Quality Management of Shotcrete in North America

by Dudley R. "Rusty" Morgan and Roland Heere

As for all construction materials, a proper program of quality management should be implemented in shotcrete construction to protect the owner's investment. This article briefly examines typical shotcrete Quality Management (QM) practice in North America. QM can be considered to be comprised of Quality Assurance (QA) and Quality Control (QC) functions.

QA starts with the development of a suitable design and set of construction drawings and specifications for the project by experienced and competent engineers, in consultation with the owner. The use of performance specifications in which the contractor is responsible for the selection of equipment and the shotcrete mixture design is the norm. This is followed by preparation of suitable contract bid documents.

On most projects, only contractors with demonstrated shotcrete skills and experience for the work-at-hand are permitted to bid on the work. The owner's designated representative (usually the engineer) assumes responsibility for implementation of a QA program. The contractor is responsible for implementing a QC program to satisfy the requirements of the project specifications. Usually, the contractor is required to conduct the necessary QC testing and report the results to the engineer. Sometimes the owner may retain an independent testing agency to conduct the QC testing.

Most specifications require a preconstruction program which is used to prequalify the nozzlemen, shotcrete crew, equipment, materials, and mixture design proposed for use on the project. The preconstruction program typically requires materials submittals and the shooting of standard shotcrete test panels. Specimens are procured from the test panels by coring or diamond saw cutting to determine properties such as compressive strength, flexural strength, boiled absorption, and volume of permeable voids, and with fiber-reinforced shotcretes, various toughness parameters. In addition, mock-up sections with reinforcing steel and any other embedments representative of the work, are shot by all nozzlemen proposed for use on the project. Cores are extracted from locations of intersecting steel for core grading to prequalify the nozzlemen.

During construction, there is ongoing QA monitoring of the shotcrete work by qualified personnel; the contractor is encouraged to remove and replace defective shotcrete while it is still plastic. Standard test panels are shot every day of shotcrete production for QC testing. Procedures are detailed for a course of action to follow in the event that shotcrete is nonconforming to the specifications. Repair, replacement or strengthening alternatives are also detailed in the specifications. Considerable emphasis is placed on safety and hazard reduction requirements, particularly for underground and overhead works. A case history example of a typical QC testing program is provided.

Introduction

Shotcrete has been used for nearly 90 years in North America for a wide range of applications, including:

- **New construction**, for example, construction of water-retaining structures, canals, structural walls, housing free-form structures such as shells and plates, artificial rockscapes, and bobsled runs;
- **Infrastructure rehabilitation**, including repair of dams, bridges, marine structures, cooling towers, and seismic retrofit of historic buildings and a variety of other structures;
- **Ground support**, for example, rock slope stabilization, creek channelization, soil-nailed wall construction, and construction of retaining walls; and
- **Support of underground openings** in tunnels, shafts, caverns, and mining applications.

Over the past two decades the writers have been involved in the provision of QM services for shotcrete for virtually all of the above shotcrete applications. The writers have also been involved in a number of failure studies and forensic engineering investigations where less than satisfactory shotcrete performance has been achieved. The common denominator to all of these projects is that the quality of work produced is only as good as the level of QM exercised.

QM is a team effort and is dependant on the combined efforts of the owner, engineer (and sometimes architect), contractor, suppliers, and the testing agency. QM can be subdivided into QA and QC functions. The following definitions apply:

Quality Assurance (QA): Those planned systematic actions necessary to assure that the final product will perform its intended function.

Quality Control (QC): Those actions related to physical characteristics of the materials, processes, and services which provide a means to measure and control the characteristics to predetermined quality standards or criteria.

The owner and engineer are responsible for development and implementation of the QA program. The contractor is responsible for the QC program. The sections which follow examine these responsibilities in more detail and provide a case history example of a QA/QC program for a typical North American shotcrete project.

Quality Management

The overall scope of the QM program should be commensurate with the size, nature, and complexity of the project. An underscoped QM program runs the risk of incurring an unacceptable number of nonconformances and unsatisfactory implementation of the design. By contrast, excessive QM provisions can become an unproductive burden on the project by introducing unnecessary costs and delays without deriving any additional significant benefits.

As mentioned previously, the chief responsibility for the QA program lies with the owner and engineer. The subdivision of responsibilities between the owner and engineer will depend on the sophistication of the owner. With large government organizations (for example, transportation departments, power supply agencies, public works department, and military organizations) or private sector companies (for example, mining companies and multinational corporations), the owner may have a sophisticated in-house engineering capability and take the prime role in development and management of the QA system. Smaller and/or less sophisticated owners with either limited or no pertinent in-house engineering capabilities (for example, certain municipal authorities, building owners, and developers) may delegate development and management of the QA system to a retained consulting engineer. The engineer should nevertheless keep the owner fully informed of progress of the work, so that the desired end objective (both technically and financially) is achieved.

Quality Assurance

QA starts with development of a conceptual design by the owner followed by development of a detailed design, drawings, and specification by the engineer (either in-house or a retained consultant) with review and approval by the owner.

The next step is development of a set of contract bid documents, which include all tendering requirements in addition to the technical specifications and design drawings. A typical set of contract bid documents would include:

- **Advertisement for tenders**: this document would include details regarding the owner, project, time of tender closure, etc.;
- **Instruction for tenderers**: this document would include items such as: work and site conditions, site visit, proprietary and environmental policies, data to be submitted with tender, bid bond and guarantee requirements, terms for acceptance and rejection of tenders, etc.;
- **Form of tender:** this document would include engineer's quantity take-offs and a form for submittal of a schedule of prices and total tender price by the contractor;
- **Terms of payment**: this document would deal with progress estimates and payments and holdbacks and retentions;
- **General conditions**: this document would cover items such as interpretation of the contract, schedule (time) requirements, authorities, equivalents and substitutes, inspection and testing obligations, site conditions, delays, cleanup, environmental protection, safety, dispute resolution, insurance requirements, confidentiality, suspension of work, etc.; and
- **Technical specifications**: these documents would include the design drawings and all detailed technical specifications including QC requirements. More details regarding the preparation of technical specifications are given in the sections which follow.

Technical specifications can be either prescription-based or performance based. In prescription-based specifications the engineer sets out in detail the type of equipment materials, methods, and procedures to be used, even down to the exact proportions of the shotcrete mixture design to be used by the contractor (that is, material source and batch quantities in kg/m^3 or L/m^3). In a performance-based specification, the engineer provides general guidance in the specifications as to the materials and methods to be used. The selection of the precise type of equipment and source of materials and shotcrete mixture proportioning is, however, left to the contractor, for example, the engineer may specify that the wet, rather than the dry-mix shotcrete process be used and that special materials such as silica fume, steel fibers, and accelerators be incorporated in the shotcrete. The contractor can then select whichever equipment and proprietary brands of materials they prefer, but is obligated to meet all the performance and safety requirements of the specification.

A few agencies in North America still use prescription-based specifications. Now the large majority of shotcrete specifications, however, are performance-based. Performance-based specifications are generally preferred, as they encourage innovation and optimization by the contractor and usually result in more economical construction. QC testing by the contractor and QA monitoring by the owner and/or engineer to verify conformance to the project specifications is, however, essential if the full benefits of performance-based specifications are to be realized. Sometimes specifications contain a mixture of performance-based and prescription-based requirements. This should only be done, however, when warranted by special circumstances.

Implementation of a proper QA program only starts with preparation of an appropriate design and set of tender documents. It is usually followed by:

- Prequalifying contractors permitted to bid the work. (Note: *With some government agencies, with open-tender policies it may not be possible to only allow prequalified contractors to submit bids*);
- Evaluating bid submittals for conformance to the contract documents and specification requirements;
- Interviewing and awarding of contract to the successful bidder;
- Reviewing of all supplier submittals and contractor proposed QC program;
- Continuous monitoring of contractor's QC test results, during both preconstruction and construction phases of the work with implementation of corrective actions if necessary at any time during progress of the work;
- Verifying quantities and payment items;
- Monitoring of contractor's safety and environmental protection practices;
- Issuing corrective action forms where warranted and acceptance/rejection of remedial work; and
- Issuing certificate of completion upon satisfactory completion of the work by the contractor.

Quality Control

The owner and/or engineer establishes the QC requirements for the project. The contractor is responsible, however, for QC of the constructed structure. The owner may hire an independent testing agency to conduct QC testing on their behalf, but this does not relieve the contractor of the responsibility for implementation of a suitable QC program for the work. Depending on the size and complexity of the project the owner may require the contractor to conduct all QC testing, or hire an independent testing agency to conduct the QC testing.

The important consideration is that the testing agency selected be suitably qualified to do the work. In North America this work is normally carried out by either American Concrete Institute or Canadian Standards Association certified concrete testing technicians/laboratories, although individuals/organizations with other certifications are also used.

QC testing must be conducted at the frequency designated in the specifications. Proper QC records must be maintained and submitted to the engineer for review on a timely basis. The sections which follow describe shotcrete performance requirements commonly specified, for which QC testing is conducted on North American shotcrete projects.

Shotcrete Specifications

ACI 506.2-95, "Specification for Materials, Proportioning and Application of Shotcrete" is the most commonly referenced shotcrete specification in North America. Additional generic guidance is given in documents such as ACI 506R-90, "Guide to Shotcrete" and the AASHTO "Guide Specification for Shotcrete Repair of Highway Bridges." Particulars of the individual specification will, of course, depend on the specific project. There is, however, considerable material that could be considered *generic* and common to most shotcrete specifications. The following is a brief outline of the material covered in most shotcrete specifications:

- **Scope:** provides details of the work required to be performed by the contractor;

- **Definitions:** defines terminology unique to the shotcrete process;
- **Standards and codes:** lists standards and codes referenced in the specifications; commonly referenced documents are given in the Bibliography at the end of this paper;
- **Materials:** provides details and requirements for: portland cement; supplementary cementing materials such as fly ash, silica fume, metakaolins or natural pozzolans; aggregates; water; chemical admixtures (including shotcrete accelerators); steel; or synthetic fibers;
- **Shotcrete proportioning and performance requirements:** specifies the required physical shotcrete properties. Table 1 provides typical shotcrete performance requirements for a wet-mix, steel fiber-reinforced, silica fume, accelerated shotcrete used for construction of a permanent tunnel lining in a hard-rock hydroelectric project in Canada;
- **Submittals:** requires submittals from the contractors which include qualifications and experience of the proposed shotcrete crew (particularly the nozzlemen); source and conformance of materials to the project specification; proposed shotcrete batching, mixing, supply and application equipment; and qualifications of the contractor(s) proposed testing agency;
- **QC program:** provides details of the QC program required to be implemented by the contractor, including frequency of tests and reporting requirements;
- **Preconstruction trials:** Requires the contractor to perform preconstruction trials on mock-up sections, representative of the work, to demonstrate that the materials, mixture design, equipment, and shotcrete crew are capable of producing shotcrete conforming to the project specifications. Preconstruction trials can also be used to prequalify (certify) nozzlemen proposed for use on the project. On certain small projects and where the contractor has demonstrated suitable experience on previous similar projects, preconstruction trials may be waived;
- **Batching, mixing, and supply:** details these requirements, be it either by the dry or wet-mix shotcrete processes, using either central or transit mixers, site volumetric batching, mixing and supply, or dry-bagged premix materials supply;
- **Shotcrete placing equipment:** provides details regarding the generic type of equipment to be used for shotcrete application, be it either dry-mix guns, wet-mix pumps, and manual or robotic (manipulator arm) shotcrete placement;
- **Auxiliary equipment:** details requirements for equipment such as compressors, hoses, and blow-pipes (for rebound control);
- **Preparation of surfaces for shotcreting:** details permitted methods and required end product for surface preparation, whether it be soil, rock, masonry, existing concrete, or other surfaces;
- **Reinforcement:** details requirements for installation of anchor bolts and reinforcement such as wire mesh, reinforcing steel, lattice girders, etc.;
- **Tolerance and thickness control:** specifies allowable tolerances and means of achieving desired shotcrete thickness;
- **Safety:** requires the contractor to implement a hazard reduction program to protect all personnel from injury or death from working

Table 1: Steel fiber-reinforced shotcrete performance requirements

Shotcrete properties	Test method	Age (days)	Specified limits
Maximum water/cementitious material ratio	—	—	0.45
Air content—as shot, %*	CSA A23.2-4C	—	4 ± 1
Slump at discharge into pump, mm	CSA A23.2-5C	—	80 ± 30
Minimum compressive strength, MPa	CSA A23.2-14C	7 28	30 40
Maximum boiled absorption, % Maximum volume of permeable voids, %	ASTM C 642	7 7	8 17
Minimum flexural strength, MPa Minimum flexural toughness	ASTM C 1018 and Ref. 1	7 7	4.0 Toughness performance level III
Shotcrete core grade	ACI 506.2-96	—	Mean core grade not greater than 2.5 No individual core grade greater than 3

* Determine air content on shotcrete shot into a CSA-A23.2-14C air pressure meter base

operations, including surface preparation procedures, projected shotcrete, compressed air, cement alkali burn, caustic accelerators, shotcrete rebound, etc.;

- **Shotcrete application:** provides details regarding good shotcrete placing practice, including achieving the correct distance and orientation of the nozzle to the receiving surface; procedures for multiple shotcrete layer construction; control of rebound and overspray; and encasement of anchors, mesh, and other reinforcement;
- **Curing and protection:** provides requirements for moist (or sometimes membrane) curing and hot and cold weather application and protection requirements;
- **Construction testing:** provides details of the QC program required to be implemented by the contractor and frequency and type of tests to be conducted by the testing agency;
- **Shotcrete acceptance/rejection:** details the basis on which shotcrete will be accepted/rejected for both the plastic (fresh) and hardened shotcrete. Deficiencies constituting cause for shotcrete rejection could include, but not be limited to:
  - failure to properly prepare the substrate and/or attain the required bond;
  - excessive voids, sagging, peeling, or delaminations;
  - incorporation of rebound and hardened overspray in the work;
  - excessive shotcrete and/or fiber rebound;
  - incomplete consolidation of shotcrete around reinforcing steel, anchors, or other embedments;
  - inadequate shotcrete thickness;
  - excessive shrinkage and/or thermally induced cracking; and
  - shotcrete in test panels or in the in-place work being nonconforming to the performance requirements in the project specifications. Note: Testing is normally conducted on shotcrete applied in 600 x 600 x 120 mm wooden test panels, with 45-degree sloped edges; if the shotcrete extracted from the test panels is non-conforming, then shotcrete is extracted from the in-place work to verify shotcrete quality. If the in-place shotcrete is nonconforming, then the engineer may specify remedial measures;
- **Remedial measures:** these may require removal and replacement or repair or strengthening of the defective shotcrete; repair procedures are provided; and
- **Clean-up:** requirements for clean-up and disposal of rebound and waste shotcrete and project close-out are provided.

Case History: Permanent Tunnel Lining

A wet-mix, steel fiber-reinforced, silica fume shotcrete (SFRS) with a liquid shotcrete accelerator

Table 2: Steel fiber-reinforced shotcrete mixture proportions

Material	Mass, kg	Density, kg/m³	Volume, m³
Portland cement (Type 10)	390	3150	0.1238
Silica fume	50	2100	0.0238
Steel fibers	60	7860	0.0076
Coarse aggregate (14-5mm)	520	2759	0.1885
Fine aggregate (SSD)	1200	2662	0.4508
Estimated water (liters)	170	1000	0.1700
Water reducing admixture	1.76		0.0018
Superplasticizer	3.5		0.0035
Air content	4.0%		0.0407
Totals	2395.3	Yield = 1.0102 m²	
Notes: Accelerator added at nozzle as required for adhesion and build-up Water/cementitious ratio = 0.39 Sand content = 69.8% Plastic density = 2371 kg/m³ Slump (after superplasticizer addition) = 70 ± 20 mm			

added at the nozzle was used for construction of the final tunnel lining in two parallel pressure headrace tunnels in a hydroelectric power generation project in Canada. The tunnel is designed for a 70-year service life and the shotcrete performance requirements are detailed in the attached Table 1. The shotcrete was transit-mixer batched and supplied. The shotcrete mixture proportions used are detailed in Table 2. The tunnels were horseshoe-shaped and 6.3 m high and wide. They were about 190 m long each and excavated by the drill and blast method. The rock was of fairly competent quality and rock bolts between 2.4 to 3.6 m long were resin grouted into place as required by geological conditions. Shotcrete anchor bolts, 1.5 m long with spider plates, were installed at 1.5 m on center. The SFRS was installed (typically in a single pass) to a minimum thickness of 100 mm. A number of preconstruction test panels were shot to optimize the shotcrete mixture design (including selection of accelerator type and addition rate) as well as prequalify four nozzlemen to apply shotcrete on the project. One test panel was shot for every day of shotcrete production. A total of some 36 panels were shot over the duration of the contract. The writers' company provided QC testing of the panels on behalf of the owner. The first nine construction test panels were batched with 59 kg/m^3 of steel fiber. Toughness performance of the shotcrete was consistently in excess of the *Toughness Performance Level III* specified[1] and so the steel fiber content was reduced to 55 kg/m^3 for the remainder of the project (27 panels). For brevity, the results for only the first nine test panels are reported.

Table 3 provides the results of averages of sets of three tests compressive strength tests at 7 and 28 days and values of boiled absorption and volume of permeable voids at age 7 days. All the shotcrete tested consistently met the specified performance requirements given in Table 3.

Figure 1 shows the results of a load versus deflection response (and a Toughness Performance Level template) for a nominal 100 x 100 x 350 mm beam tested in third point loading in flexure in accordance with the ASTM C 1018-94b test procedure (sample 1C in Table 4). Table 5 shows the results of the average of three sets of tests for various toughness parameters calculated from load versus deflection curves. All shotcrete tested consistently satisfied the minimum Toughness Performance Level III specified. Table 4 shows the results of a

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

Table 3: Properties of hardened steel fiber-reinforced shotcrete with 59 kg/m^3 steel fiber

Panel no.	Compressive strength at 7 days, MPa	Compressive strength at 28 days, MPa	ASTM C 642	
			Absorption after immersion and boiling, %	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
Coefficient of variation	13.4%	16.2%	20.6	19.0
Specified performance	≥30	≥40	≤8	≤17

QC test record (on sets of three specimens from one test panel) for one of the 9 shotcrete test panels listed in Table 5.

Some of the initial shotcrete supply during preconstruction testing was nonconforming to the project specifications and was rejected. Once the contractor had optimized the mixture design, however, no further problems relating to shotcrete quality as supplied and shot occurred and the owner was provided with a final shotcrete lining which was in full conformance with the project specification. This project demonstrates the benefits of implementation of a rigorous QM (QA and QC) system.

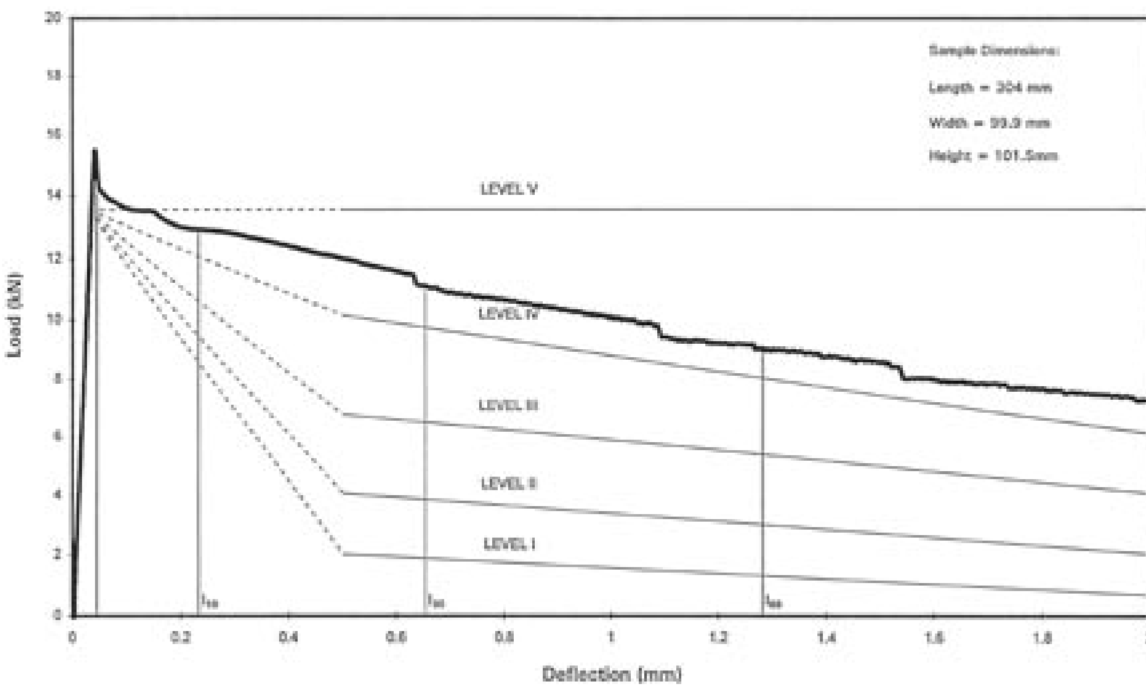

Fig. 1: ASTM C 1018 Flexural Toughness Test

Table 4: Quality control test report for steel fiber-reinforced shotcrete

Sample no.	Test method	1A	1B	1C	Average	Specified
Compressive strength, MPa at 7 days at 28 days	CSA A23.2-14C	 41.5 57.9	 40.2 54.2	 40.1 56.8	 40.6 56.3	≥30
Boiled absorption, % Volume of permeable voids, %	ASTM C 642	6.4 14.3	6.7 14.9	6.3 14.0	6.5 14.4	≤8 ≥17
First crack flexural strength, MPa Ultimate flexural strength, MPa	ASTM C 1018	5.3	4.6	4.6	4.9	≥4.0
Toughness indexes I_{10} I_{30} I_{60} Residual strength factors $R_{10,30}$ $R_{30,60}$	ASTM C 1018	8.1 22.4 41.2 71.5 62.7	8.9 25.2 46.6 78.5 65.0	8.8 24.5 44.0 78.5 65.0	8.6 24.0 43.9 77.2 66.3	— — — — —
Japanese toughness, kN·mm Japanese toughness factor, MPa	JS-SF4	23.4 3.3	22.6 3.3	20.2 3.0	22.0 3.2	— —
Toughness performance level	Morgan et al. (Ref. 1)	IV	IV	IV	IV	≥III

Table 5: Toughness of steel fiber-reinforced shotcrete with 59 kg/m³ steel fiber at age 7 days

Panel no.	First crack flexural strength, MPa	Ultimate flexural strength, MPa	ASTM C 1018 toughness parameters					Japanese toughness, kN·mm	Japanese toughness factor, MPa	Toughness performance
			I_{10}	I_{30}	I_{60}	$R_{10,30}$	$R_{30,60}$			
1	3.77	4.31	10.5	31.1	57.2	103.0	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	8.0	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	0.6	0.53	1.0	3.0	6.1	10.6	11.1	2.55	0.21	
Coefficient of variation	13.0%	11.2%	10.8%	11.9%	13.2%	12.6%	16.1%	11.6%	6.6%	
Specified performance	≥4	≥4								≥III

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