Shotcrete Design and Construction for the Stave Falls Project Power Tunnels

BC Hydro has recently completed construction of a replacement power plant at Stave Falls, near Mission, British Columbia. Two new power tunnels were constructed to carry water from the intake to the new powerhouse. The crown, walls, and invert of the power tunnels were fully lined with steel fiber-reinforced shotcrete for the primary purpose of reducing the hydraulic roughness of the drill and blast tunnel surfaces. Shotcrete was also used for the geometric transition from the horseshoe-shaped, shotcrete-lined tunnel to the circular steel lining.

by Paul Rapp

Project Background

The Stave Falls power plant is located 65 km (40 mi) east of Vancouver, British Columbia, and was constructed in stages, starting in 1909. The existing plant consists of two concrete gravity dams (Main and Intake Dams), a five-unit 52.5 MW powerhouse, tailrace, and tailrace deck switchyard. The power plant is more than 80 years old and continued service was becoming unreliable.

Starting in 1993, B.C. Hydro began work on the Stave Falls Powerplant Replacement Project, which replaced the majority of the existing plant. The new plant incorporates a new intake at the east side of the existing main dam, two power tunnels, a two-unit 90 MW surface powerhouse, an excavated tailrace channel, a tailrace berm, and a switchyard on the east terrace. The existing dams were not replaced, but will be reinforced for seismic loading with rockfill in 2000. Photo 1 shows the existing plant and the new powerhouse excavation and switchyard under construction in 1996.

Photo 1. Existing Stave Falls power house on left with new tunnel construction on right.

Geology

Bedrock at the site is primarily quartz diorite of the late Jurassic, Coast Plutonic Complex and is intruded by various pre-Tertiary dykes. The tunnels are located beneath the valley wall of the original river channel and have variable rock cover of between 15 and 25 m (49 and 82 ft). An orthogonal joint set is present at site, consisting of two subvertical (J1 and J2) and one subhorizontal (J3) joint sets. The tunnel alignments were within 20° of the strike of the J1 subvertical joint set. Rock conditions are listed below:

RQD	30 to 80	Block Size(mm)	100 to 1000 (4 in to 40 in)
UCS (MPa)	50 to 150	RMR (1976)	49 to 82
Structure	Blocky to Blocky/Seamy	Surface Condition	Fair

Tunnel Excavation

The two power tunnels are each approximately 190 m (625 ft) long and include two curves, as shown on Figure 1. Both tunnels have a straight-leg horseshoe cross section with nominal height and width of 6.7 m (22 ft), as shown on Figure 2. The maximum grade in the tunnels is 18.8% and total elevation gain from the powerhouse to the intakes is 27.2 m (89.2 ft). Maximum static head in the tunnels is 46 m (150 ft), at tunnel centerline. Maximum design flow is 140 m^3/sec (4950 ft^3/sec) in each tunnel.

The tunnels were excavated full-face by drill and blast starting from the powerhouse excavation (Photo 2) and ending at a blind face just short of the future intake excavation. A two-boom electric-hydraulic jumbo was used to drill blast holes and install rock bolts. All rock bolts were installed within 25 m (82 ft) of the excavation face and consisted of 2.4 and 3.6 m long (8 ft and 12 ft long), 25 mm (1 in) diameter resin-grouted rock bolts. Bolting averaged 2 bolts per meter of tunnel (6 bolts per 10 ft of tunnel).

Tunnel Lining Design

Two types of lining systems were considered for the tunnels:

1. An unlined tunnel with local rock bolts and shotcrete installed as required to provide long-term rock support. The majority of the tunnel walls, crown and invert would be the drilled and blasted rock.
2. A shotcrete lined tunnel with full perimeter shotcrete lining on the walls, crown and invert. Fewer rock bolts would be required compared to the unlined tunnel due to the increased rock

support provided by the full perimeter shotcrete lining.

Both of these lining types were economically optimized with respect to tunnel width (economic diameter) for the cost items listed below. All of the costs are estimated (i.e., not tendered), in 1995 Canadian dollars, and include an allowance for engineering and management. The tendered costs were somewhat different from these costs, but did not change the conclusions of the optimization.

- Excavation at $120/cubic meter ($92/cubic yard).
- Rock bolts at $60/square meter ($5.60/square foot) of tunnel requiring rock bolts.
- Shotcrete at $115/square meter ($10.70/square foot) of tunnel requiring shotcrete.
- Head losses at $1.36 million/m ($0.41 million/ft) of head per tunnel.

This optimization process yielded the following economic tunnel widths and estimated unit costs per meter of tunnel:

	Unlined	Shotcrete
Economic Width	7.2 m (23.6 ft)	6.7 m (22.0 ft)
Capital Cost	9,901 $/m (3019 $/ft)	10,172 $/m (3101$/ft)
Head Loss Cost	3,245 $/m(990 $/ft)	2,679 $/m(817 $/ft)
Total Cost	13,145 $/m(4009 $/ft)	12,852 $/m(3918 $/ft)

Although the shotcrete-lined tunnel had a lower total unit cost, the difference was judged to be less than the accuracy of the estimates. However, the shotcrete-lined tunnel also had savings for the following items:

- Rocktraps eliminated
- Shorter transitions at intakes and steel linings
- Decreased grouting at transitions
- Drain holes eliminated
- Decreased operating leakage
- Decreased tunnel maintenance

The net result was estimated cost savings of about $400,000 for the shotcrete-lined tunnels, and they were selected.

The primary design objective of the shotcrete lining is to reduce hydraulic roughness. Secondary objectives are to provide rock support, and to reduce leakage out of the tunnel during tunnel operation.

The following were identified as key requirements for the shotcrete lining in order to meet these objectives.

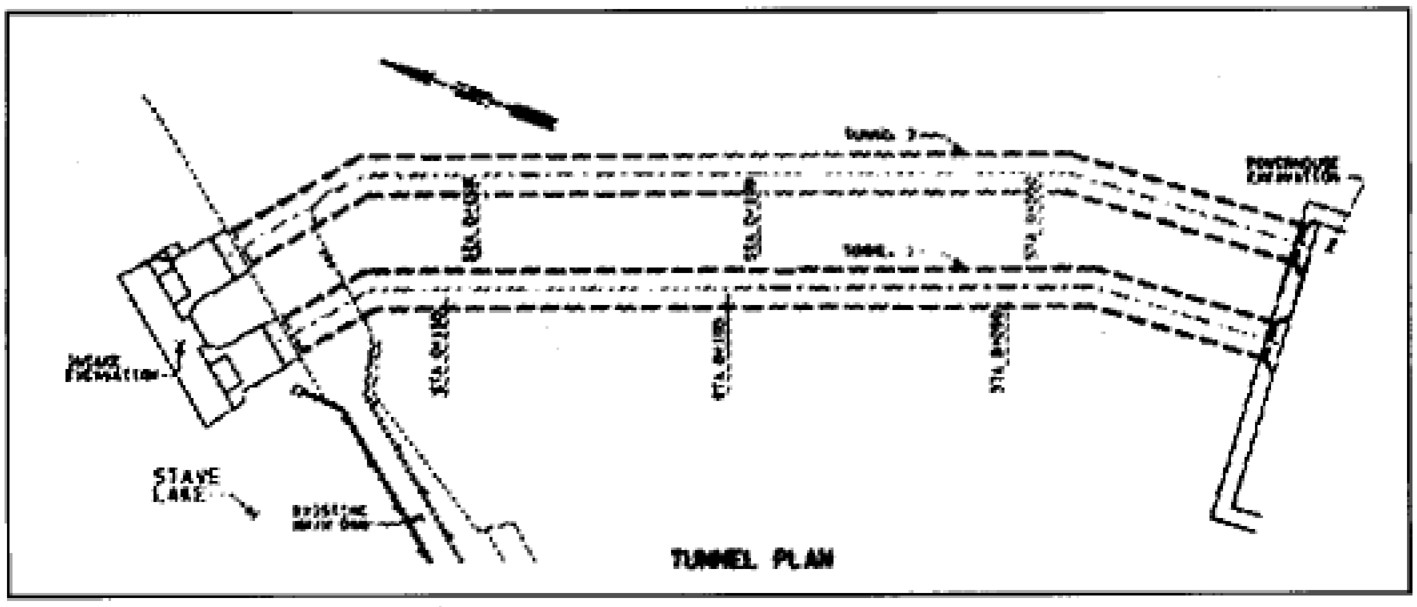

Figure 1. Plan view of tunnels.

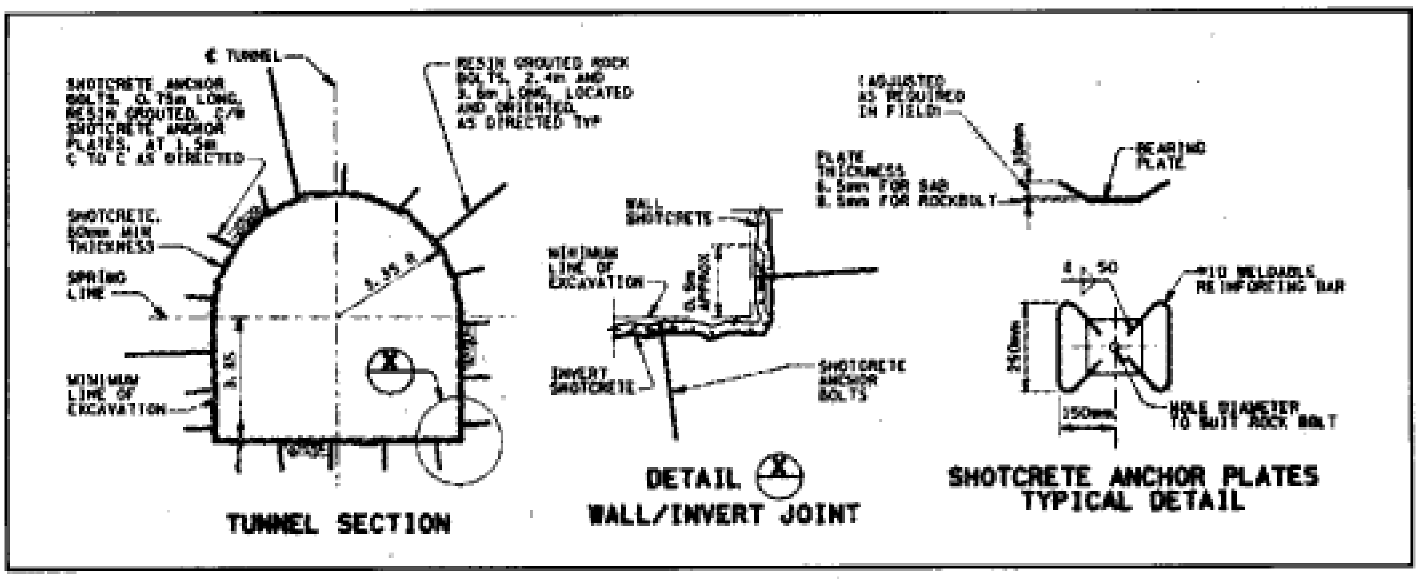

Figure 2. Tunnel geometry and tunnel reinforcing details

- Adequate thickness to provide smoothing effect.
- Good quality bond of the shotcrete to the rock to minimize spalling.
- Good quality strength, density and compaction to maximize durability.
- Steel fiber reinforcement to minimize shrinkage and stress cracks.
- Full perimeter application to reduce leakage out of the tunnel.
- Minimal penetrations of the lining in order to maximize durability of the bond, and to maximize the membrane effect (i.e., no drainholes through shotcrete).
- Anchoring of the shotcrete to both the rock bolts and shotcrete anchor bolts to promote composite action of the rock/rock bolt/shotcrete structure.

In the optimization process described above, one of the key input parameters is the hydraulic roughness of the tunnel surface, which is used to calculate the head losses. Based on available case histories and judgement, the following

Continued next page

Acknowledgments

Tunnel Designer
Bruce Ripley, BC Hydro

General Contractor
A.L. Sims and Sons Ltd.

Shotcrete Contractor
BEL Pacific Shotcrete

Shotcrete Supplier
Valley Rite Ready Mix (Lafarge)

Testing Agency
AGRA Earth and Environmental Limited

Manning's roughness coefficients were used:

Unlined	0.032
Shotcrete lined	0.024

BC Hydro plans to measure the head losses and back-calculate the roughness coefficient once the plant is commissioned.

A shotcrete thickness of 60 mm ($2\frac{3}{8}$ in) minimum was selected based on judgement and experience. Experience on several BC Hydro tunnel projects indicated that where 60 mm ($2\frac{3}{8}$ in) minimum thickness is specified, the average thickness is in the range of 80 to 100 mm (3 to 4 in). The BC Hydro experience also indicated that the local maximum thickness can be as high as 300 mm (12 in), which provided confidence that a significant smoothing effect would be obtained.

The relatively low internal pressures and relatively stiff rock mass were expected to limit deformations of the shotcrete due to internal water pressures, and thus limit cracking of the relatively thin shotcrete lining. Load transfer calculations based on elastic theory predicted crack widths similar to expected shrinkage cracking. Based on these calculations, the shotcrete lining was expected to be effective in reducing leakage from the tunnels. Tests carried out in exploratory drillholes confirmed that the rock mass surrounding the tunnels was not susceptible to hydraulic jacking in the range of design operating pressures.

External water pressures, acting on the tunnel during dewatered conditions, are resisted by the composite structure consisting of the rock, the rock bolts, and the shotcrete. The water pressures in the vicinity of the shotcrete lining are expected to be limited to leakage paths such as joints and will not penetrate the entire shotcrete/rock contact. Local penetration of the water pressures along the shotcrete/rock contact is expected and addressed by anchoring the shotcrete with shotcrete anchor plates.

Shotcrete Transition Design

Traditionally, the transition from a horseshoe-shaped drill-and-blast tunnel to a circular steel lining (penstock) is a reinforced concrete structure. The unit costs for these transitions are usually very high compared to conventional concrete tunnel linings because of the complex, unique formwork that is required.

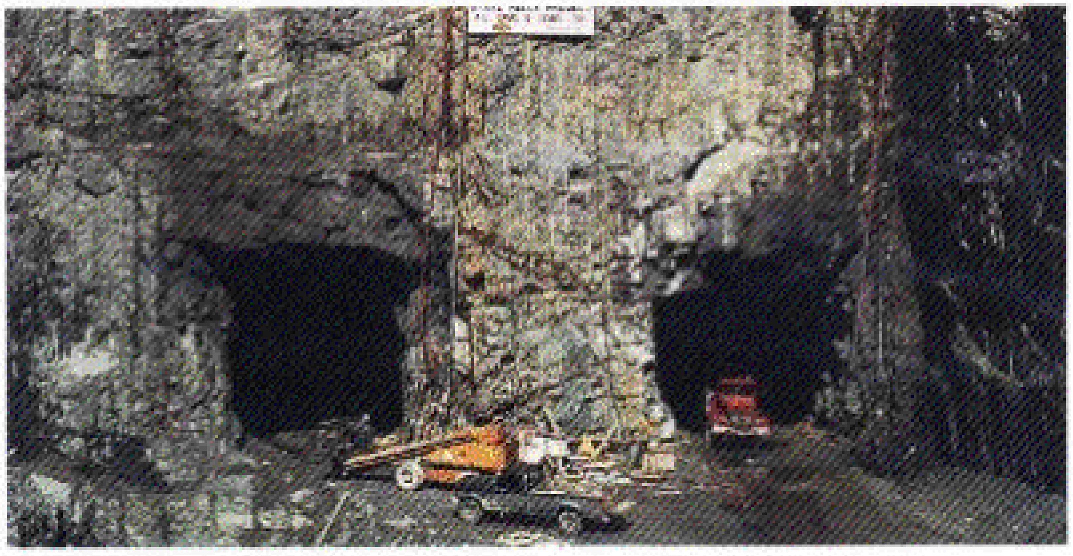

Photo 2. Downstream tunnel portals.

At Stave Falls, an attempt was made to simplify the formwork by constructing the transitions in two parts:

Upstream part (complex geometry):

- Shape change from the 6.7 m wide by 6.7 m high (22.0 x 22.0 ft) straight leg horseshoe shape to a 6.1 m (20.0 ft) diameter circle.
- 7 m (23 ft) long.
- Constructed with steel fiber-reinforced shotcrete, built up in layers.
- Constructed by the tunnel excavation contractor, prior to the steel lining being in place.

Downstream part (simple geometry):

- Shape change from 6.1 m (20.0 ft) diameter circle to 5.4 m (17.7 ft) diameter circle (steel lining diameter).
- 3.5 m (11.5 ft) long.
- Constructed with reinforced concrete.
- Constructed by the powerhouse contractor after the steel lining is in place.
- Unit bid prices for this part were significantly lower than the estimated unit prices for traditional transitions.

Shotcrete Specifications

"Performance"-based shotcrete specifications were used in the tender documents. The specifications provided general requirements for materials and methods to be used for shotcrete construction. The contractor was responsible for selecting the material sources, mix design, equipment, and placement methods. This approach is preferred to "prescription"-based specifications (where the material sources, mix design, equipment and methods are specified) for the following reasons:

- Performance specifications allow the contractor to select the most economical combination of materials, equipment and methods. This promotes innovation and usually results in lower costs to the owner.
- The contractor assumes greater responsibility for the end product. Non-conformance cannot simply be attributed to the specification of deficient materials or an inadequate mix design.

The shotcrete specifications were based on ACI 506.2-95, *Specification for Shotcrete* and the companion ACI 506R-90, *Guide to Shotcrete*, modified for use in underground construction.

All shotcrete was measured and paid on the basis of square meters of applied and accepted shotcrete, measured at the minimum line of excavation of the rock surface. This places significant responsibility on the contractor to accurately estimate rebound, overspray, sloughing and any other sources of wasted shotcrete, and to accurately control shotcrete placement.

Tunnel Lining Construction

The selection of shotcrete equipment and process was the responsibility of the contractor. Wet-mix shotcrete was chosen for the following reasons:

- A commercial batch plant was located within 8 km (5 mi.) of the site.
- Wet-mix is better suited to continuous production application.
- Reduced ventilation requirements due to significantly less dust.

The steel fiber-reinforced shotcrete (SFRS) mix design was prepared by an engineer retained by the ready-mix concrete company subcontracted to supply SFRS to the project. The mix design was reviewed by an engineer with the independent testing company appointed by BC Hydro, prior to the preconstruction trials. Key components of the mix design included:

- Silica fume added at a rate of 13% by weight of cement in order to enhance adhesion/cohesion, thickness of build-up and minimize sloughing
- Accelerator added at the nozzle and addition rates adjusted by the nozzleman to suit conditions
- Dramix ZC 30/.50 collated, hooked end, high-tensile-strength steel fibers used at an addition rate of 55 to 59kg/m^3 (92 to 100 lb/y^3)

Shotcrete was delivered to site by transit mixers from a commercial batch plant. The trucks backed into the tunnels and discharged their load directly into a Reed M20 concrete pump. The shotcrete was discharged through a Master Builders HP shotcrete nozzle. Accelerator was added at the nozzle by an independent accelerator pump. Access to the upper walls and arch of the tunnel was provided by a rough-terrain forklift fitted with a work platform.

All rock surfaces were washed with water prior to shotcrete application and allowed to dry back to a "saturated surface dry" (SSD) state. In areas where soft or friable material was present, washing was carefully controlled to avoid excessive wash-out of material. Air jetting was required in combination with water for cleaning the invert to remove loose material from hollows.

Shotcrete anchor bolts (SABs), complete with "bow tie" anchor plates, were installed intermediately between rock bolts to achieve a net spacing of approximately 1.5 m (5 ft) between shotcrete anchor points. BCH field inspectors directed the location of SABs. The SABs were installed by the contractor as fill-in work during the tunnel excavation.

The contractor chose to shoot the walls and crown of the entire tunnel, followed by the entire invert. This sequence allowed the contractor to leave the invert covered with graded tunnel muck to provide a smooth operating surface from which to shoot the walls and crown, and also prevented rebound from adhering to the rock in the invert.

Photo 3. Transition from shotcrete lined tunnel to circular steel lining.

Transition Construction

The downstream portion of the transition to the steel lining required total shotcrete thickness of about 1.5 m (5 ft). The shotcrete was applied in layers of up to 500 mm (20 in) in the invert and 200 mm (8 in) in the arch. Each layer was allowed to achieve initial set prior to placement of the next layer. Infill shotcrete without steel fibers was used for the first layers in some areas to reduce cost, but all shotcrete applied within about 0.5 m (1.6 ft) of the final surface contained steel fibers.

A bulkhead form was constructed at the downstream end of the shotcrete transition and incorporated a shear key and reinforcing dowels to provide a tie-in for the concrete part of the transition (Photo 3). The upstream end of the shotcrete transition was smoothly joined to the shotcrete-lined tunnel.

The transition shotcrete was anchored using 25 mm (1 in) Dywidag bolts up to 2.4 m (8 ft) long installed in the rock and fitted with shotcrete anchor plates. The bolts were installed prior to the start of shotcrete application and were used as depth gauges to guide the shotcrete application. Shotcrete anchor plates were installed on the bolts prior to placement of the final layer of shotcrete.

Quality Assurance

For performance-based specifications to be successful, a thorough quality assurance (QA) and quality control (QC) program is required. The owner is responsible for implementing the QA program and for outlining the QC requirements. The contractor is responsible for implementing the QC program.

Continued on p. 40

Shotcrete Design and Construction for the Stave Falls Project Power Tunnels

Continued from p. 23

At Stave Falls, the owner retained an independent CSA-certified concrete testing laboratory to conduct the QA testing.

A preconstruction QC testing program was implemented in order to:

- Evaluate the conformance of the contractor's proposed shotcrete materials to the specifications.
- Assess the conformance of the contractor's proposed mixture design to the specifications.
- Qualify (certify) the nozzlemen proposed for the project. For this, panels were shot in orientations fixed to simulate crown, wall, and invert application, and included shotcrete anchor plates.
- Assess the suitability of the contractor's shotcrete supply, delivery and application equipment (including pump, hoses, nozzle, manlift and ancillary equipment) to produce quality shotcrete conforming to the specifications.

The contractor was required to shoot one test panel for each 50 m^3 (65 y^3) of shotcrete, or each day of shotcrete production—whichever occurred more frequently. These test panels did not contain any reinforcement and were used for extraction of test specimens for determination of the following.

- Compressive strength at 7 and 28 days on 75 mm (3 in) diameter cores.
- Absorption after immersion and boiling, and volume of permeable voids to ASTM C 642 at 7 days on 75 mm (3 in) diameter cores.
- Flexural strength and toughness to ASTM C 1018-94b at 7 days on 100 x 100 x 350 mm (4 in x 4 in x 14 in) saw-cut beams.

With few exceptions, the shotcrete test panels met or exceeded the specified parameters and indicated that a very high quality lining was achieved in the tunnels.

Performance During Operation

Tunnel and plant commissioning was carried out in August/September 1999 for Tunnel #1, and in November/December 1999 for Tunnel #2. For each tunnel, initial filling and dewatering rates were carefully controlled to prevent rapid changes in the loading of the shotcrete lining. Tunnel inspections were carried out at several points to confirm satisfactory performance of the lining. As confidence in the lining performance grew, filling and dewatering rates were increased. The inspections found only local, minor cracking of the shotcrete lining. Overall, the shotcrete lining performance was excellent.

References

Ripley, B. D.; Rapp, P. A.; Morgan, D. R., 1998, "Shotcrete Design, Construction, and Quality Assurance for the Stave Falls Tunnels," 15th *Canadian Tunnelling Conference*, Vancouver, Canada.

Paul Rapp graduated from The University of British Columbia in 1987. He is a senior geotechnical engineer with BC Hydro and was the resident geotechnical engineer for the Stave Falls Project from 1996 to 1999.

ADVERTISERS IN THIS ISSUE

Reader Response Numbers in Parentheses

	Page
AGRA Earth & Environmental Ltd.(6)	38
Alabama Metal Industries Corp.(10)	36
Bekaert Corporation (5)	38
Cemen Tech Inc. (16)	14
Elkin (8)	15
Exterior Services of Ohio (9)	38
Hall Contracting Corp. (12)	31
Johnson Western Gunite (19)	2
Mayco (18)	3
Putzmeister (25)	Inside Back Cover
Master Builders Inc. (11)	Back Cover
Schwing America/Small Line Div. (14)	34
Spec Mix (21)	7
Structural Shotcrete Systems, Inc. (20)	38
Synthetic Industries/Novocon (15)	Inside Front Cover
Woody Douglas Gunite Co. (26)	32
Zimmerman Industries (17)	5

American Shotcrete Association

Reader Response Service

Please send information on the products or services circled below:

1	2	3	4	5	6	7	8	9
10	11	12	13	14	15	16	17	18
19	20	21	22	23	24	25	26	27
28	29	30	31	32	33	34	35	36
37	38	39	40	41	42	43	44	45
46	47	48	49	50	51	52	53	54

Please Print Clearly

Name

Company

Address

City

State/Province Zip/Postal Code

Country

Phone:

Fax:

Fax or mail to: American Shotcrete Association
38800 Country Club Dr. • Farmington Hills, MI 48331
Phone: (248) 848-3780 • Fax: (248) 848-3740

May2000