirements.

Performance-Based Specifications

In *performance-based* specifications the engineer will often specify the following items:

- The type of cement e.g. ASTM C150 type 1.
- The type and sometimes minimum and maximum permissible addition rate of supplementary cementing material (e.g. fly ash or silica fume) as a percent by mass of cement. Note: Supplementary cementing materials are often used for reasons such as mitigation of the potential for alkali aggregate reactivity, sulfate attack, heat of hydration, chloride intrusion, etc. As such, the engineer is fully entitled to specify their use in a *performance-based* specification.
- The maximum size aggregate permitted and an aggregate gradation envelope that the combined coarse and fine aggregates should satisfy e.g. ACI 506R-90, Table 2.1, Gradation No. 2.
- The types of chemical admixtures that should be used.
- Whether the use of shotcrete accelerators is permitted.
- Whether steel or synthetic fibers should be used. Note: Sometimes engineers will specify a minimum tensile strength for steel fibers (e.g. minimum 1000 MPa) in order to guard against use of lesser quality fibers. Specifying fiber length and aspect ratio as well is, however, considered inappropriate in a *performance-based* specification.
- The allowable slump range at discharge into the pump for wet-mix shotcretes.
- The in-place (as-shot) air content in wet-mix shotcretes. Note that about half the as-batched air content is lost during shooting and in order to end up with 4 ± 1% air content in-place, it is usually necessary to start with about 8 to 10% air content in the shotcrete discharged into the pump. The as-shot air content can be determined by shooting directly into an ASTM C231 air pressure meter base and then conducting the test in the normal way used for plastic concrete.
- For accelerated mixes the engineer may specify maximum initial and final setting times. Such tests should be conducted on shot test panels using the ASTM C1117 Penetration Resistance test method.
- The compressive strength, typically at 7 and/or 28 days. For accelerated shotcretes, earlier age strengths may also be specified, e.g. 8 hour, 12 hr, or 24 hr. strengths, if this is an important requirement for the construction process.
- For fiber-reinforced shotcretes, flexural strength at 7 and/or 28 days is often specified, together with flexural toughness.

Table 2: Shotcrete Mixture Design Stave Falls, BC Hydroelectric Project

Material	Mass(kg)	Bulk Density (kg/m3)	Volume (m3)
Portland Cement, CSA Type 10	385	3150	0.122
Silica Fume	50	2100	0.0238
Steel Fibres	59	7860	0.0075
Coarse Aggregate, 14-5 mm	520	2759	0.1885
Fine Aggregate, SSD	1200	2662	0.4508
Water	180	1000	0.1800
Water-Reducing Admixture	1.76L	1000	0.0018
Superplasticizer	3.5 L	1000	0.0035
Air Content as shot	4.0%		0.0408
Total	2399		1.0188

Slump (after superplasticizer addition) = 70 ± 20 mm
Water: (Cement + Silica Fume) Ratio = 0.41
Calculated Plastic Density = 2355 kg/m3
Accelerator added at nozzle as required

Table 3: Shotcrete Compressive Strength, Boiled Absorption and Volume of Permeable Voids Performance Test Results, Stave Falls, BC Hydroelectric Project

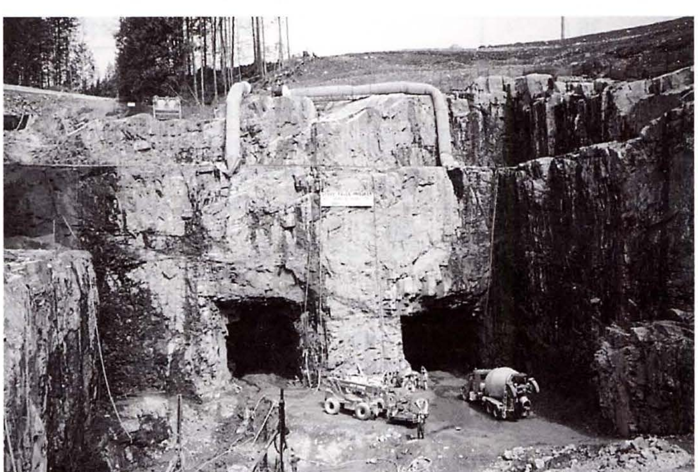
Panel No.	Compressive Strength (MPa) At 7 days	Compressive Strength (MPa) At 28 days	Boiled Absorption (%)	Volume of Permeable Voids (%)
1	47.5	71.5	4.6	10.5
2	45.1	68.6	3.4	8.1
3	38.5	66.7	4.9	11.0
4	48.0	72.2	3.5	8.1
5	36.8	56.6	4.8	11.0
6	36.7	47.0	6.2	13.7
7	38.5	57.7	5.9	13.3
8	33.0	45.9	5.8	13.2
9	36.8	62.0	4.5	10.2
Mean	40.1	60.9	4.8	11.0
Standard Deviation	5.4	9.9	1.0	2.1
Spec.	Min. 30	Min. 40	Max. 8	Max. 17

Table 4: Shotcrete Flexural Strength and Toughness Performance Test Results
Stave Falls, BC Hydroelectric Project

Panel No.	First Crack Flexural Strength MPa	Ultimate Flexural Strength MPa	ASTM C1018 Toughness Parameters					Japanese Toughness Factor (kNmm)	Japanese Toughness Factor (MPa)	Toughness Performance Level
			I_{10}	I_{30}	I_{60}	$R_{10,30}$	$R_{30,60}$			
1	3.77	4.31	10.5	31.1	57.2	103	87.1	21.70	3.13	III-IV
2	5.17	5.26	9.3	26.6	45.5	86.5	62.8	23.26	3.28	IV
3	4.66	4.77	8.8	25.6	46.2	84.1	68.8	21.92	3.17	IV
4	5.86	5.92	7.6	23.7	40.1	80.3	54.6	23.55	3.34	IV
5	4.49	4.52	9.6	27.6	49.1	89.7	72.0	23.21	3.24	IV
6	4.67	4.67	8.1	22.8	41.6	73.7	62.4	17.60	2.96	IV
7	4.83	4.83	8	22.8	41.8	74.2	63.4	22.77	3.10	III-IV
8	4.13	4.25	9.3	28.3	53.9	94.7	85.7	25.26	3.50	IV
9	4.37	4.37	8.0	22.1	40.7	70.8	62.0	17.99	2.79	III-IV
Mean	4.66	4.77	8.8	25.6	46.2	84.1	68.8	21.92	3.17	IV
Standard Deviation	0.60	0.53	1.0	3.0	6.1	10.6	11.1	2.55	0.21	
Spec.	Min. 4	Min. 4								Min. III

In North America flexural toughness is usually determined using the ASTM C1018 test method. There are, however, various ways of interpreting the data from this test method, e.g. toughness indices, residual flexural strengths calculated from toughness indices (or directly from the load vs deflection curve), Japanese JSCE-SF4 toughness parameters, toughness performance levels, etc. For more details on this subject see Reference 1.

- Some engineers specify limits on values for boiled absorption and volume of permeable voids in tests conducted to ASTM C642 on cores extracted from shotcrete test panels. Correspondence has been found between durability and resistance to leaching in shotcrete linings and these parameters.



BC Hydro Stave Falls Hydroelectric Project: Downstream outlet of SFRS-lined pressure head race tunnel.

- Some engineers also place limits on the maximum allowable water/cement ratio; control of this parameter helps to prevent excessive water addition to the shotcrete, which could adversely affect shrinkage, cracking, and durability of the in-place shotcrete.
- Finally, for reinforced shotcrete linings the (somewhat controversial) ACI 506.2-95 Core Grade system is sometimes specified. This test is usually used to prequalify nozzleman for shooting on the project, but is also sometimes used to evaluate the adequacy of encasement of reinforcing steel on the job. It should, however, be used with caution, as interpretation of core grading is somewhat subjective.

Case History Example of a Performance Specification

A performance specification for a wet-mix, air-entrained, steel fiber reinforced shotcrete for use in the Stave Falls Hydroelectric tunnel lining project in British Columbia, Canada (Reference 2) is shown in Table 1. This specification was for a high quality hydro power pressure headrace tunnel final lining with a 70-year design life. Table 2 shows the mixture design used by the contractor. The contractor was able to consistently meet the specified performance requirements for the project. Table 3 shows actual compressive strength and boiled absorption and volume of permeable voids test results for the first 9 of over 40 test panels shot on the project. (One test panel was shot for each day of shotcrete production or every 50 m^3 (65 cu.yd.) of shotcrete, whichever occurred first). Table 4 shows flexural strength and toughness test results for these same test panels.

Closure

The specifying engineer should avoid placing unnecessary limits on the contractor regarding shotcrete batching, mixing, supply, and application procedures. While it is perfectly legitimate to specify whether the wet-mix or dry-mix shotcrete process should be used on a project, it may be unnecessarily restrictive to write *prescription-based* specifications which allow the contractor to only use central mix batching, with transit mixer supply, and manipulator arm placement of the shotcrete. The contractor may, for a given site, be able to produce an economical, high-quality shotcrete, meeting all the engineers/owners expectations using a site-produced, dry-batched, pre-mix supply and hand nozzling from a platform mounted on a manlift (as is currently being successfully used in several projects in North and South America).

In summary, the engineer is encouraged to write *performance-based* specifications. The engineer should tell the contractor what performance is required and let the contractor select the materials, mixture proportions, and production methods. This will usually result in the lowest cost shotcrete installation for the owner. The owners interests can be protected by the engineer specifying and enforcing a suitable quality assurance (QA)/quality control (QC) testing program. Good guidance regarding preparation of shotcrete specifications and design of suitable QA/QC programs is provided in ACI 506.2-95, ACI 506R-90 and References 3 and 4.

Dudley R. (Rusty) Morgan, Ph.D., P.Eng. is a Vice President and Chief Materials Engineer with AGRA Earth & Environmental Limited in Vancouver, BC, Canada. Dr. Morgan is Secretary of the American Shotcrete Association and is also a member of various ASTM and Canadian Standards Association (CSA) technical committees. He is a Fellow of the American Concrete Institute and is Secretary of the ACI 506 Shotcrete Committee. He is also a member of the ACI 234 Silica Fume and ACI 544 Fiber Concrete Committees. He has been active in design, specification, QA/QC and shotcrete research and development projects in numerous countries worldwide over the past two decades and has authored and coauthored over 60 shotcrete publications

References

1. Morgan, D.R., Chen, L. and Beaupré D., *Toughness of Fibre Reinforced Shotcrete,* Shotcrete for Underground Support VII, Telfs, Austria, June 1995, published by ASCE, pp. 66-87.

2. Ripley, B.D., Rapp, P.A. and Morgan, D.R., *Shotcrete Design, Construction and Quality Assurance for the Stave Falls Tunnel,* Tunnelling Association of Canada, Canadian Tunnelling, 1998, pp. 141-156.

3. AASHTO-AGC-ARTBA Joint Committee, Task Force 37 Report, *Guide Specifications for Shotcrete Repair of Highway Bridges,* February 1998, published by AASHTO, Washington, DC pp. 108.

4. Morgan, D.R. and Heere, R., *Quality Management of Shotcrete in North America,* Laich SA Colloquium on Shotcrete Technology, Wildegg, Switzerland, September 26, 1997, p. 8.