Shotcrete

A quarterly publication of the American Shotcrete Association

MAGAZINE

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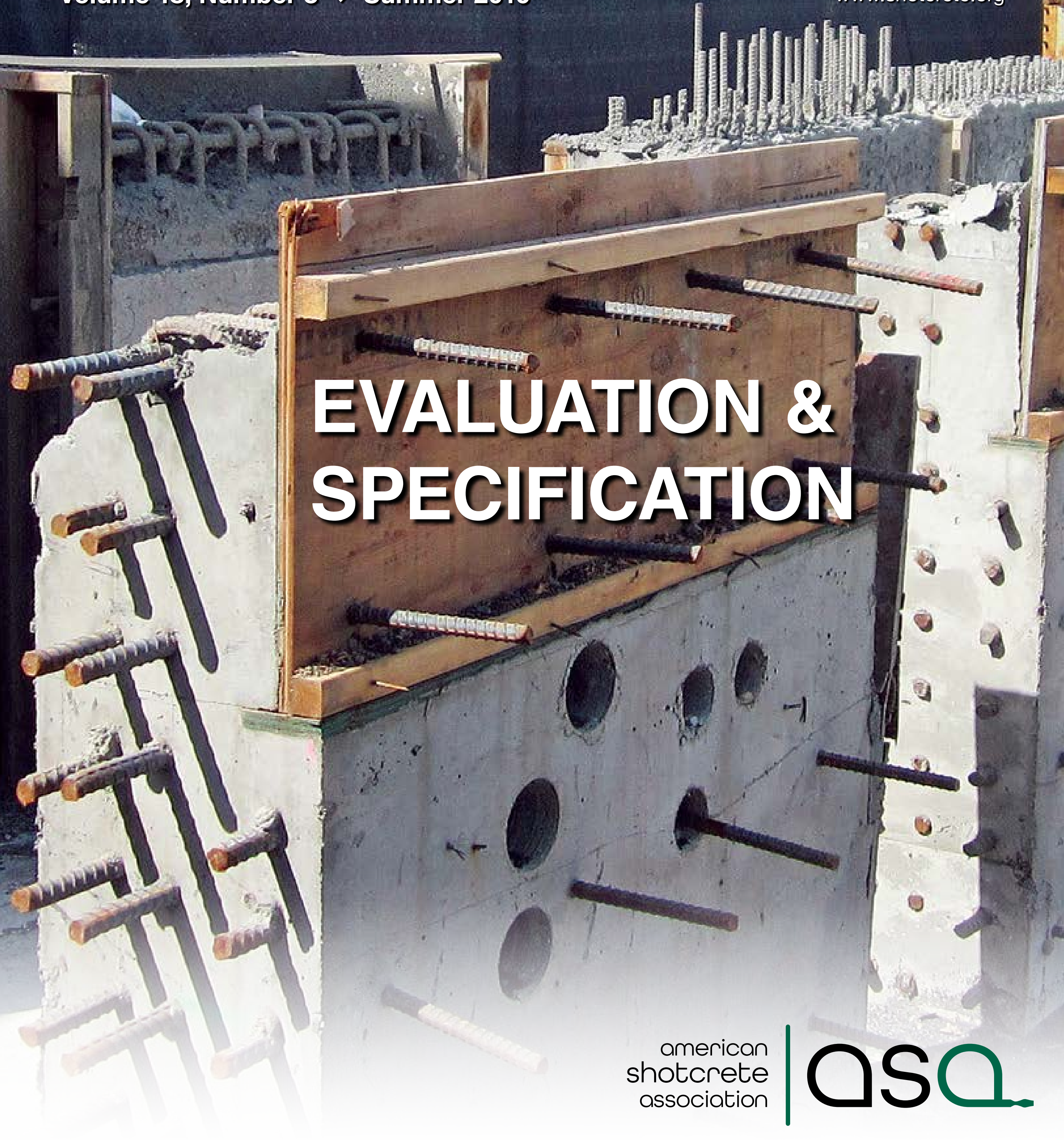

EVALUATION & SPECIFICATION

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Shotcrete MAGAZINE

Volume 18, Number 3
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On the cover: Thick, heavily-reinforced shotcreted project preconstruction panels with cores extracted for evaluation. Photo courtesy of Chris Zynda.

Lots to Do

By Bill Drakeley

As we enter the middle of the shotcrete season, our ASA committees are hard at work carrying out the action plans that support our organization's newly invigorated Strategic Plan. Scott Rand has taken this plan and put a new emphasis on actionable levels, creating a veritable checklist that will be reported on at our next gathering in Philadelphia, PA. I raise these points not only as a report to the shotcrete industry but also as a subtle reminder to those involved that their continued involvement is crucial. As an example of our current efforts, here are some committee actions happening now:

Contractors Qualification Committee—This committee is being chaired by Chris Zynda of JJ Albanese in California. With Chris' leadership, ASA aims to establish an identifier in determining contractors' credibility in the shotcrete world. The Contractors Qualification Committee is more than capable of guiding engineers and specifiers as they determine a contractor's qualifications and appropriateness for shotcrete projects. With this committee's efforts, we not only hope to gain ASA and industry approval of the committee mission but also improve the industry as a whole in the future.

Membership Committee—The Membership Committee is being led by its new chair, Cathy Burkert. Previously, the membership drive had limited progress. As the lifeblood of ASA, membership growth and contribution is key to our continued success. Cathy has taken the figurative bull by the horns and initiated various strategies, all with the goal of expanding membership in different areas of the shotcrete industry. The committee is currently on track this year to add 12 new active committee members, retain 85% of corporate members from certification activity, and grow membership by at least 10%. They are also working to target and recruit members from Latin America in the future.

Pool & Recreational Shotcrete Committee Outreach—In the past few years, we have gathered a healthy list of contacts who have attended pool shotcrete seminars, including ASA presentations or Onsite Seminars, ASA Nozzleman Education programs, and the Genesis 3 Design Group educational courses. In our quest to raise the bar in pool shotcrete, the Pool & Recreational Shotcrete Committee will be reaching out and recruiting new members, contributors, and active participants within ASA. Make no mistake, the pool industry is full of cowboys and know-it-alls. This has been the problem for the last 40 years as shotcrete knowledge and expertise has dwindled. By gathering all our colleagues under one informational roof, we can only get better. We have broken down the contact list for distribution to committee members, and we eagerly await an update at our meeting in Philadelphia.

Scott Rand, who is spearheading this Strategic Plan, has helped us redefine our association's goals and targets. Each of these goals has been broken down into specific contributions with assigned leadership. This has gotten the ball rolling. Our approach is action-based and results-oriented.

Clearly, every one of us has a day job, so we fully understand the time constraints when dedicating service to a volunteer organization. However, without all of us banding together to get the job done, we all take a huge step back. George Yoggy, a founding member of ASA, once told me that when you enter that meeting room, the only hat you wear has the initials "ASA." If you come in wearing any other hat and try to maintain a personal agenda, you will do nothing for yourself or the industry in the long run.

The shotcrete industry is at a crossroads. We must all remember the importance of promoting proper practices while growing and maintaining the health of ASA. Doing so will benefit all those involved. Our current leadership understands and supports this stance, and this is the message to future contributors.

ASA Safety Committee

By Andrea Scott

Greetings from the ASA Safety Committee Chair. My name is Andrea Scott and I, following my mentor and predecessor Oscar Duckworth, have accepted the challenge of leading the ASA Safety Committee. I have some very large shoes to fill! I work as the Director of Safety and Quality Control for Hydro-Arch in Henderson, NV. My background is in special inspection, as well as in safety training and education.

As ASA continued to mature as an organization, we adopted a comprehensive strategic plan to better serve our growing membership. Our new logo and rebranding efforts, *Shotcrete* magazine articles, position statements, expanded training and education programs for inspectors and nozzlemen, as well as seminars offered at World of Concrete, have all contributed to establishing ASA as a respected source of shotcrete knowledge and experience to better serve the industry. Within the Safety Committee we are also called upon to advance by making more materials available to achieve our mission statement of exploring and promoting safety issues within the shotcrete industry. One would think that with the shotcrete process in place for over 100 years there ought to be a great deal of shotcrete-specific safety materials available, correct? Sadly, this is not the case. As an organization, we realize that this is an area where growth is not only needed, but necessary.

Each issue of *Shotcrete* magazine has a Safety Shooter column that focuses on a specific issue pertaining to safety. One way to get more involved and contribute to ASA's mission is to become an author for one of these columns. Our committee is always looking for topics to keep these columns relevant and useful and would welcome both topic suggestions as well as author submissions. If you would like to contribute, simply send your ideas and comments to ASA at info@shotcrete.org.

Our committee developed the "ASA Safety Guidelines for Shotcrete" that was recently published after Board approval. This guide document was sorely needed, filling a void in safety information specific to shotcrete operations. Creation of this valuable guide was only made possible by the hard work of many people generously donating their time and expertise to help make our industry safer. With construction an inherently dangerous vocation, it is imperative to focus awareness on the specific hazards that need to be addressed to ensure the safety of the workforce. As each company develops and refines their own safety training programs, I urge our members to use this document, as it can serve as a great addition to their training materials. It is laid out in a easy-to-understand format, while covering many important topics such as different kinds of safety training, personal protective equipment (PPE), materials, equipment, and placement. It can be purchased in hard copy or as a digital, secured PDF. New Corporate members receive a complimentary copy of this document in their choice of formats. We encourage our equipment manufacturers and suppliers to also review this document as planning for safety is not limited to just field personnel. Manufacturers and suppliers may consider purchasing additional copies with their corporate discounts for distribution to their clients to help show their commitment to shotcrete safety!

During our last meetings in Milwaukee, WI, we were fortunate to have in attendance visitors from other industries who offered us examples of their safety and education programs.

Committee Chair Memo

ASA Safety Committee

Andrea Scott, Chair | HydroArch

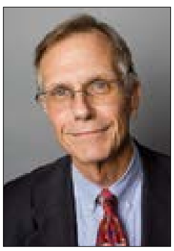
Patrick Bridger | King Shotcrete Solutions
John Carmack | Geostabilization International
Oscar Duckworth | Valley Concrete Services
Roman Gillund | GeoStabilization International
Roberto J. Guardia | Shannon & Wilson Inc.
Warren Harrison | WLH Construction Company
Ron Lacher | Pool Engineering Inc.
Dudley R. (Rusty) Morgan | AMEC
Ryan Poole | Consultant
Raymond Schallom III | RCS Consulting & Construction Co., Inc.
Ted Sofis | Sofis Company Inc.
Marcus H. von der Hofen | Coastal Gunite Construction Co.
Ezgi Yurdakul | GCP Applied Technologies
Lihe (John) Zhang | LZhang Consulting & Testing Ltd.

Upon reviewing them, we found them to be both comprehensive and informative. Our industry deserves to have high-quality programs to help create a construction team well informed on shotcrete-specific safety and ultimately ensure every member of the crew goes home safely at the end of the day. As our Safety Committee moves forward, we are working on a stand-alone educational seminar that will address the topics covered in our "Safety Guidelines for Shotcrete." This tool would be very useful for companies as part of their initial training for new hires as well as serving as a refresher course during ongoing training for nozzlemen or any of the field employees who make up the shotcrete placement crew.

Safety is a mindset that affects every member of the team from the owner of the company to the newest employee. The goal of our Safety Committee is to provide more in-depth materials and products to empower participants from all levels to grow in their knowledge and promote the use of our versatile shotcrete process. We hope you will consider joining us in these efforts!

The Lazy Days of Summer? Not at ASA!

By Charles S. Hanskat, PE, FACI, FASCE, ASA Executive Director



Talking with our members, it seems business is booming in the shotcrete industry. Despite our active committee and Board members being tied up with their own business responsibilities, we've had great participation on ASA committees, task groups, and Board and Executive Committee activities. Here's a rundown of the various activities we've been working on.

Board of Directors—Since our last face-to-face meeting in Milwaukee, WI, the Board has had four web ballots on topics, including:

- Review and approval of our student outreach and scholarship program. The Student Scholarship program has had very limited applications in the last few years. Several options were presented to the Board to revitalize and extend our student outreach. The Board has decided to eliminate the open scholarship program and retain a standing fellowship at Laval University, where we usually have at least one scholarship awardee each year. The Board is now considering a ballot on whether to support a student shotcrete competition (similar to the ACI Concrete Liaison Committee competition we participated in last year) or make a significant increase in effort to get ASA shotcrete presentations given at engineering and construction management schools around North America.
- Review and approval of a policy on "open" nozzleman sessions. In the past, we've had many nozzleman certification sessions where the host will invite many outside nozzlemen to participate in a certification session. This helps to defray the cost to the host, as well as giving many smaller firms with a nozzleman or two an opportunity to become certified or recertified. However, there was a concern that these sessions should be given more oversight because attendees from outside the host company would be exposed to different equipment, mixture designs, and shooting environments than they may be familiar with. The new policy defines an open session as any session where an ASA member approaches ASA seeking to conduct a session with more than 50% of the nozzlemen to be certified from outside companies. The additions further address requiring the examiner to participate in the education portion, a limit to two sessions per year for a host company, qualification of host experience, equipment, facilities, materials, and resources available during the session. It is hoped these additions to our policy will make these sessions a great experience for all participants.
- Review and approval of our Shotcrete Inspector Education program. The proposed education module provides content for a full-day seminar geared toward educating inspectors, engineers, architects, and owners on the benefits and proper application of shotcrete. Using a full-day format allows us to cover shotcrete in much more detail than afforded in our 1-hour on-site seminars. The Board reviewed the PowerPoint presentation encompassing nearly 400 pages of images and text. The Board has approved the program in concept, but is currently working on revising specific changes to portions of the content.

Contractor Qualification Committee (CQC)—The CQC, chaired by Chris Zynda, has been very active in refining the Shotcrete Contractor Qualification program. This program is a straightforward program that helps to establish a shotcrete contractor's qualifications with a review of the contractor's work by ASA experts with extensive experience in successful shotcrete work. The CQC Committee has conducted a web ballot, held several web meetings, and polled members by e-mail. The basics of the program have been finalized within the committee. The next steps for the CQC include developing a 1-day education program for shotcrete contractors and a written exam to be taken by a qualifying individual from the company seeking qualification.

Meeting Format Task Group—As mentioned in last month's column, we've reached a point where the 1-day format for our committees has become unwieldy. The task group with Cathy Burkert and Scott Rand, along with ASA staff, was assigned to review potential committee meeting formats and make recommendations for possible changes to increase our efficiency and effectiveness at the committee meetings. The task group finalized their recommendations in a web meeting and subsequent e-mail correspondence. Their final recommendation was to still keep our meetings to 1 day, usually the Saturday before The ACI Concrete Convention and Exposition, and have a dual committee meeting track in the morning, then have only the Board meeting after lunch. The recommendation was reviewed and approved by the Executive Committee at their meeting at the end of May. The new schedule will be in place at this fall's committee meetings in Philadelphia, PA. (See the new schedule in the Association News on page 66.)

Revised On-Site Seminar Task Group—The task group, chaired by Frank Townsend, along with Lars Balck and Scott Rand, is reviewing draft revisions to our "Introduction to

Shotcrete" and "Shotcrete for Repair and Rehabilitation." The task group is also considering a format for student presentations that may be slightly different than presentations geared toward practicing engineers and specifiers. The task group hopes to have their work completed before the Philadelphia meeting after holding web meetings to review and agree on content.

New Brochure Task Group—This task group, comprised of Marketing Chair Joe Hutter and Publications Chair Ted Sofis, is meeting at the ASA offices in Farmington Hills, MI, in early August to develop new brochures for ASA. Complimentary brochures are available to corporate members with annual membership renewal, and handed out at our trade shows and seminars. We're working toward producing several shorter brochures targeted toward particular markets (including new construction, repair/rehabilitation, pool and recreational, and underground), rather than the rather lengthy current brochure that attempts to cover everything. It is hoped that these targeted brochures would provide our members with a more cost-effective promotional tool for the industry.

Tradeshow Monitoring and Assignments—The Board recently approved improving our monitoring and accountability for exhibiting at tradeshows such as World of Concrete. The upcoming exhibit at the AREMA convention in Orlando, FL, at the end of August is the first tradeshow that falls under this policy. Cathy Burkert has volunteered to be the ASA member lead for the show. Frank Townsend, Marcus von der Hofen, and Dennis Bittner have volunteered to help staff the booth. We hope that with the increased documentation of the various aspects of the exhibits (cost, traffic, and leads), we can give the Marketing Committee more data to make decisions on future trade show participation.

Executive Committee—The Executive Committee meets monthly by web meeting and actively monitors our Association's status. This includes finances, meetings, exhibits, certification, committee activities, and all other ASA activities. Additionally, the Executive Committee has a sharp focus on moving the Strategic Plan forward. With that, we've seen a significant increase in our ASA member involvement between our twice a year face-to-face committee meetings.

Thanks to all who participated on the Executive Committee, Board of Directors, committees, and task groups. Your active member participation is the key to getting our strategic goals realized, moving ASA forward, and advancing the safe and proficient placement of shotcrete in the industry.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Shotcrete Panels for Evaluation and Testing

By Chris Zynda

Shotcrete panels come in a variety of sizes and shapes, and with differing purposes. I will discuss the three most common types:

- Preconstruction;
- Mockup; and
- Production.

Preconstruction Test Panels

Preconstruction test panels are used to qualify the shotcrete nozzleman, crew, equipment, and material. It takes a complete, experienced team for a successful concrete project using shotcrete placement. The preconstruction panel should represent the most difficult-to-shoot part of the proposed project. This will often be the sections with the most congested reinforcing, large or irregular shaped block-outs or embeds, or a complicated geometry. I suggest doing a shop drawing for all preconstruction test panels. The shop drawing would include plan size and depth of the panel along with the layout of all the reinforcing and embeds to be included (refer to Fig. 1).

The test panel shown in Fig. 2 was designed for qualifying two nozzlemen, one on the left and one on the right. The reinforcement layout has three curtains of reinforcing with vertical No. 11 (No. 36M) bars with staggered couplers; the boundary elements have No. 5 (No. 16M) stirrups spaced at 6 in. (150 mm). The test panel section was 24 in. (600 mm) thick. The minimum crew to prepare this representative panel required a nozzleman, an air lance tender, a hose tender, and a concrete pump operator. Note in the picture, the nozzleman (on the right) is shooting the face of the panel with an air lance tender (on the left). With this heavily congested section and with large reinforcing bars, an experienced, qualified contractor is a must for a quality job.

Note in Fig. 3, the plywood at the top of panel was placed to represent the beam that will be shot against in the structural section. You should also note there is no sag of the shotcrete below the beam. The reinforcing bars sticking out represent the dowels that will be coming out of the existing building after the epoxy-set dowels are installed. Typical preconstruction panels will have three cores taken for evaluation of encasement and consolidation, while three additional cores are taken for evaluation of compressive strength.

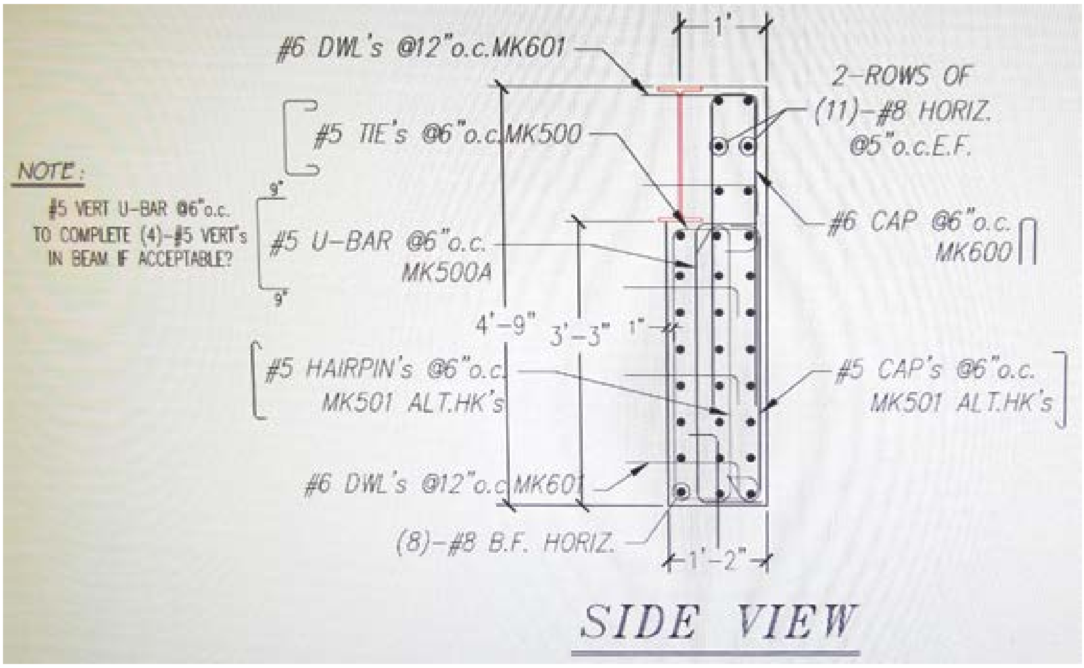


Fig. 1: Section drawings of a heavily reinforced wall

Fig. 2: Crew shooting preconstruction test panel

Fig. 3: Preconstruction test panels have been stripped, cored, and inspected

Core grading is a term that has been used for years for the evaluation of the concrete cores taken from preconstruction shotcrete test panels. This method has been linked to photos for acceptable and non-acceptable work taken from a now severely outdated version of ACI 506.2, "Specification for Shotcrete," published over 20 years ago in 1995. The current version of ACI 506.2 was printed in 2013 and no longer includes core grading as an evaluation method due to its lack of consistency and the inability to relate a "grade" to actual structural performance. This antiquated "core grading" method is very subjective and interpretation can vary widely from one person to another. I have been in concrete testing labs that use a paper clip to measure voids. We need to remember shotcrete is concrete, and no concrete is perfect.

The team approach is the best way to approach cores when evaluating the quality of in-place shotcrete in the pre-production test panel. By team, I mean the contractor and the engineer. Here are the steps I use to best evaluate the panels:

- Start with a good mixture design and a qualified shotcrete team;
- Submit shop drawings for all anticipated test panels;
- Meet with the structural engineer responsible for evaluating the project and explain the shotcrete process (this is a must and I have been doing this for over 40 years)—it will be the best conversation you will have with the structural engineer, and he should have a much better appreciation for all the factors required for a successful shotcrete project. When the cores are ready for inspection, lay them out so you can get an overview of their sample locations in the test panel; and
- Review the shop drawing—look at the consolidation of the concrete around the reinforcing where small voids or rock pockets may be, and report the percentage of embedment around bars.

Please remember when larger 6 in. (150 mm) cores are taken through the full depth of the test panel, the surface area is much greater than

Fig. 4: Cores taken from thick wall preconstruction panels

Fig. 5: Core drilling with a large barrel in a thick wall condition

anticipated from the outdated ACI 506.2-95 grading system. The cores shown in Fig. 4 are from 12 in. (300 mm) and 24 in. (600 mm) thick test panels representing walls on the proposed project. All cores are 6 in. (150 mm) in diameter and drilled through the full depth of the panel. Figure 5 shows the core drill setup on the mockup panel for extracting the needed cores. These cores may vary in surface area from 50 in.^{2} (3200 mm^2) to over 300 in.^{2} (19,000 mm^2). I suggest a minimum 6 in. (150 mm) diameter core for best evaluation of the shotcrete in congested test panels. This size core will help prevent the core from breaking during the coring operation and will also have more surface area for evaluation.

Fig. 6: Cores taken from a 24 in. (600 mm) wall that went to the testing lab for inspection

Fig. 7: Irregularities in one of the cores

Fig. 8: Lightweight shotcrete mockup panel

In Fig. 6, all the cores taken from the test panels were good except for the core shown in Fig. 7, which had a few voids adjacent to the reinforcing bars. All cores were evaluated by the structural Engineer of Record for the project, and based on the results, approved the shotcrete team for this project. When the cores exhibit some voids, closer inspection is required, and the larger cores with more surface area and embedded reinforcement can help give the engineer a better idea of how the shotcrete placed can perform in their structural sections. Core evaluation can be very subjective, as stated previously, and it is extremely helpful to have the engineer doing the evaluation be familiarized with the shotcrete process. My practice, which I've used successfully for years, is to submit shop drawings, check for workable mixture designs, use the proper equipment (it takes horsepower to shoot heavy bar), use a qualified crew, and both communicate and involve the special inspector, testing lab, and engineer on the project. I have looked at cores for over 40 years and I have seen some that may look marginal to the inexperienced eye, but when presented to the knowledgeable Engineer of Record, are approved for the proposed project. The team approach with the qualified shotcrete contractor, the testing lab, and informed Engineer of Record really works.

Mockup Panels

The second type of panel common in shotcrete construction is the mockup panel. These panels are used to show the finish of the final exposed shotcrete surface for review and approval by the owner, engineer, or architect. Mockup panels can vary in size and shape. Often, multiple panels are shot to show the variety of finishes possible for the final project appearance. The mockup panels will be shot with either the wet- or dry-mix process according to the process to be used on the project. Sometimes both processes are used on the same project. Shotcrete finishing can be a very creative vehicle for a talented contractor to express their artistic side. The finish can vary from a plain float finish on a highway wall to a creative carved rock design with a variety of coloring to give the appearance of natural, weathered rock. Figure 8 shows a mockup panel shot with lightweight concrete. The panel is 4 x 4 ft (1.2 x 1.2 m) and 24 in. (600 mm) deep. This is the same thickness as the walls on the project. This mockup used a color additive to help match the existing building and also included a heavy sandblast finish. This is the final finish for all the exterior walls of the project.

Production Panels

After all the preconstruction and mockup test panels are complete and accepted, and shotcrete

Fig. 9: Heavy reinforcing layout for a parking garage wall

Fig. 10: Completed parking garage wall

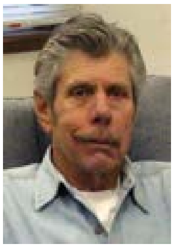
is finally approved as the method to place concrete on the project, it's time to build the job. Figure 9 shows why it is so important to have all submittals complete. This project is an advanced shotcrete project. To properly shotcrete this type of project with thick walls, heavy reinforcing bar sizes, and tight spacing requires using a qualified shotcrete contractor with a proper concrete mixture design, well-maintained and smoothly operating equipment, and a highly trained crew. In Fig. 10, you'll see the completed wall depicted in Fig. 9. Note the steel trowel finish with chamfered corners that resulted from excellent shotcrete finishing; there was no forming or sacking required.

Fig. 11: Typical daily wet-mix shotcrete production panel

Production panels are the equivalent of concrete cylinders used to evaluate compressive strength of the concrete material. Because shotcrete cannot be shot into a closed cylinder form, the shotcrete is shot into an open-faced form. Cores taken from the panel are then tested at the appropriate age to establish the strength of the shotcreted concrete. These panels do not contain any reinforcing. ASTM C1140, "Standard Practice for Preparing and Testing Specimens from Shotcrete Test Panels," provides testing requirements for production test panels. Figure 11 shows a typical production panel. Care must be taken in the handling and storing of production panels. Don't move the panels and disturb the concrete before they gain adequate strength. Also, don't expose the panels to environments that are significantly different than the exposed project's sections (much hotter, colder, or drier).

There are many different size requirements for production panels. This includes both plan dimensions and thickness. For example, a 12 x 12 in. (300 x 300 mm) panel 3 in. (75 mm) deep may cause problems down the road. The panel may not have enough room for removing all the cores required. ASTM testing requires cores not be taken closer than the depth of the panel plus 1 in. (25 mm). So in a 12 x 12 in. (300 x 300 mm) by 3 in. (75 mm) deep panel, the outer 4 in. (100 mm) of the panel can't be cored, and leaves only a 4 in. (100 mm) square area in the center of the panel. If taking a 3 in. (75 mm) diameter core (the recommended minimum core diameter), you could only get one core out of each panel. Also, the 3 in. (75 mm) thickness doesn't allow any additional length to square up the ends of the core for testing. I suggest a minimum shotcrete production panel be 24 x 24 in. (600 x 600 mm) by 5.5 in. (140 mm) deep. This is 2 in. (50 mm) deeper than the ASTM C1140 minimum panel size of 24 x 24 in. (600 x 600 mm) by 3.5 in. (90 mm). The added plan dimensions leave enough room to stay well off the edge and other cores for a non-disturbed sample, and the added length allows the lab to square up the end before testing. Remember, the production panel is a sample of the concrete material as shot in-place. If panel sizes are not thought out in advance, you may not be able to get enough cores for the testing at the desired ages. If the panels are damaged in handling or storage, low strength results could result despite the fact that the concrete in-place is perfectly good. Thus, proper sizing, preparation, and handling of production panels are essential to make sure the cores are truly representative of the work.

In summary, with all three test panels, planning ahead, educating the team members, good communication, quality concrete mixtures, and shotcrete placement by a qualified and experienced shotcrete contractor with proper equipment and a well-trained crew will make your job run much more smoothly.



Chris Zynda *is a Past President of the American Shotcrete Association, current President of the Shotcrete Concrete Contractors Association, General Manager with JJ Albanese Concrete—Shotcrete Operations, and an ACI-approved Examiner for Shotcrete Nozzleman Certfication. He is a member of ACI Committees 506, Shotcreting, and C660, Shotcrete Nozzleman Certification, and ASTM Committee C09, Concrete and Concrete Aggregates. Zynda is also an approved Underground Examiner with California Transportation Agency.*

Guide to Shotcrete

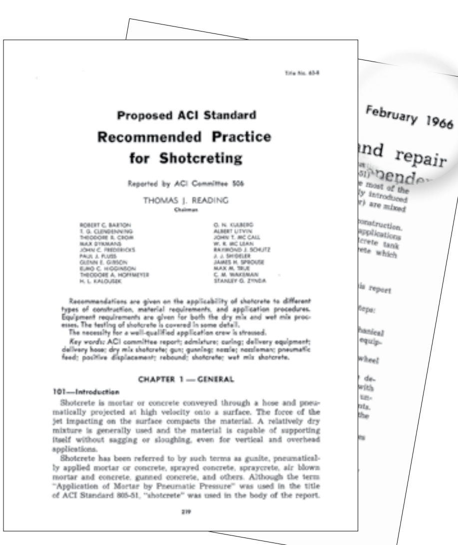
By Lars Balck

In 1910, naturalist Carl Akeley introduced a machine he invented to build mortar models of animals at the cement show in New York. Shortly after, the Cement Gun Product Company was formed and the term "gunite"—what we now call dry-mix shotcrete—was coined. The cement gun was a breakthrough for concrete construction. Mortar could now be conveyed long distances and produce high-strength concrete (shotcrete).

By 1916, however, manufacturing problems, the failure of a test application on the Panama Canal, and bickering among the original partners put the Cement Gun Product Company on the verge of bankruptcy. Samuel Taylor, a munitions and mining equipment manufacturer, bought the Cement Gun Company later the same year. He recognized both the potential of the cement gun and knew that the poor reputation gunite had developed impeded its success. To turn things around, Taylor consolidated control of the company and became the sole manufacturer. He then put together an experienced team and organized a contracting company to specialize in the placement of gunite. Engineering articles in the *Cement Gun Company Bulletin* were produced and reprinted in a number of engineering periodicals. These articles documented many of the merits of using gunite, including producing compressive strengths as high as 10,000 psi (69 MPa). Those strengths were extremely impressive for that time. Mixture proportions of 1-2-3 concrete (one shovel of cement, two shovels of sand, and three of large aggregate) were customary for site-mixed concrete and generally only achieved strengths of 3000 psi (21 MPa).

Between 1916 and 1920, Taylor improved gunite's reputation and reversed the cement gun sales decline. Everyone wanted a cement gun, and many were sent overseas. Of course success also attracted imitators. By 1950, with no standards for equipment, a variety of manufacturers around the world produced inferior equipment that impeded the proper application of gunite. On top of that, inexperienced contractors with no idea of the details required for good gunite field application produced poor-quality gunite on many projects. Once again, gunite developed a bad reputation.

Although the American Concrete Institute (ACI) was organized in 1913, the Institute didn't establish a shotcrete technical committee until 1960. The term "shotcrete" was adopted by ACI because the original "gunite" was a registered tradename. The new committee was charged with revising ACI Standard 805-51, "Recommended Practice for the Application of Mortar by Pneumatic Pressure." In 6 years, the committee made up of experienced shotcrete contractors, owners (including the U.S. Army Corps of Engineers), and testing laboratories published the ACI Standard, "Recommended Practice for Shotcreting (ACI 506-66)." This was essentially the first version of the document we now call the "Guide to Shotcrete." The purpose of the Recommended Practice was to educate engineers, owners, and contractors about shotcrete and to provide practice standards to improve the quality of shotcrete projects. Much of the content in the early ACI 506-66 document is still contained in the present Guide. Updated versions were published in 1985, 1990, 1995, and 2005.



Proposed ACI Standard

Recommended Practice for Shotcreting

Reported by ACI Committee 506

THOMAS J. READING

Chairman

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Recommendations are given on the applicability of shotcrete to different types of construction, material requirements, and application procedures. Equipment requirements are given for both the dry mix and wet mix processes. The testing of shotcrete is covered in some detail.

The necessity for a well-qualified application crew is stressed.

Key words: ACI committee report; admixture; curing; delivery equipment; delivery hose; dry mix shotcrete; gun; gunning; nozzle; nozzleman; pneumatic feed; positive displacement; rebound; shotcrete; wet mix shotcrete.

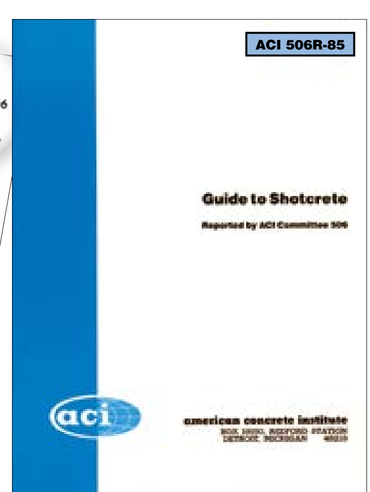
CHAPTER 1 — GENERAL

101—Introduction

Shotcrete is mortar or concrete conveyed through a hose and pneumatically projected at high velocity onto a surface. The force of the jet impacting on the surface compacts the material. A relatively dry mixture is generally used and the material is capable of supporting itself without sagging or sloughing, even for vertical and overhead applications.

Shotcrete has been referred to by such terms as gunite, pneumatically applied mortar or concrete, sprayed concrete, spraycrete, air blown mortar and concrete, gunned concrete, and others. Although the term "Application of Mortar by Pneumatic Pressure" was used in the title of ACI Standard 805-51, "shotcrete" was used in the body of the report.

February 1966



ACI 506 continued to develop an assortment of documents to provide the engineering and construction industry comprehensive technical information on shotcrete. Currently, the 506 committee's catalog of documents includes:

- ACI 506.1R-08, "Guide to Fiber-Reinforced Shotcrete";
- ACI 506.2-13, "Specification for Shotcrete";
- ACI 506.4R-04, "Guide for the Evaluation of Shotcrete"; and
- ACI 506.5R-09, "Guide to Specifying Underground Shotcrete."

The latest version of the specification document, ACI 506.2, "Specification for Shotcrete," was published in 2013. Because ACI's format for specification documents requires concise, mandatory language without any explanatory commentary, it was decided to reorganize the next revision of the Guide to serve as a commentary for the new specification. ACI 506.2-13, "Specification for Shotcrete," is organized in standard three-part format (1.0 General, 2.0 Materials, and 3.0 Execution). The new Guide follows the same format with the addition of extra sections on equipment and crew responsibilities, which were part of the old Guide. A new section on sustainability has also been added to the new Guide.

The front end of the Guide was rearranged to accommodate sections on History, Application, New Developments, and Research. These sections form the Preface in the front to the Guide.

Here are some of the key changes in the new Guide:

Scope—ACI 506.2-13 directs the engineer to specify whether the shotcrete is structural or nonstructural. The new Guide defines structural shotcrete as shotcrete with a compressive strength of 4000 psi (28 MPa) or greater.

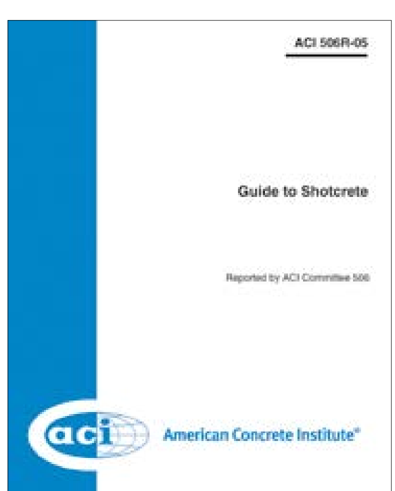
After considerable discussion, it was decided to not address polymer shotcrete due to the numerous field problems and dwindling use. The Guide does not recommend use of polymer shotcrete.

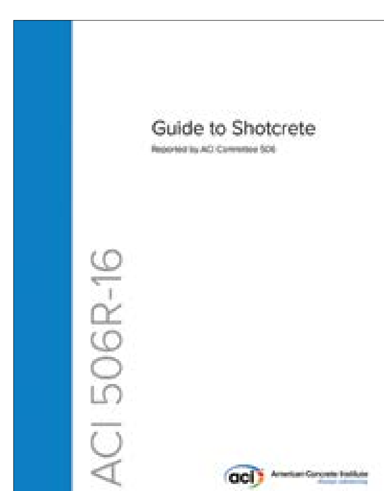
Submittals—This is a new section in the Guide. The purpose is to provide a handy cross-reference for the contractor when preparing project submittals. It should also help the engineer when reviewing submittals.

Preconstruction testing by contractor—Another new section. Increasingly, shotcrete is replacing "form-and-pour" concrete. Many engineers, however, are unfamiliar with shotcrete, so preconstruction testing by the contractor is recommended. This section gives guidance to both the engineer and contractor as to when preconstruction testing best serves the purpose and scope of the project. Preconstruction testing is typically needed to demonstrate that the contractor can properly encase complex reinforcing steel layouts on the project. In some cases, use of special concrete mixtures will necessitate preconstruction testing. Mockup panels are helpful for demonstrating a particular shotcrete surface finish early in the project. Agreement by the A/E on a mockup panel can prevent a lot of future conflict. On a side note, this section started out as a separate document but the committee eventually decided to include it in the Guide instead of referring to a separate document.

Testing during construction—In the previous version of the Guide there was just a brief section on testing. Quality assurance and quality control (QA/QC) guidance has been expanded. However, implementing a QA/QC program requires a holistic approach so the size and character of the project should determine the amount of effort given to QA/QC. The Guide provides some guidance for making this determination.

Shotcrete samples for compressive testing, unlike concrete cylinder samples, are cores taken from a shot panel. Compressive strength testing of samples of the concrete mixture taken from the back of a concrete truck only verifies concrete mixture capability. Because shotcrete placement uses high-velocity impact for consolidation and it has some change in mixture proportions as a





result of rebound, it does not represent in-place shotcrete strength. The only way to know the shotcrete strength is to take a core from a shot sample panel. Typically, the compressive strength of shotcrete cores exceeds the compressive strength of molded cylinder samples of the shotcrete mixture as delivered in the truck. Because there are different shotcrete panels used for shotcrete sampling, the new guide describes both the difference and purpose of three different shotcrete panels:

1. Material panels;
2. Nozzleman/project qualification panels; and
3. Nozzleman certification panels.

Admixtures—Advances in chemistry have improved admixtures and made dramatic impact on plastic concrete properties. In the past, shotcrete had to have a 2 to 3 in. (50 to 75 mm) slump. Today with admixtures, we are able to pump high-slump concrete through a small-diameter line long distances, and yet hang or stack the shotcrete as needed. The increased use of admixtures is one reason shotcrete contractors are competing and winning projects based on cost from traditional form-and-pour concrete contractors. Also, throughout the Guide, the committee recommends testing if a contractor is trying anything new.

Shotcrete properties—Shotcrete properties have remained the same with the default compressive strength for structural shotcrete in ACI 506.2-13 as 4000 psi (28 MPa).

Air content—Air content in shotcrete has been a source of friction between contractors and inspectors/engineers. Inspectors familiar with concrete become alarmed if the air content in the shotcrete mixture is greater than 6%. It has been repeatedly demonstrated that even with air content in the delivered concrete as great as 10%, the resultant in-place air content will be only 3 to 5%.

Most concrete specifications call for 5 to 6% air content for concrete to provide resistance to frequent freezing-and-thawing cycling. Dry-mix shotcrete, however, has for years demonstrated excellent freezing-and-thawing resistance with only 2 to 3% in-place air content. Likewise, wet-mix shotcrete when shot with 5 to 6% entrained air has also demonstrated excellent freezing-and-thawing resistance, although the in-place air content of the as-shot shotcrete is only 3 to 5%. In practice, we find about half of the entrained air in concrete is lost during wet-mix shotcrete placement. Shotcrete, however, due to its low water-cementitious materials ratio (*w/cm*) and the high level of compaction that occurs during placement has proven to be resistant to repeated freezing-and-thawing cycles.

Boiled water absorption (BWA)—The BWA test can also cause controversy so clarification has been added. The BWA test and volume of permeable voids test is widely used in Canada. However, testing labs in the continental United States don't have much experience with BWA testing, so erratic results have been reported and often lead to questions about the ability of the testing laboratory to properly conduct the test. A baseline BWA for the concrete mixture (not shot) should be conducted before testing shotcrete cores.

Bond strength—The bond strength of shotcrete continues to be one of shotcrete's main attributes. Because shotcrete is physically driven into the receiving surface by the high-velocity impact of the fresh concrete particles, excellent bond is achieved. Studies focusing on the bond qualities of shotcrete have proven that high-velocity placement to a sound substrate surface with adequate roughness provides durable bond.

Multiple layers—This section has been added to help inform engineers who often confuse placement of multiple layers of shotcrete with the cold joints experienced with form-and-pour concrete. Shotcrete provides excellent bond between layers due to the consolidation and densification by high-velocity impact of fresh concrete onto a properly prepared concrete substrate. Studies of bond between multiple layers of shotcrete have proven shotcrete achieves excellent bond between layers, and provides a structural section that acts as if placed monolithically.

Finishing—The Guide has expanded the section on finishes. The preferred finish is still a "gun" or "natural as-shot" finish. However, to compete with form-and-pour concrete, some owners want a smooth trowel finish which, for shotcrete, requires a two- or three-step procedure.

Tolerances—The tolerance section has been expanded. Because shotcrete permits a wider variety of applications and surface finishes than form-and-poured concrete, ACI 117, "Specification for Tolerances for Concrete Construction and Materials," specifically excludes shotcrete. ACI 117 provides excellent guidance for reinforcement placement and cover. The Guide gives the shotcrete project specifier criteria for specifying tolerances.

Repair—A section on shotcrete repair was added to provide commentary to the ACI 506.2-13 repair section.

Sustainability—In recent years, ACI has requested that new documents address sustainability. Shotcrete shares not only concrete's durability, but because of its unique characteristics, also enhances concrete's sustainability. Shotcrete promotes sustainability in many ways, including but not limited to:

- A repair material that extends a structure's life;
- Formwork reduction, which saves resources;
- Reduction of equipment needs on a project;
- Reduction of the time for construction; and
- Promotes creativity due to the ease of construction of curved sections.

Safety—Early in preparation of the Guide, a chapter on safety was compiled. Traditionally, however, ACI has not produced safety documents. As we were developing the Guide, the American Shotcrete Association (ASA) put together a safety document far more encompassing than what was planned for the guide so the safety chapter was discarded.

Summary

Shotcrete has come a long way. The new ACI 506R-16, "Guide to Shotcrete," builds on the original 1966 ACI Standard ACI 506-66, "Recommended Practice for Shotcreting," and has been reorganized to serve as commentary to ACI 506.2-13, "Specification for Shotcrete." A section, "Preconstruction testing by contractor," was added to provide guidance of when to include and what to include preconstruction testing. Also, "Testing during construction," which is QA/QC guidance, was expanded. The QA/QC section defines the different types of shotcrete panels for testing or evaluation. The section on admixtures has been updated. The new Guide continues to emphasize the superior bond strength shotcrete achieves and explains why multilayered shotcrete should not be considered multiple cold joints. Lastly, shotcrete enhances the sustainability properties of concrete.

The new Guide, like the first guide, is a consensus document compiled by volunteers with the goal of improving the quality of shotcrete projects. The volunteers, to be sure, have differences of opinion most often driven by different experiences in different regions. Thank you to all the Guide volunteers who devoted many, many hours of their time.

References

Rodriquez, L., *From Elephants to Swimming Pools: Carl Akeley, Samuel W. Taylor, and the Development of the Cement Gun*, Canal History and Technology Press, Easton, PA, 2006, 150 pp.

***Lars Balck** is a concrete consultant and ASA/ACI Nozzleman Examiner. He recently retired from CROM, LLC, as a Senior Vice President. He has been involved in the design and construction of prestressed concrete tanks built with shotcrete for over 40 years. He received his bachelor's degree in civil engineering from the University of Florida and served with the U.S. Army as First Lieutenant in Vietnam as a Combat Engineer. Balck is a Past President of ASA. He is Chair of ACI Subcommittee 506-C, Shotcreting-Guide; a past Chair and current member of ACI Committee 506, Shotcreting; and member of ACI Committees 376, Concrete Structures for Refrigerated Liquefied Gas Containment; 563, Specifications for Repair of Structural Concrete in Buildings; and C660, Shotcrete Nozzleman Certification.*

AA 020 Piccola Gunite Machine

MasonMate

RD6536 Skid Steer Pump

ACI Committee 506, Shotcreting—Activities Update

By Marc Jolin

ACI Committee 506, Shotcreting, is one of the most active technical committees of the American Concrete Institute (ACI). Formed in 1960 to address some of the needs of the industry, the committee has evolved over the years to cover many aspects of the shotcrete process. Today, the ACI 506 library includes a guide, a specification document, and other documents pertaining to the evaluation of shotcrete, underground applications, and fibers (refer to Table 1).

As many readers may know, one of the biggest challenges for a technical committee covering a number of documents is to preserve coherence between those documents while keeping their content up to date and as valuable as possible to the industry. Needless to say, this can prove difficult to achieve across the entire document library. Very conscious of the rapid evolution of the industry over the last two decades (one simply has to look at the content of this magazine over the last 15 years to verify that statement!), and the increasing attention given to quality control and acceptance as a whole, all of the subcommittees started in a serious effort to address this challenge a few years ago. The strategy was to start with our core documents (Guide and Specification documents) and then follow with our equally important companion documents. This article therefore aims at presenting some of the advances made so far, as well as the strategy adopted for some of the documents currently being revised/rewritten.

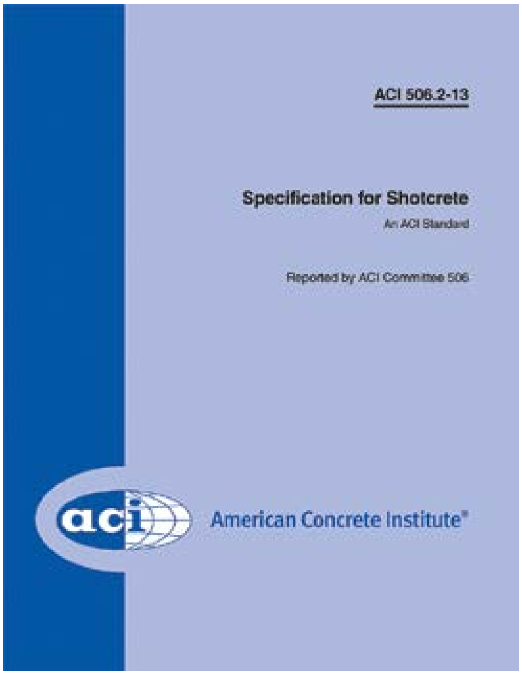
Table 1: ACI Committee 506 Library as of July 2016

Current Documents	Subcommittee Name	Subcommittee Chair
506R-16, Guide to Shotcrete	506-C, Guide	Lars Balck Jr.
506.1R-08, Guide to Fiber-Reinforced Shotcrete	506-B, Fiber-Reinforced	Jeffrey Novak
506.2-13, Specification for Shotcrete 506.2M-13, Specification for Shotcrete (Metric)	506-E, Specifications	James Ragland
506.4R-94, Guide for the Evaluation of Shotcrete	506-A, Evaluation	Simon Reny
506.5R-09, Guide for Specifying Underground Shotcrete	506-F, Underground	Lihe (John) Zhang

Guide and Specification

One of the first steps taken was to initiate a parallel revision of our aging 506.2-13, Specification for Shotcrete, document (previous version dated back to 1995) and our 506R-16, Guide to Shotcrete (previous version dated back to 2005). Indeed, years of feedback from the industry showed that these two documents were often confused or considered as one by many specifiers[1]; although this can be an advantage, because it puts the Guide in more hands (therefore disseminating more information on proper shotcreting technique), it had the potential to create complex situations—and even legal problems—if there were any discrepancies between the Specification and the Guide at any given point in time. This is where the first steps in our efforts to align our document

[1] It should be noted that the only document that can appear in contractual documents is the ACI 506.2, Specification for Shotcrete, because it is the only one written in enforceable mandatory language and offering defaults, values appropriate for specifications.



library were taken. Following the publication of a completely new version of our Specification in 2013, the Guide was revised both for content and format. The later was adapted to match the organizational structure of the specification document; although still a complete stand-alone document that merits reading on its own, it can also be considered to be a commentary to the Specification document. To illustrate this, Table 2 shows a simple example of the correlation between both documents about construction joints. In the left column, the specification tells us concisely how to do something, while in the right column, the guide provides further explanations. It is the intent of the committee to maintain the synchronization between these two documents in the future.

One important change that was made in the 2013 Specification, and later supported by the Guide in 2016, is the removal of the Core Grading system. This is noteworthy because it leaves an apparent gap in our documents, as they offer little guidance to the engineer on the acceptance of shotcrete. In fact, the subject of shotcrete acceptance was (and still is!) an important part of the consideration in rewriting the 506.4R-94, Guide for the Evaluation of Shotcrete, document. It was also felt that that aging document (1994!) needed a complete rewriting to better address the changes in QA/QC seen in recent years.

Evaluation of Shotcrete

The document currently being revised by the committee will cover all the usual aspects of QA/QC for shotcrete, from the tests to run on fresh material, all the way to durability-related tests, with emphasis on the frequency of testing, the interpretation of the results, and typical expected

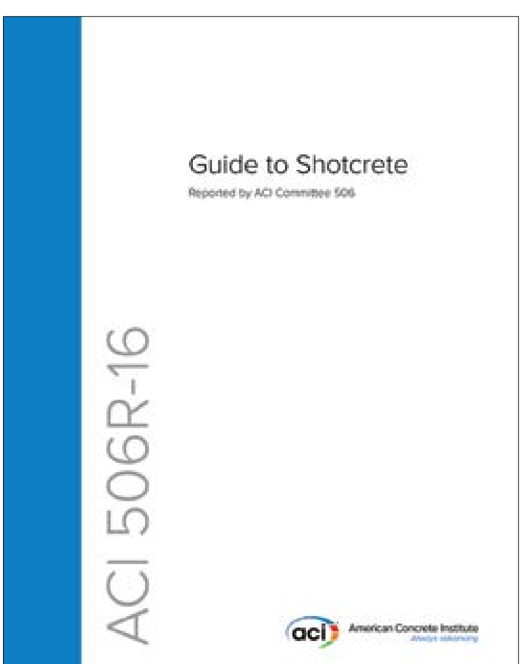
Table 2: Excerpt from the Specification (left) and Guide (right) documents on the topic of construction joints
(underlined words to illustrate difference of language)

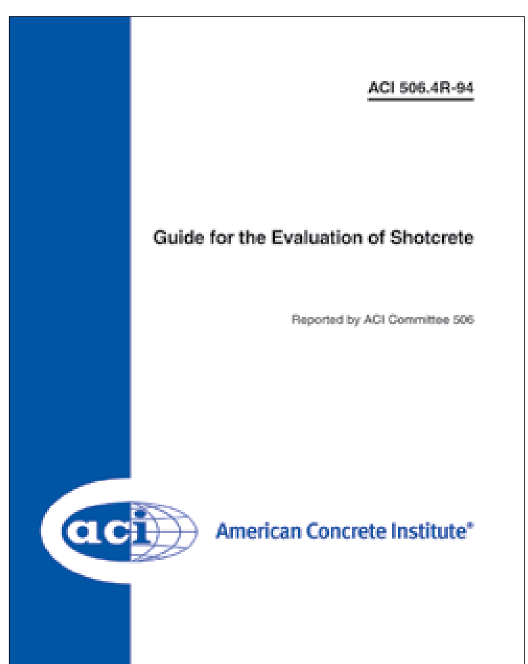
506.2-13, Specification for Shotcrete	506R-16, Guide to Shotcrete
*3.2.1 - Construction joints_* Taper construction joints at approximately 45 degrees from receiving surface. Form joints by cutting plastic shotcrete. Roughen shotcrete in the joint face while shotcrete is still plastic.	*3.2.1 - Construction joints_* Square construction joints are generally avoided in shotcrete construction because the corner is a trap for rebound and overspray. Construction joints are usually constructed at a 45-degree angle. Where the joint will be subjected to compressive stress, however, square joints are sometimes required, in which case, the crew should take the necessary steps to…

values. For example, special care is being given to the "Compressive Strength" section and especially panel handling or core extraction, as experience has shown it is often the source of erroneous noncompliant results.

A novel addition, however, is the inclusion of a special section on the "acceptance of shotcrete." The openly stated objective of the acceptance of shotcrete section is to guide the engineer to evaluate what is and is not acceptable for the specific job at hand and realize that, similar to cast-in-place concrete, some limited defects may be present, especially as the complexity of the work increases.

The task to define what "acceptable" shotcrete has turned out to be a complex one. It was decided by the committee to separate the exercise into two parts. The first part consisted of producing a methodology aimed at evaluating the quality of a set of shotcrete cores. These cores may come from pre-





construction test panels (the ideal approach) or from the shotcreted structure itself (for particular cases where in-place quality is questionable). The outcome of this evaluation of core quality is a qualitative judgment such as "good" or "fair." The hope of the committee is to have this methodology published as a Technical Note (a short standalone ACI technical document) to facilitate its updating and revision. The second part is a dedicated section in the Evaluation document on the Acceptance Criteria that is based on a number of difficulty levels, which address many aspects of the jobs such as section thickness, reinforcement layout, orientation, and need for certified nozzleman. This section of the Evaluation document will therefore guide the engineer in identifying the Difficulty Level related to the work in progress (a jobsite may present several different difficulty levels) and in selecting the Quality Level the engineer is willing to work with. In effect, the engineer is creating project-specific acceptance criteria.

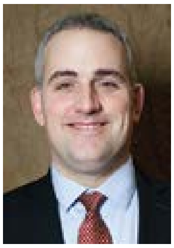
Although briefly hinted at previously, it is noteworthy to mention that the Evaluation document being developed will also include a complete section on mockup panels and preconstruction trials, an increasingly popular qualification method. The objective here is to illustrate what has been successfully done in the past on projects, and then point out what information can be gained from these tests.

Fibers and Underground

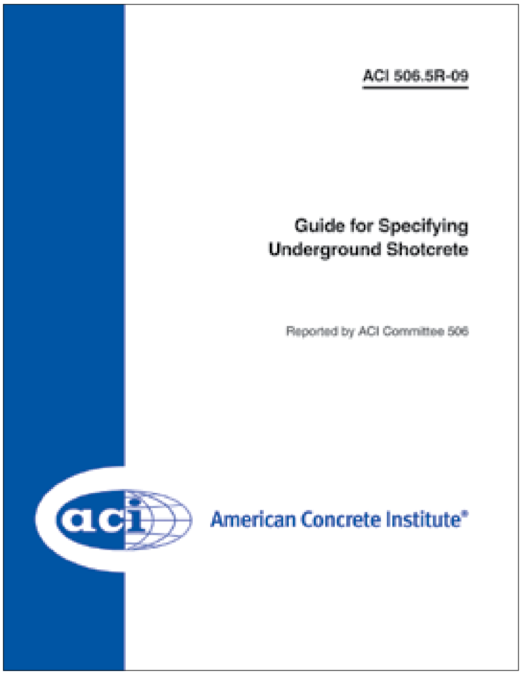
Our two remaining subcommittees are working on 506.5R-09, Guide for Specifying Underground Shotcrete, and 506.1R-08, Guide to Fiber-Reinforced Shotcrete. Although slightly less impacted by the ongoing effort, they are nonetheless both in the process of being reapproved and the committee members are hard at work revising them to make sure they reflect the most recent advances and good practices.

Conclusions

ACI Committee 506, Shotcreting, is busy and actively working on offering the most useful and complete document library for the entire shotcrete industry. With the rewriting and revision of our documents to reflect the most recent changes in the industry, the goal to make them coherent and synchronized across the whole library is well under way. As we look toward the future, we are also actively working on extending shotcrete acceptance into the concrete-specific Codes and standards that can benefit from incorporating shotcrete placement for many types of structural concrete construction.



***Marc Jolin**, FACI, is a Full Professor in the Department of Civil and Water Engineering at Laval University. He received his PhD from the University of British Columbia, Vancouver, BC, Canada, in 1999. An active member of Centre de Recherche sur les Infrastructures en Béton (CRIB), he is currently involved in projects on service life, reinforcement encasement quality, new admixtures, and rheology of fresh shotcrete. Jolin is an ASA member; an ACI Examiner for Shotcrete Nozzleman Certification (wet- and dry-mix processes); Chair of ACI Committee C660, Shotcrete Nozzleman Certification; and Chair of ACI Committee 506, Shotcreting.*



ACI 506.5R-09

Guide for Specifying Underground Shotcrete

Reported by ACI Committee 506

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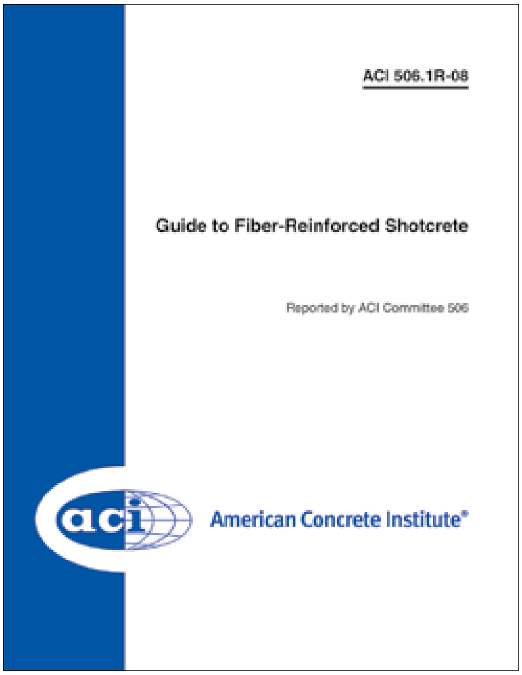


ACI 506.1R-08

Guide to Fiber-Reinforced Shotcrete

Reported by ACI Committee 506

American Concrete Institute®

Shotcrete Pool Inspection—Checklist

By Chris Zynda

Swimming pools have been around for over 100 years, and the water-containing pool shells have been built in many different ways, including fiberglass, concrete block, vinyl-lined, and concrete. We must remember that a swimming pool is a large investment and, like any structure, needs a good foundation and quality construction to last for the decades intended.

Shotcrete (wet- and dry-mix process) is the most common method for placing the concrete in swimming pool floors, coves, and walls. Quality shotcrete placement creates the foundation for a lifetime concrete shell. The first step in shotcrete pool construction is to understand the two processes—wet-mix and dry-mix—used in shotcrete placement. After a specific process has been selected for the project, the owner or the engineer or designer responsible for qualifying the contractor and their field performance should put together an evaluation checklist as shown below.

Fig. 1: A pool wall installed with wet-mix shotcrete before the pool floor has been placed. As a result, the pool floor is now contaminated with the rebound and cuttings from the shotcrete operation. This sloppy material sitting on the floor has not been vibrated or consolidated and must be considered as waste material and removed. Leaving this material in place would weaken the pool structure and significantly reduce the long-term durability of the pool shell. Unfortunately, incorporation of rebound and cuttings in the pool shell is the cause in 95% of swimming pool failures

Fig. 2: The shotcrete (wet-mix process) floor being installed first

Preconstruction

1. Pool contractor: years of experience with overall pool construction.
2. Past shotcrete pool projects of similar size and scope.
3. Shotcrete contractor experience: years of experience and projects of similar size and scope.

Fig. 3: Another pool floor being placed first with a concrete boom pump and the placement crew vibrating the concrete and screeding to the desired height. Installing the floor before the walls helps to guarantee no cuttings or rebound will be used in the structure. Also, note that a board is used at the edge of the floor to create a consistent joint. This allowed the joint to be prepped with water blast at 0.25 in. (6.35 mm) roughness before shotcreting the wall

Fig. 4: Experienced ACI Certified Nozzleman shooting a beam—no cuttings will be reused in the structure. Also, note the blue tarp providing protection from overspray

4. Shotcrete nozzleman should have a minimum of 3 years of experience and hold a current ACI nozzleman certification in the process being used.
5. Listing of the type of equipment: dry-mix gun, wet-mix pump, and air compressor size (minimum 250 cfm compressor for wet-mix and 500 cfm for dry-mix).
6. Concrete mixture design: minimum 4000 psi (28 MPa).

During Construction

7. Proper setup of grades (including set wires for floor, walls, beam, and lights).
8. Prepare templates for radius sections (no steel stakes allowed in soil that may contact reinforcement).
9. Shooting sequence (cast or shoot floor FIRST).
10. **NO rebound, cuttings, or spoils to be incorporated in fresh concrete sections.**
11. **All joints must prepped in the first 30 minutes.**
12. Air lance used for shotcrete application.
13. Predampen subgrade or substrate before shooting.
14. Consider the shooting sequence for attached spa or wading pool.
15. Production rate (how many days for shotcrete placement).
16. Proper disposal of rebound removed from pool during shooting.
17. Proper curing.
18. Shotcrete materials, testing, and placement should meet the guidelines of ACI 506R-16, "Guide to Shotcrete."

Fig. 5: ACI-certified nozzleman shooting walls with air-lance (blow pipe) tender cleaning the floor/wall joint before shotcreting so no rebound is used in the structure. Also, note the floor was completed first. The reinforcement at the bottom of the wall is for a bench that will be shot after the wall is complete. The contractor will need to clean all rebound and cuttings out from the bench area before shooting it

Fig. 6: When checking reinforcement, make sure the bars have proper clearance and cover. Reinforcing bars should be separated to meet the requirements of the project specifications and applicable local building codes. Stagger laps when possible to avoid bundling bars at contact laps, as seen at the top of the reinforcement in this image. Non-contact lap splices are preferred in shotcrete applications. Preconstruction shotcrete test panels may be required for contact laps that exceed No. 4 (No. 13M) reinforcement

Fig. 7: Plumbing is a major component of most pools. Often, the plumbing components need to be placed in a way to allow for proper shotcrete placement. Enough room needs to be provided in the design for the plumbing, skimmer, lights, and reinforcing steel; pools take a lot of pre-planning with a qualified contractor and experienced crews

Safety

19. Hard hats, safety glasses, boots, dust mask, or respirator.
20. Proper coverage of worker's skin against exposure to cement.
21. Screen must remain in place over the hopper of the wet-mix pump or dry-mix rotary gun while in operation.
22. Scaffolding: properly sized, supported, and braced (no jiffy jacks allowed).

Fig. 8(a) and (b): Construction joints being prepared

Construction joints

Construction joints are one of the most important aspects in construction and performance of all concrete structures. Shotcrete is no different, but we do get a second chance. With pools having varying shapes and many accessory placements, construction joints (as many as 50 per pool) are a way of life. All construction joints are required to be prepped within the first 30 minutes of placing the fresh shotcrete. Preparation includes shaping the joint to a 45-degree angle, cleaning overspray from adjacent reinforcement not yet embedded, and roughening the surface of the joint with a stiff broom or brush. The joint can then stand for as long as needed before the next placement. When it is time to complete the area, the joint must be pre-dampened to a saturated surface-dry damp condition. When properly shooting and curing the subsequently placed shotcrete, the concrete will act as a monolithic section, just as if there was never a joint there to begin with. The secret in making this a joint that acts monolithically with perfect bond is the combination of the proper surface preparation of the joint and high-impact velocity (60 to 80 mph [27 to 36 m/s]) of the shotcrete stream. The shotcrete is a cement-rich concrete paste that is pneumatically driven by impact into the rough surface left by the joint preparation. No bonding agents are needed, and indeed no bonding agents should be used because they interfere with the bond of the fresh paste to the rough substrate.

Rebound

With shotcrete, the high-impact velocity used in the shooting process produces a certain percentage of material that doesn't stick and bounces off the substrate or the previously shot concrete surface. This is called "rebound" and is mostly composed of the larger rock and sand particles that did not stick to the surface. These aggregates lack the concrete paste essential for a complete concrete mixture and *MUST NOT be used in the structure*.

Cuttings and Overspray

When shotcreting, the wall section is generally shot out to and slightly beyond a grade wire, and then finishers cut the shotcrete back to the surface defined by the grade wire (refer to Fig. 4). The cuttings from the finisher cutting the shotcrete back to the grade wire lack consolidation and may be quite variable in composition. They may also have passed the setting time for the mixture design used. Similarly, overspray cleaned off formwork or reinforcement doesn't have the same aggregate and paste mixture that is desired in the concrete in place. Thus, cuttings or overspray *MUST NOT be used in the structure*.

Summary

Gathered from over 45 years of experience in swimming pool construction, I have listed some key performance aspects of the shotcrete construction process to ask your contractor. These should be your primary concerns in the construction of shotcrete swimming pools.

The first and foremost step is to use a qualified shotcrete contractor with an experienced crew.

Next, look at these key aspects of the shotcrete process:

a. Does the contractor have the proper equipment for thorough mixing of the shotcrete material? (Dry-mix may be mixed on site or supplied in large premixed bags. Some wet-mix may be mixed on site, adding water to premixed bags.)
b. A quality source of sand and aggregates (must be clean, washed, and well-graded and meets the ASTM requirements for concrete sand). Dry-mix aggregates entering the gun should have a 3 to 4% moisture content to help reduce dust, enhance hydration, and reduce wear on the equipment. This may require predampening equipment if the contractor is using bone-dry bagged shotcrete materials. No rebound or cuttings are to be reused in the structure.
c. Properly functioning, well-maintained wet-mix pump or dry-mix gun and a properly sized and functional air compressor are required.

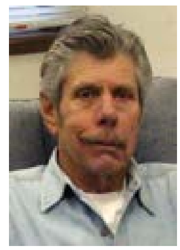
You must have enough air flow to accelerate the shotcrete stream to a high velocity.

d. A well-proportioned concrete mixture design. The concrete must be pumpable in wet-mix and, in either process, have adequate materials to achieve the desired strength. 4000 psi (28 MPa) compressive strength at 28 days should be the minimum acceptable.

e. Ensure the 30-minute construction joint rule is used.

f. Use proper curing procedures as detailed in ACI 506R-16, "Guide to Shotcrete," Section 3.6.

Although the basic concepts for construction of a pool shell with shotcrete may be straightforward, a quality shotcrete contractor must pay attention to all the details needed to make the pool shell functionally watertight and durable to last for decades. The checklists and topics covered previously certainly help to show which aspects of the work should be closely monitored. However, one of the best ways to get the quality desired is to hire a shotcrete contractor who has demonstrated in previous work that their company has the experience, resources, well-trained crew with ACI Certified Nozzlemen, and commitment to quality and safety that shotcrete pools demand.



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OSHA's New Crystalline Silica Rule—Potential Impact on Shotcrete Operations

By Charles S. Hanskat

Background

The Occupational Safety and Health Administration (OSHA) recently issued a final rule dealing with worker exposure to crystalline silica. The rule represents years of effort by OSHA to develop a standard that is intended to help protect over 2 million construction workers from respirable crystalline silica. This is one of the biggest rules OSHA has developed, and it is addressed to two different workplace environments: construction and general industry/maritime operations. Our field shotcrete operations fall into the construction category. This is a very comprehensive standard addressing not only permissible levels of exposure but also exposure monitoring, medical surveillance, and housekeeping.

Crystalline silica has been a known health hazard for decades. Significant levels of exposure can lead to silicosis, lung cancer, other respiratory diseases, and kidney disease. How is one exposed to respirable crystalline silica? Common jobsite concrete work including cutting, drilling, jackhammering, chipping, grinding, or sand blasting of concrete present the highest potential for exposure above the safe limits established in the rule.

The new rule was published June 23, 2016, and requires compliance of the rule by June 23, 2017, except for the requirements for laboratory evaluation of exposure samples that will begin 1 year later. The rule deals with all exposures of respirable crystalline silica, except those environments that have proven exposure less than an action level of 25 $\mu g/m^3$ over an 8-hour time-weighted average (TWA). Many contend the 25 $\mu g/m^3$ level is at or below the limit that can be measured accurately and consistently with current technology.

So what about silica fume, a common supplemental cementitious material widely used in shotcrete? ACI defines silica fume in CT-13, ACI Concrete Terminology, as "very fine noncrystalline silica produced in electric arc furnaces as a byproduct of the production of elemental silicon or alloys containing silicon." The key here is that silica fume is a noncrystalline material. However, most producers of silica fume do note that trace amounts of crystalline silica—less than 0.5% of the overall silica fume material—are present in their materials.

Thus, as OSHA significantly reduces the permissible exposure limits (PEL) in construction environments from the previous 250 $\mu g/m^3$ over an 8-hour TWA to 50 $\mu g/m^3$, there may be concern that even trace amounts of crystalline silica in silica fume may impact our shotcrete crew's exposures. All of our shotcrete mixtures use sand as an aggregate, so handling of quantities of sand in site-batching operations or from rebound may also produce small amounts of crystalline silica that add to the worker exposure. Also, many of our shotcrete projects involve repair of existing concrete, so surface preparation techniques may produce crystalline silica.

Two Alternative Approaches for Compliance Provided in Rule

Work Tasks Covered by Table 1: The new rule offers two ways to be in compliance. The first method, and the one OSHA expects most contractors to use, provides a table (refer to Table 1) that predefines specific equipment and associated exposure conditions, along with control and respiratory protection measures required. If the work environment is covered in Table 1 and the specified engineering and work practice control methods are met, along with the required respiratory protection, there is no need to monitor for crystalline silica or comply with the PEL. It is also noted that if combined tasks from Table 1 sum more than 4 hours, over-4-hour respiratory protection must be used.

Active Monitoring: The second method applies to any tasks that are not listed in Table 1, and can be selected as an alternative by the Contractor for tasks in Table 1. Unfortunately, shotcrete is not covered in Table 1, so the assumption is this method will be the only option available to shotcrete contractors. This method requires monitoring for crystalline silica at prescribed times and with activities that represent the highest exposure conditions, if the amount of silica may be at or above the action level of 25 $\mu g/m^3$. If above the action level, the contractor must:

- Measure and record the amount of silica that workers are exposed to over an 8-hour TWA for all the tasks the employee may be reasonably exposed to. Exposure assessments must be repeated every 6 months or less if the exposure is above the action level but below PEL. If exposures are above the PEL, assessments must be made every 3 months or less;
- Protect workers from exposure to crystalline silica above the PEL of 50 $\mu g/m^3$ over an 8-hour TWA. If control of the PEL below the 50 $\mu g/m^3$ is not feasible, supplemental respiratory equipment may be needed;
- Use dust controls to protect from silica exposures above the PEL of 50 $\mu g/m^3$; and
- Provide proper respirators to workers when dust control measures are not adequate to limit exposures to the PEL.

The monitoring option further requires employees to be notified in writing of the assessment results of the monitored levels of crystalline silica within 5 days. Also, if the PEL of 50 $\mu g/m^3$ is exceeded, the employees must receive written notification of the corrective actions taken. Additionally, the employee (or their designated representative) must be allowed to observe the monitoring. The observer must also be provided clothing and equipment to protect them from exposure at no cost to the observer.

Additional Requirements for BOTH Alternatives

The construction employer must:

- Produce and implement a written exposure control plan. The plan must identify tasks that produce exposure, and engineering and work practice methods used to protect workers. This may include restricting access to partic-

Excerpt from Table 1: Specified Exposure Control Methods When Working with Materials Containing Crystalline Silica

Equipment/task	Engineering and work practice control methods	Required respiratory protection and minimum assigned protection factor (APF)	
		≤ 4 hours per shift	> 4 hours per shift
(x) Jackhammers and handheld powered chipping tools	Use tool with water delivery system that supplies a continuous stream or spray of water at the point of impact.		
	• When used outdoors.	None	APF 10
	• When used indoors or in an enclosed area.	APF 10	APF 10
	OR		
	Use tool equipped with commercially available shroud and dust collection system.		
	Operate and maintain tool in accordance with manufacturer's instructions to minimize dust emissions.		
	Dust collector must provide the air flow recommended by the tool manufacturer, or greater, and have a filter with 99% or greater efficiency and a filter-cleaning mechanism.		
	• When used outdoors.	None	APF 10
	• When used indoors or in an enclosed area.	APF 10	APF 10

ular work areas where high exposures may occur. Also, the plan must include housekeeping methods for dust control.

- Designate a competent person to implement the written exposure control plan in the workplace, with frequent and regular inspections to verify compliance. The competent person must be capable of identifying existing and foreseeable respirable crystalline silica hazards, and have authorization to take prompt corrective measures to eliminate or minimize them.
- Implement housekeeping methods to control and limit dust that may contain silica. This includes prohibiting any dry sweeping or brushing, and no cleaning of clothes or surfaces with compressed air. Wet sweeping or HEPA-filtered vacuuming are allowable options.
- Must offer medical exams including chest X-rays and lung function tests every 3 years for workers who are required to wear a respirator for 30 or more days a year. The medical exams must be conducted by a physician or other licensed health care professional (PLHCP) whose legally permitted scope of practice allows them to independently provide these medical evaluations. Employers must make an initial baseline medical exam available within 30 days after the initial assignment to the work covered by the rule. The PLHCP provides a written medical report to the employee within 30 days that includes: the results of the exam indicating any medical condition that would increase their risk after material exposure to silica; any recommended limitations on employee's use of respirators; recommended limits on the exposure to silica; and if there are concerns about the results of the chest X-ray where additional evaluation by a specialist is appropriate. The PLHCP must give the employer a report with much more limited information, including only the date of the exam, a statement that they have met the

requirements of the OSHA rule, and any recommended limitations on the employee's use of respirators.

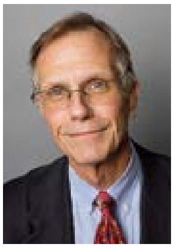
- Communicate to all workers potentially exposed to silica the health hazards associated with exposure to respirable crystalline silica, and identify all MSDS that include crystalline silica. The employer must communicate at least the potential hazards that result in cancer, lung effects, immune system effects, and kidney effects.
- Provide information and training sessions that identify: work operations that could produce silica exposure; specific measures the employer implemented to protect employees from exposure to silica; the identity of the competent person; and the purpose and description of the medical surveillance program. The contractor must further ensure that each employee can demonstrate knowledge and understanding of the training.
- Maintain accurate records for 30 years of:
  - All exposure measurements, including name, social security number (SSN), and job classification of all employees represented by the monitoring, and indication of those employees who were actually monitored.
  - Objective data including the crystalline-containing material, the source of the data, and the testing protocol with results of the testing.
  - Each employee covered by medical surveillance including name, SSN, all PLHCP reports, and information provided by employer to the PLHCP.

Summary

OSHA's new rule for control of exposure to crystalline silica is intended to protect workers on our jobsites. This is one of the most comprehensive rules OSHA has promulgated, and introduced extensive medical monitoring and recordkeeping requirements that will require a significant increase in the contractor's required duties that will certainly require more staffing to implement. In this article, most of the key points are introduced; however, extensive documentation leading to the new rule—along with FAQ and the text of the rule—are readily available at the OSHA website (**www.osha.gov/silica**).

There is a debate on whether the action level of 25 μg/m^3 is able to be accurately and consistently measured. Also, many feel that some of the other provisions seem overly burdensome for the desired results. As a result, several groups involved in the construction industry, including the Construction Industry Safety Coalition, are mounting efforts to get the rule reviewed and revised to provide a more practical, yet still fully effective standard. ASA is monitoring these efforts to modify the new rule.

Unfortunately, no one can predict whether the OSHA rule will be modified before the June 23, 2017, date for compliance. Thus, one should certainly review all the provisions of the new rule, and determine what your company needs to do to meet the requirements.



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Comparative Evaluation of Transport Properties of Shotcrete Compared to Cast-in-Place Concrete

by Lihe Zhang, Dudley Morgan, and Sidney Mindess

The question is sometimes asked: "How does the durability of shotcrete compare to that of cast-in-place concrete?" The durability of shotcrete and concrete structures is strongly influenced by their transport properties. While considerable data are available regarding the transport properties of cast-in-place concrete, little has been published concerning shotcrete transport properties. This study is directed at addressing this deficiency so that factual data are made available regarding the comparative transport properties of both wet, and dry-mix shotcretes and comparable cast-in-place concretes. In this study, a comparative evaluation was conducted on cast-in-place concrete; cast wet-mix shotcrete; sprayed wet-mix shotcrete; and sprayed dry-mix shotcrete in mixtures with and without fly ash, silica fume, and accelerators. Plastic concrete and wet-mix shotcrete tests conducted included slump, air content, and setting time. Hardened concrete and shotcrete tests conducted included compressive strength at 7 and 28 days; ASTM C642 boiled absorption and volume of permeable voids; ASTM C1202 rapid chloride permeability (RCP); ASTM C1792 rate of water absorption; and U.S. Navy specification UFGS 03 31 29-3 (chloride permeability test). Calculated transport property values compared included boiled absorption (BA) and volume of permeable voids (VPV), Coulomb values in RCP test, coefficient of diffusion (Diff[OH^-]), effective coefficient of diffusion (Diff[OH^-] x VPV), permeability (k) and tortuosity, in U.S. Navy specification UFGS 03 31 29-3 tests. This study demonstrates that properly applied wet-mix and dry-mix shotcretes can provide equivalent or superior transport properties (for example, ionic diffusion and permeability), and hence durability, to cast-in-place concrete.

Keywords: absorption; accelerator; boiled absorption; coefficient of diffusion; dry-mix; durability; ionic diffusion; permeability; rapid chloride penetration; shotcrete; tortuosity; transport properties; volume of permeable voids; wet-mix.

INTRODUCTION

Shotcreting refers to the process of pneumatically conveying concrete materials at high velocity to a receiving surface to achieve compaction. While shotcrete has been used for over a century, the use of shotcrete instead of conventional cast-in-place concrete has greatly increased in the past several decades, both for new construction and for repair, rehabilitation, and seismic upgrading of existing structures. The range of shotcrete applications is wide, including structural walls and other elements for commercial, industrial, institutional, and residential buildings; repair and rehabilitation for bridges, dams, reservoirs, and marine structures; stabilization of rock faces; and underground support in tunnels and mines. Both wet-mix and dry-mix shotcrete processes are available. Shotcrete can be applied by a nozzleman or by remote control with a robotic sprayer. The advantages of shotcrete are many:

- Compared to cast-in-place concrete, shotcrete is able to minimize or eliminate the need for the formwork required for conventional concrete construction;
- Shotcrete is compacted by high-velocity impact and can thus achieve increased compaction compared to cast-in-place concrete;
- With an aging infrastructure, more and more shotcrete is being used for structural repair and rehabilitation, especially where the use of formwork and access are challenging; and
- In underground applications in tunnels and mines, shotcrete has proven to be a cost-effective and safe method of ground support.

With the increasing use of shotcrete, however, questions have been raised with regard to its long-term performance and durability. In particular, how does the durability of shotcrete compare to that of cast-in-place concrete? This question is of interest to owners, structural engineers, transportation agencies, architects, and equipment and materials suppliers. Unfortunately, there is a lack of adequate comparative data about the basic durability of shotcrete compared to cast-in-place concrete.

Durability factors such as resistance to weathering, corrosion, chemical attack, alkali-aggregate reaction, carbonation, and freezing-and-thawing deterioration are all influenced by the transport properties of the concrete or shotcrete during the service life of the structure. Therefore, the objective of this study is to determine the transport properties of shotcrete compared to conventional cast-in-place concrete. The transport properties evaluated herein include absorption (liquid uptake in a porous medium); diffusion (liquid, gas, or ion movement under a concentration gradient); permeability (resistance to flow of a liquid under a pressure gradient); sorptivity (absorption of a liquid by capillarity); and wicking (capillary transport through a porous medium to a drying surface). The tests that were conducted to quantify the transport properties in concrete and shotcrete were boiled water absorption, water absorption, drying, chloride ponding, chloride diffusion, and rapid chloride penetration for samples from both shotcrete and concrete.

RESEARCH SIGNIFICANCE

Relatively little has been published about the transport properties of shotcrete. Information on this topic is needed because shotcrete is increasingly being used in various new construction and repair applications. This research program compares the transport properties of cast-in-place concretes with wet-mix shotcretes and dry-mix shotcretes with similar

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Table 1—Summary of mixtures included in this test program

Mixture type	Cast concrete	Cast wet-mix shotcrete	Shot wet-mix shotcrete	Shot wet-mix shotcrete with 5% accelerator	Shot dry-mix shotcrete	Shot dry-mix shotcrete with 3% accelerator
Portland cement	A1	A2	A3	A4	A5	A6
Fly ash modified	B1	B2	B3	B4	B5	B6
Silica fume modified	C1	C2	C3	C4	C5	C6

Fig. 1—Concrete pan mixer and wet-mix shotcrete pump (left) and after mixing, shotcrete was discharged into shotcrete pump (right).

water-cementitious materials ratios (*w*/*cm*). These data can be used to provide a comparison of expected durability and predicted service life of structures made with these different materials/systems. The effect of different cementitious materials in the mixtures on transport properties, such as cement, fly ash, and silica fume, was also studied.

This research program also provides the opportunity to compare the various testing methods used and assesses their suitability for the purposes of qualification of the mixture, qualification of the nozzleman, and quality control. Current testing methods being used for qualification and quality control of concrete and shotcrete are compared against the findings of the transport properties tests, and recommended testing method(s) are proposed for use in the field.

EXPERIMENTAL PROGRAM

Mixture designs and materials

Determination of the transport properties in this study was based on tests conducted according to:

- ASTM C642[1]: Density, boiled absorption, and volume of permeable voids. This test method is widely used as a qualification and quality control test method in the shotcrete industry.
- ASTM C1202[2]: Electrical indication of concrete's ability to resist chloride ion penetration. This test method is frequently used as a method to qualify the shotcrete or concrete mixture, as well as a quality control test. However, the test itself is controversial in that rather than measuring actual chloride penetration, it measures current flow in Coulombs (1 Coulomb = 1 amp/s), which in turn is related to electrical resistivity (Ω = Volt/Amp). It actually measures the flow of OH^- ions as charge carriers, and thus is not just an indirect measure of resistivity through the measurement of the charge passed.
- ASTM C1792[3]: Rate of water absorption (drying test)
- Ionic migration test to U.S. Navy Specification UFGS 03 31 29-3.[4] This test method is a modified version of the ASTM C1202 test and is described later in this paper.

Cast-in-place concrete mixtures, cast shotcrete mixtures, and sprayed shotcrete mixtures (hereafter referred to as shot shotcrete mixtures) were all subjected to these test methods. For each mixture, in addition to cement-only mixtures, mixtures with fly ash or silica fume were included to represent mixtures commonly used in the industry. The different mixtures studied are summarized in Table 1.

The as-batched mixture proportions are provided in Tables 2 through 4. All mixtures were dry-batched by the same supplier from Vancouver, BC, Canada and provided as prebagged materials in bulk bin bags. Mixtures of cast concretes (A1, B1, and C1), cast wet-mix shotcretes (A2, B2, and C2), shot wet-mix shotcretes (A3, B3, and C3), and shot wet-mix shotcretes with 5% accelerator (A4, B4, andC4) all have the same *w*/*cm* of 0.40. All mixtures used aggregates conforming to the ACI 506R[5] Gradation No. 2 requirements. A high-range water-reducing admixture was used for wet-mix shotcretes at the dosages needed to produce the required slump.

For the dry-mix shotcretes, the exact *w*/*cm* is not available as the water content was controlled by the nozzleman by adjusting the water added at the nozzle. For these specimens, the *w*/*cm* of 0.40 is an estimate.

Such concretes and shotcretes would satisfy CSA A23.1 Table 2[6] (equivalent to ACI 318 Table 4.3.1[7]) requirements for a C-1 exposure condition (that is, structurally reinforced concrete exposed to chlorides with a maximum *w*/*cm* of 0.40 and minimum 56-day compressive strength of 35 MPa (5076 psi). Additional air entrainment would be required for use of such concrete or shotcrete in freezing-and-thawing exposure environments.

Batching, mixing, and production

Concrete mixtures A1, B1, and C1 were hand-cast in the laboratory and are described as cast concrete. Test panels with

Table 2—As-batched wet-mix shotcrete mixture proportions

Mixture No.	Mixture description	Placement method	Mixture ID	As-batched mixture proportions for 1.0 m^3								
				Cement (Type GU), kg	Fly ash, kg	Silica fume, kg	Coarse aggregate (ten 5 mm, SSD), kg	Fine aggregate, SSD, kg	Water, L	High-range water-reducing admixture, L	Total mass, kg	*w/cm*
A1	Portland cement	Cast concrete	C-Cast	415	0	0	1027	691	168	0	2329	0.40
A2	Portland cement	Cast wet-mix	C-Wet-Mix-Cast	439	0	0	419	1256	177	0.525	2291	0.40
A3	Portland cement	Shot wet-mix	C-Wet-Mix-Shot	445	0	0	425	1273	179	0.533	2322	0.40
A4	Portland cement	Shot wet-mix 5% accelerator	C-Wet-Mix-Shot-5%	443	0	0	423	1267	179	0.530	2313	0.40
B1	Fly ash modified	Cast concrete	FA-Cast	334	79	0	1023	688	166	0	2319	0.40
B2	Fly ash modified	Cast wet-mix	FA-Wet-Mix-Cast	343	85	0	409	1224	173	0.622	2233	0.40
B3	Fly ash modified	Shot wet-mix	FA-Wet-Mix-Shot	351	86	0	418	1252	176	0	2284	0.40
B4	Fly ash modified	Shot wet-mix 5% accelerator	FA-Wet-Mix-Shot-5%	349	86	0	416	1246	176	0.633	2274	0.40
C1	Silica fume modified	Cast concrete	SF-Cast	379	0	34	1005	676	166	0.585	2263	0.40
C2	Silica fume modified	Cast wet-mix	SF-Wet-Mix-Cast	395	0	38	414	1239	175	1.259	2262	0.40
C3	Silica fume modified	Shot wet-mix	SF-Wet-Mix-Shot	404	0	39	422	1265	178	1.285	2310	0.40
C4	Silica fume modified	Shot wet-mix 5% accelerator	SF-Wet-Mix-Shot-5%	400	0	38	418	1253	177	2.036	2287	0.40

Notes: 1 kg/m^3 = 1.68556 lb/yd^3; 1 L/m^3 = 29.5 fl oz/yd^3.

Table 3—Calculated dry-mix shotcrete mixture proportions

Mixture No.	Mixture description	Placement method	Mixture ID	Calculated mixture proportions for 1.0 m^3								Air content, as-shot, %
				Cement (Type GU), kg	Fly ash, kg	Silica fume, kg	Coarse aggregate (ten 5 mm), SSD, kg	Fine aggregate, SSD, kg	Estimated water, L	Total mass, kg	Estimated *w/cm*	
A5	Portland cement	Shot dry-mix	C-Dry-Mix-Shot	450	0	0	430	1290	180	2351	0.40	3.20
A6	Portland cement	Shot dry-mix 3% accelerator	C-Dry-Mix-Shot-3%	450	0	0	430	1290	180	2351	0.40	4.20
B5	Fly ash modified	Shot dry-mix	FA-Dry-Mix-Shot	360	90	0	430	1290	180	2351	0.40	2.60
B6	Fly ash modified	Shot dry-mix 3% accelerator	FA-Dry-Mix-Shot-3%	360	90	0	430	1290	180	2351	0.40	4.10
C5	Silica fume modified	Shot dry-mix	SF-Dry-Mix-Shot	410	0	40	430	1290	180	2351	0.40	4.10
C6	Silica fume modified	Shot dry-mix 3% accelerator	SF-Dry-Mix-Shot-3%	410	0	40	430	1290	180	2351	0.40	2.60

Notes: 1 kg/m^3 = 1.68556 lb/yd^3; 1 L/m^3 = 29.5 fl oz/yd^3.

dimensions of 600 x 600 x 125 mm (24 x 24 x 5 in.) were hand-cast with sufficient vibration to achieve full compaction.

Wet-mix shotcrete was dry-batched and supplied in 0.76 m^3 (1 yd^3) bulk bin bags. It was discharged and mixed in a pan mixer with a batch size of 0.76 m^3 (1 yd^3) (Fig. 1). Water and the high-range water-reducing admixture were dosed and added manually. The wet-mix shotcrete pump was typical of that used in the shotcrete industry and conformed to ACI 506 requirements.[5] Wet-mix shotcrete mixtures A2, B2, and C2 were mixed and cast in the field. Test panels for these mixtures were cast manually with sufficient vibration to achieve full compaction. Mixtures A3, B3, and C3 were

Table 4—As-batched cast concrete mixture proportions

Mixture No.	Mixture description	Placement method	Mixture ID	Mixture proportions for 1.0 m^3									
				Cement (Type GU), kg	Fly ash (Class F), kg	Silica fume, kg	Coarse aggregate (ten 5 mm) SSD, kg	Fine aggregate SSD, kg	Water, L	Water reducing admixture, L	*w/cm*	Total mass, kg	Air content, as-batched, %
A1	Portland cement	Cast concrete	C-Cast	415	0	0	1027	691	168	0	0.40	2329	5.50
B1	Fly ash modified	Cast concrete	FA-Cast	334	79	0	1023	688	166	0	0.40	2319	5.30
C1	Silica fume modified	Cast concrete	SF-Cast	379	0	34	1003	671	167	0.538	0.40	2263	7.20

Notes: 1 kg/m^3 = 1.68556 lb/yd^3; 1 L/m^3 = 29.5 fl oz/yd^3.

Fig. 2—Dry-mix shotcrete gun with pre-dampener.

shot in the field (refer to Fig. 3). Wet-mix shotcrete mixtures A4, B4, and C4 were shot with 5% by mass of cement of a non-alkali accelerator added at the nozzle during shooting.

Dry-mix shotcrete was also dry batched and supplied in 0.76 m^3 (1 yd^3) bulk bin bags. It was discharged into a predampener and then into the dry-mix machine (gun). The moisture content of the predampened dry-mix shotcrete was estimated to be between 4 and 6%. The dry-mix shotcrete predampener and machine (Fig. 2) are typical of the dry-mix shotcrete setup used in the shotcrete industry and conformed to ACI 506[5] requirements. Dry-mix shotcrete mixtures A5, B5, and C5 and A6, B6, and C6 were shot in the field. Mixtures A6, B6, and C6 contained 3% by mass of cement of a chloride-free dry powder accelerator added to the mixture at the time of batching.

An ACI Certified Nozzleman (certified for shooting wet-mix overhead and vertical, and dry-mix overhead and vertical) conducted the shooting (Fig. 3). Rebound and overspray were properly controlled. The nozzleman controlled the nozzle angle, nozzle distance, air flow from the air compressor, and water addition for the dry-mix process in a proper way, as required by ACI 506. It is estimated that approximately 4 to 6% rebound occurred with the wet-mix process, and less than 15% rebound occurred with the dry-mix process.

In summary, the shotcrete application met ACI 506[5] recommendations and was representative of proper application. The mixing and shooting were conducted at the first author's laboratory in Vancouver in October 2013. On-site monitoring of shotcrete batching, mixing, and test panel production was provided by experienced shotcrete engineers. Testing for plastic properties of the concrete and shotcrete was provided by an ACI Certified Concrete Testing Technician.

BASIC CONCRETE AND SHOTCRETE TEST RESULTS AND DISCUSSION

Test results for basic plastic and hardened concrete and shotcrete properties and for transport properties are presented and discussed in this section. Test results for three transport properties—that is, ASTM C642 boiled absorption test, ASTM C1792 water absorption test, and U.S. Navy Specification UFGS 03 31 29-3 ionic migration test—are also presented and discussed in this section. These transport properties results will be input into the STADIUM[8] service life model to provide a comparative evaluation of the predicted service life of the concretes and shotcretes tested in this study. The results of this service life analysis are not included in this report, but will be presented in a separate paper.

Fresh properties

Plastic properties of shotcrete were tested according to ACI 506 requirements and are summarized in Table 5.

The air contents for as-batched shotcrete and as-shot shotcrete were tested separately. The as-batched air content was tested on samples from the shotcrete pump. The as-shot air content was tested on samples extracted from the in-place shotcrete. Slumps for non-accelerated wet-mix shotcrete ranged from 80 to 120 mm (3 to 5 in.). For the accelerated wet-mix shotcretes, the slump was increased to the 180 to 220 mm (7 to 9 in.) range to allow for proper dispersion of the accelerator at the nozzle, as is standard industry practice. This increase in slump was achieved by increasing the high-range water-reducing admixture dosage, with no increase in the *w/cm*.

Compressive strength

For each mixture, two cores were extracted and tested for compressive strength at 7 days, and three cores were extracted and tested for compressive strength at 28 days. Seven-day and 28-day compressive strength results are listed in Table 6.

The 28-day compressive strength for cast concretes and wet-mix shotcretes, including results from both cast and shot wet-mix shotcretes' processes, ranged from 35 to 64 MPa

Fig. 3—Shotcrete test panels were shot by an ACI Certified Nozzleman for both wet-mix shotcrete (left) and dry-mix shotcrete (right).

(5076 to 9283 psi). Compressive strength for dry-mix shotcrete varied from 35 to 63 MPa (5076 to 9138 psi).

Compressive strengths of shot wet-mix shotcrete versus cast wet-mix shotcrete and cast concrete—If one compares like mixtures (for example, cement-only mixtures with cast concrete, cast wet-mix shotcrete, and shot wet-mix shotcrete) and the same for fly ash and silica fume mixtures, then it is evident that sprayed shotcrete mixtures without accelerators consistently produce higher 7- and 28-day compressive strengths compared to cast shotcrete mixtures, or cast concrete mixtures. The differences are not large, but they are (with one exception) consistent. This supports the statement that "shotcrete, when properly applied, provides superior compaction to the cast-in-place concrete process."[9] Table 7 shows these comparisons at the age of 28 days.

Compressive strength of dry-mix shotcrete—Most of the dry-mix shotcrete mixtures displayed higher 28-day strengths than like wet-mix shotcretes. This is possibly attributable to a slightly lower *w/cm* in some of the dry-mix shotcrete mixtures.

Effect of accelerator on wet-mix and dry-mix shotcrete compressive strength—The addition of an accelerator is a common practice in the shotcrete industry—in particular, in underground shotcrete application. Accelerators help shotcrete to stick overhead and increase early-age (up to the first 24 hours) compressive strength development. However, compared to mixtures without accelerator, they tend to reduce the 7- and 28-day compressive strength, depending on the accelerator addition rate. With 5% by mass of cement of non-alkali accelerator added to the wet-mix shotcrete, the compressive strength for fly ash and silica fume mixtures decreased relative to the mixtures with no accelerator. The same effect also occurred with dry-mix shotcretes with 3% accelerator added. This is consistent with typical findings in the shotcrete industry.[9]

Boiled absorption (BA) and volume of permeable voids (VPV)

BA and VPV tests were conducted to evaluate the porosity of the concrete and shotcrete. Test results from cores tested at 28 days are plotted in Fig. 4. ACI 506 recommends that values for BA and VPV not exceed 8% for BA and 17% for VPV. All of the 18 mixtures tested produced BA values less than 6.5% and VPV values less than 14.5%.

Test results for both BA and VPV consistently decreased from cement to fly ash to silica fume irrespective of the placement method. This is consistent with the results of previous research conducted in North America, Australia, South Africa, and Europe.[9] Table 8 summarizes the BA and VPV results for shot wet-mix shotcrete versus cast wet-mix shotcrete versus cast concrete. Cast concrete mixtures have almost the same BA and VPV values as cast wet-mix shotcrete. This is because the *w/cm* for both groups of mixtures is the same.

BA and VPV test results for shot wet-mix shotcretes without accelerator are slightly lower than for cast wet-mix shotcretes for the cement and fly ash mixtures, and equal to or slightly higher for cast wet-mix shotcrete with silica fume. This indicates that, overall, the shooting process tends to produce lower permeability than the casting process. However, BA and VPV test results for the shot wet-mix shotcretes with 5% accelerator are higher than for the shot wet-mix shotcrete without accelerator, or the cast wet-mix shotcrete. This shows that when accelerator is added, the permeability of the shotcrete increases. This is consistent with findings on numerous underground support projects.[9]

Table 9 presents the BA and VPV results for shot dry-mix shotcrete compared to cast concrete (note: one cannot cast dry-mix shotcrete). These results show that non-accelerated dry-mix shotcrete has lower values of BA and VPV for the fly ash and silica fume mixtures and a similar value for the cement-only mixture. By contrast, the dry-mix shotcrete mixtures with 3% non-alkali accelerator had consistently higher BA and VPV values than the cast concrete. This shows that when accelerator is added into the shotcrete, the permeability increases. It should, however, be noted that all the dry-mix shotcrete BA and VPV values are consistently well below the maximum acceptable values of 8% for BA and 17% for VPV provided in ACI 506R.

Rapid chloride penetration resistance (RCP)

The ASTM C1202 rapid chloride penetration (RCP) test is one of the most widely used test methods to evaluate the chloride penetration resistance of concrete. Although the RCP test provides a measure of current flow, rather than the chloride ion diffusion rate or actual chloride penetration resistance, it does provide information on the electrical resistivity of concrete. Table 10 shows the results of all RCP tests.

Table 5—Plastic properties

<table>
<tr><th>Mixture No.</th><th>Mixture description</th><th>Placement method</th><th>Mixture ID</th><th>Air content, % (as-batched)</th><th>Air content, % (as-shot)</th><th>Slump, mm</th><th>Initial set, h:mins</th><th>Final set, h:mins</th><th>w/cm</th><th>Shotcrete temperature, °C</th><th>Air tempera-ture, °C</th></tr>
<tr><td>A1</td><td>Portland cement</td><td>Cast concrete</td><td>C-Cast</td><td>5.50</td><td>Not applicable</td><td>85</td><td rowspan="3" colspan="2">Not available</td><td>0.40</td><td>21</td><td>19</td></tr>
<tr><td>A2</td><td>Portland cement</td><td>Cast wet-mix</td><td>C-Wet-Mix-Cast</td><td>4.50</td><td>Not applicable</td><td>120</td><td>0.40</td><td>15</td><td>7</td></tr>
<tr><td>A3</td><td>Portland cement</td><td>Shot wet-mix</td><td>C-Wet-Mix-Shot</td><td>4.50</td><td>3.20</td><td>120</td><td>0.40</td><td>15</td><td>7</td></tr>
<tr><td>A4</td><td>Portland cement</td><td>Shot wet-mix 5% Accelerator</td><td>C-Wet-Mix-Shot-5%</td><td>5.90</td><td>3.60</td><td>190</td><td>12 min</td><td>1 h 20 min</td><td>0.40</td><td>14</td><td>9</td></tr>
<tr><td>B1</td><td>Fly ash modified</td><td>Cast concrete</td><td>FA-Cast</td><td>5.30</td><td>Not applicable</td><td>155</td><td rowspan="3" colspan="2">Not available</td><td>0.40</td><td>21</td><td>19</td></tr>
<tr><td>B2</td><td>Fly ash modified</td><td>Cast wet-mix</td><td>FA-Wet-Mix-Cast</td><td>5.60</td><td>Not Applicable</td><td>180</td><td>0.40</td><td>Not available</td><td>8</td></tr>
<tr><td>B3</td><td>Fly ash modified</td><td>Shot wet-mix</td><td>FA-Wet-Mix-Shot</td><td>5.40</td><td>3.50</td><td>80</td><td>0.40</td><td>14</td><td>7</td></tr>
<tr><td>B4</td><td>Fly ash modified</td><td>Shot wet-mix 5% accelerator</td><td>FA-Wet-Mix-Shot-5%</td><td>5.60</td><td>3.90</td><td>180</td><td>32 min</td><td>2 h</td><td>0.40</td><td>13</td><td>8</td></tr>
<tr><td>C1</td><td>Silica fume modified</td><td>Cast concrete</td><td>SF-Cast</td><td>7.20</td><td>Not applicable</td><td>40</td><td rowspan="3" colspan="2">Not available</td><td>0.40</td><td>22</td><td>19</td></tr>
<tr><td>C2</td><td>Silica fume modified</td><td>Cast wet-mix</td><td>SF-Wet-Mix-Cast</td><td>5.10</td><td>Not applicable</td><td>100</td><td>0.40</td><td>14</td><td>7</td></tr>
<tr><td>C3</td><td>Silica fume modified</td><td>Shot wet-mix</td><td>SF-Wet-Mix-Shot</td><td>5.10</td><td>3.40</td><td>100</td><td>0.40</td><td>15</td><td>7</td></tr>
<tr><td>C4</td><td>Silica fume modified</td><td>Shot wet-mix 5% accelerator</td><td>SF-Wet-Mix-Shot-5%</td><td>6.60</td><td>4.00</td><td>220</td><td>10 min</td><td>1 h 15 min</td><td>0.40</td><td>13</td><td>8</td></tr>
<tr><td>A5</td><td>Portland cement</td><td>Shot dry-mix</td><td>C-Dry-Mix-Shot</td><td rowspan="6">Not testable</td><td>3.20</td><td rowspan="6">Not Test-able</td><td>Not available</td><td>3 h 30 min</td><td rowspan="6">Not test-able</td><td>15</td><td>10</td></tr>
<tr><td>A6</td><td>Portland cement</td><td>Shot dry-mix 3% accelerator</td><td>C-Dry-Mix-Shot-3%</td><td>4.20</td><td>6 min</td><td>16 min</td><td>16</td><td>10</td></tr>
<tr><td>B5</td><td>Fly ash modified</td><td>Shot dry-mix</td><td>FA-Dry-Mix-Shot</td><td>2.60</td><td>Not available</td><td>3 h 25 min</td><td>14</td><td>10</td></tr>
<tr><td>B6</td><td>Fly ash modified</td><td>Shot dry-mix 3% accelerator</td><td>FA-Dry-Mix-Shot-3%</td><td>4.10</td><td>6 min</td><td>38 min</td><td>16</td><td>12</td></tr>
<tr><td>C5</td><td>Silica fume modified</td><td>Shot dry-mix</td><td>SF-Dry-Mix-Shot</td><td>4.10</td><td>Not available</td><td>3 h 30 min</td><td>14</td><td>10</td></tr>
<tr><td>C6</td><td>Silica fume modified</td><td>Shot dry-mix 3% accelerator</td><td>SF-Dry-Mix-Shot-3%</td><td>2.60</td><td>5 min</td><td>15 min</td><td>14</td><td>12</td></tr>
</table>

Note: 1 mm = 0.039 in.; 1°C = 5(F – 32)/9.

Cast concrete versus cast wet-mix shotcrete versus shot wet-mix and dry-mix shotcretes—The RCP results for cast concrete and cast wet-mix shotcrete are similar for each of the cement, fly ash, and silica fume mixtures. However, RCP results for the shot wet-mix shotcretes are consistently lower than for comparable cast concrete and cast shotcrete mixtures. This is attributed to the superior compaction achieved during the shooting process compared to casting. When 5% accelerator is added, the RCP results for shot wet-mix shotcrete increase for the cement-only and fly ash mixtures, but not for the silica fume mixtures. This shows that the 5% accelerator has little effect on the chloride penetration resistance for mixtures with silica fume. The wet-mix shotcrete with 5% accelerator has similar RCP results to the cast concrete and cast shotcrete mixtures. This shows that the negative effect of accelerator addition on permeability tends to be offset by the beneficial effect of superior compaction achieved by the shooting process.

The dry-mix shotcrete with no accelerator produced the lowest RCP test results of all the mixtures tested. When 3% accelerator was added to the dry-mix shotcrete, the RCP test results were still lower than for similar cast concrete, cast wet-mix shotcrete, or shot wet-mix shotcrete mixtures. It should be noted that the *w*/*cm* of the dry-mix shotcrete is not predetermined and is dependent on the nozzleman. The results herein are attributed to two factors—that is, first, the shooting process improves compaction, which reduces permeability, and second, the actual *w*/*cm* for the dry-mix shotcrete might be lower than that for like cast concrete, cast wet-mix shotcrete, or shot wet-mix shotcrete.

Table 10 also shows the CSA A23.1 performance requirements of the significance of RCP Coulomb numbers. All the cement mixtures (with the single exception of the dry-mix shotcrete) fall into the "moderate" rating. The fly ash cast concrete, cast wet-mix shotcrete, and shot wet-mix shotcrete all fall into the "low" rating. The fly ash shot wet-mix shotcrete and dry-mix shotcrete and all the silica fume mixtures fall into the "very low" category.

Table 6—Compressive strength

Mixture ID	Compressive strength	
	7 days, MPa	28 days, MPa
C-Cast	37.2	46.5
FA-Cast	36.6	48.8
SF-Cast	32.8	39.4
C-Wet-Mix-Cast	32.5	40.4
FA-Wet-Mix-Cast	29.3	39.3
SF-Wet-Mix-Cast	33.7	45.1
C-Wet-Mix-Shot	38.5	47.1
FA-Wet Mix-Shot	39.7	44.9
SF-Wet-Mix-Shot	38.1	51.5
C-Wet-Mix-Shot-5%	31.5	49.9
FA-Wet-Mix-Shot-5%	37.5	41.9
SF-Wet-Mix-Shot-5%	29.4	38.1
C-Dry-Mix-Shot	29.5	34.9
FA-Dry-Mix-Shot	32.2	52.6
SF-Dry-Mix-Shot	45.0	64.3
C-Dry-Mix-Shot-3%	24.6	35.9
FA-Dry-Mix-Shot-3%	26.6	43.5
SF-Dry-Mix-Shot-3%	30.3	47.9

Note: 1 MPa = 145 psi.

IONIC MIGRATION TEST

The ionic migration test (a modified chloride penetration test) was conducted in accordance with U.S. Navy Specification UFGS 03 31 29-3. Compared to ASTM C1202, rapid chloride penetration test, the ionic migration test employs a larger testing chamber (150 mm [6 in.] diameter) that provides a more stable environment. Na(OH) solutions are placed in both the upstream and downstream containers to stabilize the Cl^- ion and other species (Fig. 5). The measured values for current (I, in milliamp) is input into the STADIUM Lab program[8] and the rate of diffusion for each chemical species is calculated based on Fick's Second Law of diffusion.

Results for the ionic migration test produce diffusion coefficient values for all of the species in the concrete, including OH^-, Na^+, K^+, SO_4^- Ca^{2+}, Cl^-, and enable a calculation of tortuosity and are listed in Table 11.

The ionic migration test takes into account the species of OH^-, Cl^-, Na+, K+, SO_4^{2-}, $Fe(OH)^{4-}$, and $H_2SiO_4^{2-}$. OH^- is one of the most representative species and the coefficient of diffusion (CoD) of all the species is represented by Diff [OH^-]. CoDs are related to the porosity, which can be characterized by the volume of permeable voids (VPV). To take into consideration both CoD and VPV, a new parameter is introduced as

$$\text{Effective Coefficient of Diffusion (ECoD)} = \text{CoD} \times \text{VPV}$$

Table 7—28-day compressive strength for shot versus cast shotcrete

	Cast concrete, MPa	Cast wet-mix shotcrete, MPa	Shot wet-mix shotcrete, MPa	Increase of strength of shot shotcrete versus cast shotcrete, %	Shot wet-mix shotcrete with 5% accelerator, MPa	Increase of strength of shot shotcrete with 5% accelerator versus cast shotcrete, %
Cement	46.5	40.4	47.1	17	49.9	24
Fly ash	48.8	39.3	44.9	14	41.9	7
Silica fume	39.4	45.1	51.5	14	38.1	–16

Note: 1 MPa = 145 psi.

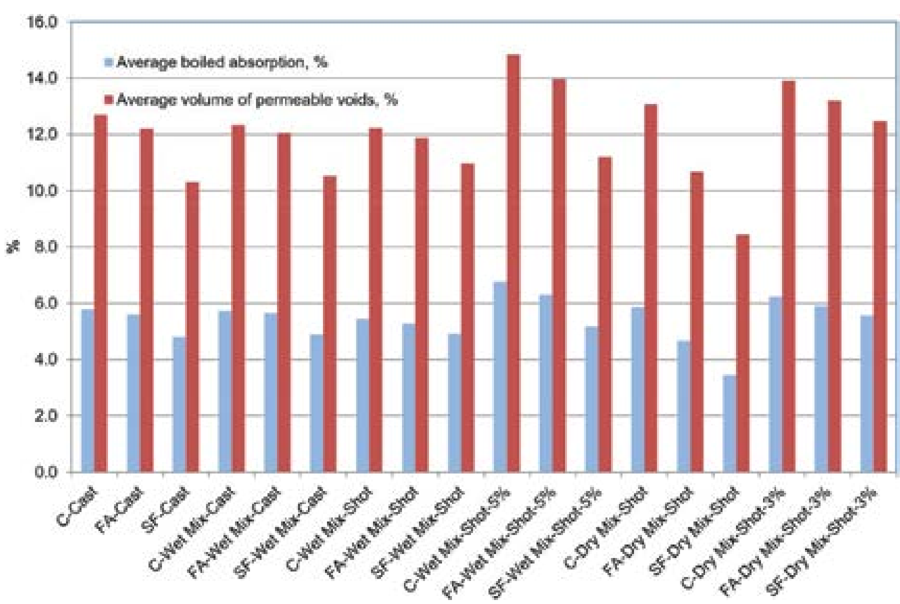

Fig. 4—Test results for boiled absorption and volume of permeable voids.

Table 8—BA and VPV voids for shot wet-mix shotcrete versus cast wet-mix shotcrete and cast concrete

Boiled absorption	Cast-in-place concrete, %	Cast wet-mix shotcrete, %	Shot wet-mix shotcrete, %	Decrease in BA of shot shotcrete versus cast shotcrete, %	Shot wet-mix shotcrete with 5% accelerator, %	Increase in BA of shot shotcrete with 5% accelerator versus cast shotcrete, %
Cement	5.8	5.7	5.4	5	6.8	19
Fly ash	5.6	5.6	5.3	5	6.3	13
Silica fume	4.8	4.9	4.9	0	5.2	6
Volume of permeable voids	Cast-in-place concrete, %	Cast wet-mix shotcrete, %	Shot wet-mix shotcrete, %	Decrease in VPV of shot shotcrete versus cast shotcrete, %	Shot wet-mix shotcrete with 5% accelerator, %	Increase in VPV of shot shotcrete with 5% accelerator versus cast shotcrete, %
Cement	12.7	12.3	12.2	1	14.8	20
Fly ash	12.2	12.0	11.9	1	14.0	17
Silica fume	10.3	10.5	11.0	–5	11.2	7

Table 9—BA and VPV for shot dry-mix shotcrete versus cast concrete

Boiled absorption	Cast concrete, %	Dry-mix shotcrete, %	Decrease in BA of shot dry-mix shotcrete versus cast concrete, %	Dry-mix shotcrete with 3% accelerator, %	Increase in BA of shot dry-mix shotcrete versus cast concrete, %
Cement	5.8	5.9	-2	6.2	7
Fly ash	5.6	4.7	16	5.9	5
Silica fume	4.8	3.5	27	5.6	17
Volume of permeable voids	Cast concrete, %	Dry-mix shotcrete, %	Decrease in VPV of shot dry-mix shotcrete versus cast concrete, %	Dry-mix shotcrete with 3% accelerator, %	Increase in VPV of shot dry-mix shotcrete versus cast concrete, %
Cement	12.7	13.1	–3	13.9	9
Fly ash	12.2	10.7	12	13.2	8
Silica fume	10.3	8.4	18	12.5	21

Table 10—Rapid chloride penetration test results (Coulombs)

Coulombs	Cast concrete	Cast wet-mix shotcrete	Shot wet-mix shotcrete	Shot wet-mix shotcrete with 5% accelerator	Dry-mix shotcrete	Dry-mix shotcrete with 3% accelerator
Cement	3052	2884	2047	2937	1582	2274
Fly ash	1108	1054	912	1259	637	752
Silica fume	374	361	305	269	250	295

Notes: CSA A23.1/23.2 performance requirements: chloride ion penetrability is high (>4000 Coulombs); moderate (2000 to 4000 Coulombs); low (1000 to 2000 Coulombs); very low (100 to 1000 Coulombs); and negligible (<100 Coulombs).

ECoD values include the effects of both the CoD and VPV and are more representative for the diffusion properties for the species.

Results of the coefficient of diffusion (CoD) test are plotted in Fig. 6. All CoD values for all 18 mixtures are in the range of 2 to 20 × 10^{-11} m^2/s. Although there are various species in both upstream and downstream solutions, OH^- is one of the most representative ions. CoD (OH^-) values are determined by the test and are used to characterize the diffusion properties for all the species, including Cl^-, SO_4^-, and so on.

ECoD values for the different mixtures/processes are plotted in Fig 7.

Effect of shotcrete process on ECoD

The cast-in-place concrete mixtures have similar ECoD values when compared with similar cast wet-mix shotcrete, except that the ECoD for the cast-in-place concrete mixture for the cement-only mixture is very high. This is attributed to the high CoD for the cast-in-place concrete mixture with cement only (Fig. 7).

Shot wet-mix shotcrete mixtures have similar ECoD values when compared with similar cast shotcrete mixtures. This shows that the shotcrete process, which involves high-velocity impact, does not adversely affect the ECoD of the chemical ions.

Accelerated wet-mix shotcrete—that is, mixtures with 5% non-alkali accelerator—show slightly higher ECoD values compared to the equivalent shot wet-mix shotcrete mixtures and cast shotcrete mixtures.

Dry-mix shotcrete mixtures show similar ECoDs values to shot wet-mix shotcrete. It is known that the *w/cm* of dry-mix shotcrete is dependent on the nozzleman's skill, as it is controlled by the nozzleman during shooting. Therefore, the results presented herein provide a good indication that the dry-mix shotcrete was properly applied, as it achieved similar ECoDs values to the shot wet-mix shotcrete.

Effect of supplementary cementitious materials (SCMs) on ECoD

The ECoD values of all the mixture groups decreased from the cement-only mixtures, to fly ash mixtures, to silica

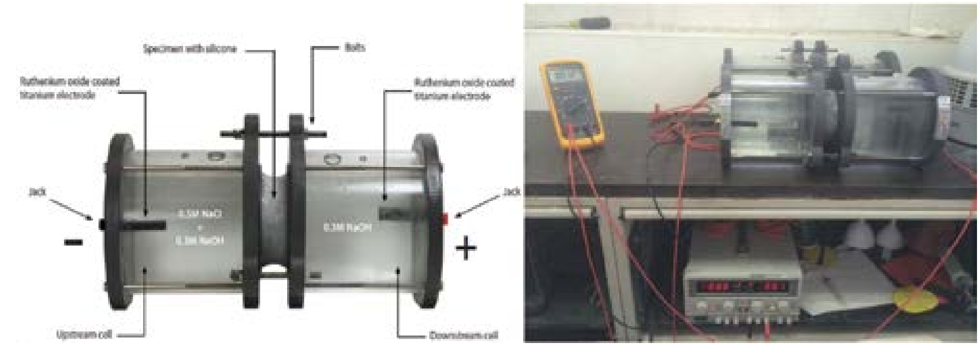

Fig. 5—Ionic migration test setup illustration (left) and laboratory setup (right).

Table 11—Results for ionic migration test and drying test

Mixture ID	Coefficients of diffusion, Diff[OH^-] (10^{-11} m^2/s)	Effective coefficient of diffusion, Diff[OH^-] × VPV% (10^{-11} m^2/s)	Tortuosity	K, permeability, 10^{-22} m^2
C-Cast	18.49	2.35	28.5	9.31
FA-Cast	8.67	1.06	61.0	8.51
SF-Cast	4.92	0.51	107.5	3.94
C-Wet Mix-Cast	10.78	1.33	49.0	9.65
FA-Wet Mix-Cast	10.23	1.23	51.5	8.05
SF-Wet Mix-Cast	6.05	0.64	87.0	6.53
C-Wet Mix-Shot	10.37	1.27	51.8	4.84
FA-Wet Mix-Shot	7.35	0.87	71.9	4.76
SF-Wet Mix-Shot	5.7	0.63	92.6	2.66
C-Wet Mix-Shot-5%	11.45	1.69	46.1	5.02
FA-Wet Mix-Shot-5%	10.36	1.45	61.0	4.97
SF-Wet Mix-Shot-5%	5.04	0.56	104.2	2.69
C-Dry Mix-Shot	12.01	1.57	43.9	3.3
FA-Dry Mix-Shot	6.77	0.72	78.1	2.88
SF-Dry Mix-Shot	5.19	0.44	102.0	1.57
C-Dry Mix-Shot-3%	8.94	1.24	58.8	2.83
FA-Dry Mix-Shot-3%	5.97	0.79	88.5	1.45
SF-Dry Mix-Shot-3%	3.38	0.42	156.3	1.29

fume mixtures. This is inconsistent with the general understanding of the effects of supplementary cementitious materials (SCMs) on permeability—that is, the addition of the SCMs reacts with the $Ca(OH)_2$ in the concrete to reduce the porosity and permeability of the concrete matrix, thus reducing the ECoD of the chemical species.

The silica fume-modified mixtures have the lowest ECoD values. This is due to the fineness and high reactivity of the silica fume with its ability to refine the microstructure of the shotcrete, thus greatly reducing the porosity and permeability, and hence reducing the values of ECoD.

In summary, the ECoD values can be significantly reduced by using SCMs. The reduction of ECoD values achieved with SCMs occurred consistently for cast-in-place concrete, cast shotcrete, shot wet-mix shotcrete, shot wet-mix shotcrete with non-alkali accelerator, as well as with dry-mix shotcrete and dry-mix shotcrete with accelerator. This demonstrates that the use of SCMs is a valuable way of enhancing the durability of shotcrete.

WATER ABSORPTION/DRYING TEST

A water absorption/drying test was conducted using a modified version of ASTM C1585—that is, U.S. Navy Specification UFGS 03 31 29-3, which later became the ASTM C1792 water absorption test. There are two dimensions of test samples: 50 mm (2 in.) thick x 100 mm (4 in.) in diameter and 10 mm (3/8 in.) thick x 100 mm (4 in.) diameter. All samples were kept in the drying shrinkage room and tested for weight loss over 120 days. Weight loss was recorded every 2 to 3 days and plotted as shown in Fig. 8. The mass loss curve for 50 mm (2 in.) samples was used to calculate permeability—that is, K, while the mass loss curve for 10 mm (3/8 in.) samples was used to calculate the moisture isotherm parameters at equilibrium when saturation is reached at 50% relative humidity. The moisture diffusivity model used is based on the drying process for concrete and shotcrete and has both a liquid contribution and vapor contribution that are obtained by separately measuring the mass loss of 50 mm (2 in.) samples and 10 mm (3/8 in.) samples.[10]

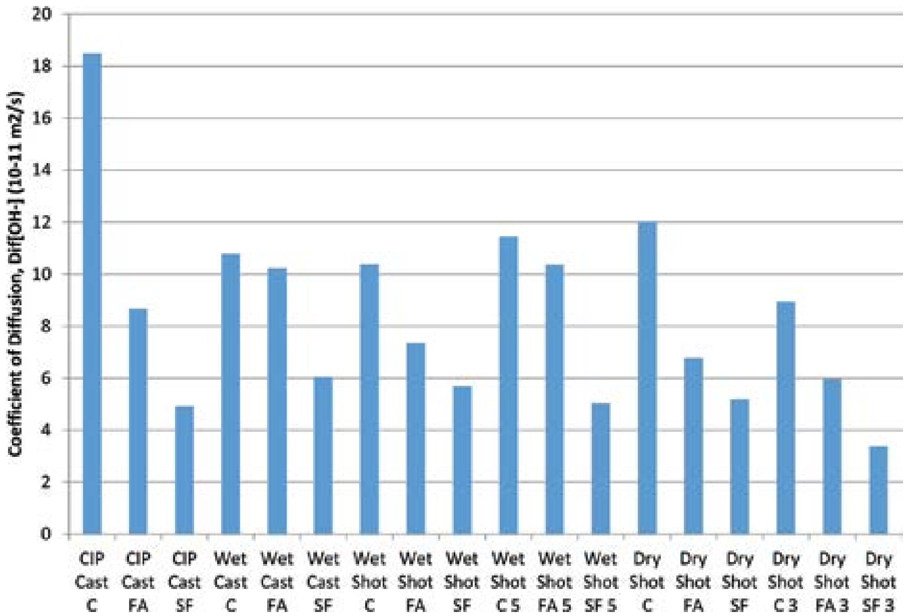

Fig 6—Coefficient of diffusion for all mixtures/processes.

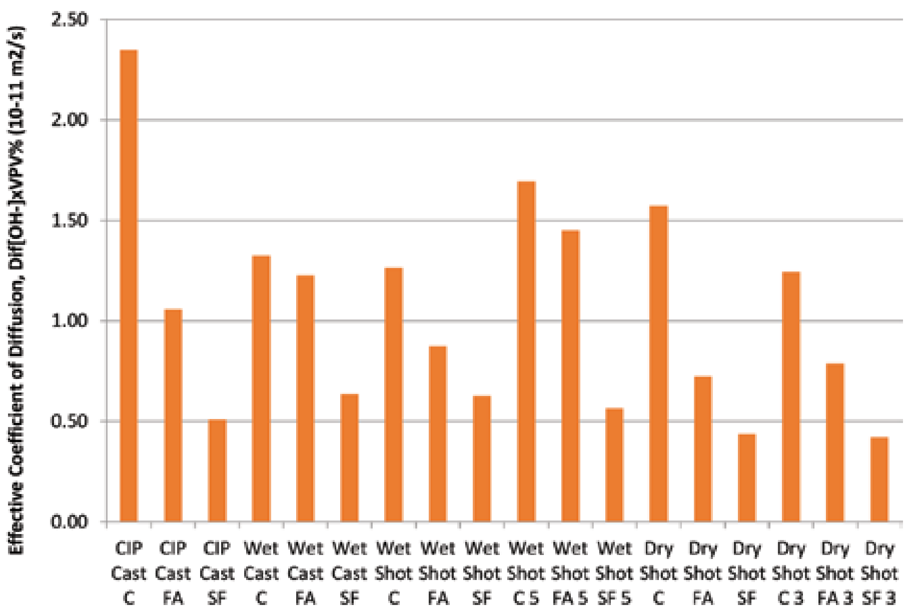

Fig. 7—Effective coefficient of diffusion (OH^-) for all mixtures/processes.

Table 11 and Fig. 9 show the calculated permeability (*K* values) of all mixtures. All test results are in the range of 1 to 10 × 10^{-22} m^2.

Effect of shotcrete process

K values for similar mixtures for cast shotcrete and cast-in-place concrete are very close (Table 11). *K* values for shot wet-mix shotcrete are lower than those for cast shotcrete and cast-in-place concrete. This shows that the shotcrete process, which involves high-velocity impact, results in a less permeable concrete matrix.

K values for dry-mix shotcrete are very low when compared with both cast and shot wet-mix shotcrete and cast-in-place concrete. This is likely due in part to the fact that the water content is not determined by a need to provide a pumpable mixture but is controlled by the water added by the nozzleman at the nozzle to provide a shootable mixture.

Effect of SCMs on permeability

It is a general trend that the permeability (*K* values) decrease from the mixtures with cement to the mixtures with fly ash to the mixtures with silica fume (Table 11 and Fig. 9). This trend is significant with cast-in-place concrete, cast shotcrete, and dry-mix shotcrete, but less significant with shot wet-mix shotcrete and shot wet-mix shotcrete with 5% accelerator in which mixtures with fly ash show similar permeability with a mixture with cement only. Overall, mixtures with silica fume have the lowest K values; this is inconsistent with test results from ECoD and other permeability-related tests.

Effect of accelerator on permeability

Permeability test results (*K* values) for shot wet-mix shotcrete with 5% non-alkali accelerator are slightly higher than for shot wet-mix shotcrete (Table 11 and Fig. 9). This is due to the fact that the accelerator speeds up the initial setting of the cement, thereby creating a more porous matrix with higher permeability. The same effect occurred with the dry-mix shotcrete. The dry-mix shotcrete with 3% accelerator shows a slightly higher K value than that of dry-mix shotcrete without accelerator.

Tortuosity

Tortuosity is a measure of the extent to which a chemical species must deviate from a direct route when diffusing from Point A to Point B through the pore network of concrete.[11] A low diffusion coefficient (and hence a low rate of diffusion) is achieved when the total volume fraction of porosity is low, its constrictivity is low, and its tortuosity is high. The constrictivity is a measure of the extent to which changes in the width of pores along their length hinder the diffusion of chemical species. Tortuosity in this study was defined based on the moisture diffusion model and the ionic migration model.[10]

The higher the number that comes out of the analysis, the higher the tortuosity, which means it is more difficult for a chemical species to deviate from a direct route when diffusing from Point A to Point B through the pore network of concrete. Therefore, a low diffusion rate is related to high tortuosity. To make comparisons simple, the tortuosity values are plotted in Fig. 10.

Tortuosity test results clearly show that mixtures with cement only have the lowest tortuosity, mixtures with fly ash have higher tortuosity, and mixtures with silica fume have the highest tortuosity. This is consistent with the beneficial effects of adding SCMs into concrete and shotcrete—that is, SCMs react with $Ca(OH)_2$ to reduce the porosity of the concrete matrix and therefore reduce the diffusion rate of chemical species.

Tortuosity test results also show that tortuosity ranges between 20 and 120 (unitless) for cast concrete, cast wet-mix shotcrete, shot wet-mix shotcrete, and dry-mix shotcrete. This shows that the extent for chemical ions to deviate from one point to another point in the matrix network is not adversely affected by the shotcrete process. Although there are exceptions, both the wet-mix and dry-mix shotcrete processes typically produce a matrix network that has tortuosity as high as or higher than that of cast-in-place concrete.

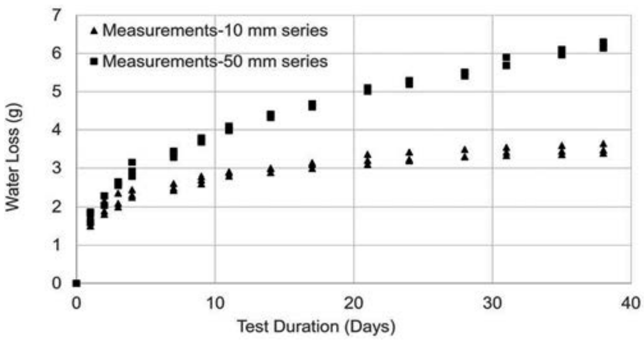

Fig 8—Example of drying test results: liquid contribution and vapor contribution are obtained by measuring mass loss of 50 mm samples and 10 mm samples separately. (Note: 1 g = 0.035 oz; 1 mm = 0.039 mm.)

FURTHER RESEARCH

To further evaluate the properties of shotcrete, it is recommended to conduct research on different mixtures, including mixtures with ground-granulated blast-furnace slag and limestone.

CONCLUSIONS

Test results for BA and VPV correlate well with the CoD. BA and VPV results also correlate well with parameters such as permeability (K values) and tortuosity. More specifically:

1. All transport properties show, consistently, that the porosity decreases from mixtures with cement only, to fly ash, to silica fume. This is consistent with the general understanding of the effect of supplementary cementitious materials, which involves

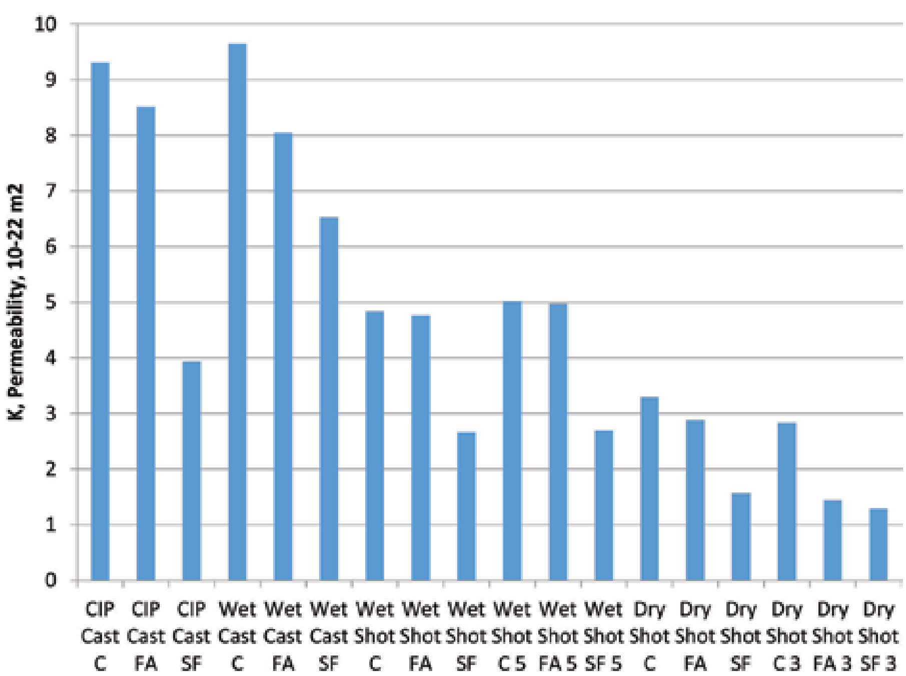

Fig. 9—Permeability from water absorption test.

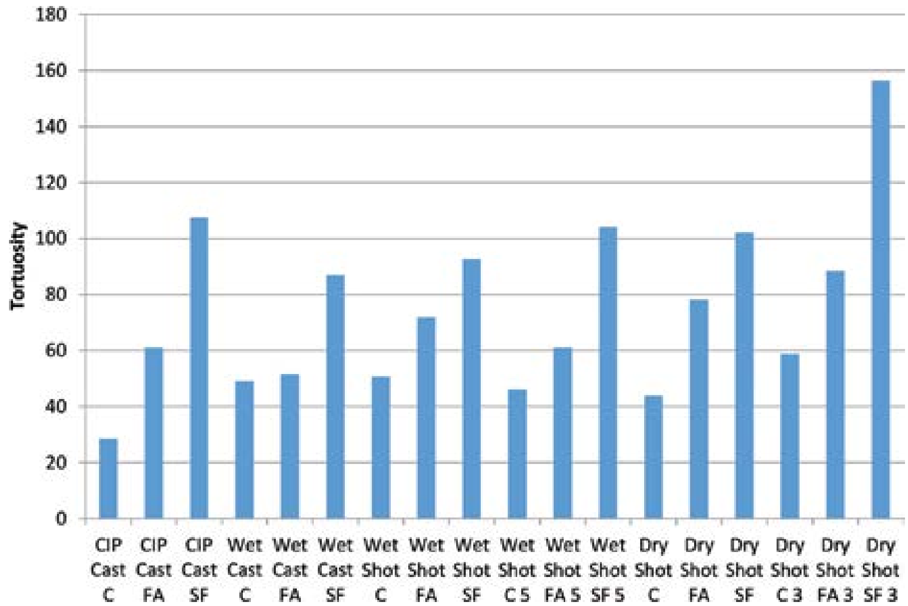

Fig. 10—Tortuosity for all mixtures.

pozzolanic reactions that refine the pore structure of the matrix, thus reducing permeability and enhancing durability.

2. All transport properties show that the shotcrete process, including mixtures of shot wet-mix shotcrete with and without accelerator, and dry-mix shotcrete with and without accelerator have transport properties that are close to or even better than that of cast shotcrete and cast-in-place concrete.

3. All of these improved transport properties, including reduced boiled absorption and volume of permeable voids, reduced rapid chloride penetration resistance, reduced coefficient of diffusion, increased tortuosity, and reduced permeability lead to reduced porosity for the samples from the shotcrete process. The lower porosity leads to a lower coefficient of diffusion of chloride, which means that it will take a longer time for Cl^- to diffuse to the depth of the reinforcement. Therefore, the matrix is more protective and results in a more durable structure.

4. BA and VPV results correlate well with the CoDs and permeability. Considering the fact that it takes a complex array of tests values to get values for CoDs and permeability, it might be a better choice to use BA and VPV as durability indicators for shotcrete quality control proposes.

In summary, the results of this extensive comparative study of the basic and transport properties of wet-mix and dry-mix shotcretes, compared to cast concrete, demonstrates that properly applied shotcrete can provide equivalent or superior durability performance to cast-in-place concrete for like mixtures.

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GUNNING RIG
STANDALONE SOLUTION
MEETS MOBILE REVOLUTION.

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Nondestructive Approach for Shotcrete Lining Strength Monitoring

By Vishwajeet Ahuja and Benoit Jones

Shotcrete lining forms an integral part of conventional tunneling and is widely applied for underground excavations. Early strength gain of the shotcrete is a crucial aspect for ground support and safety of operatives. Strength requirements are dependent on various factors such as lining thickness, ground type, excavation size, and tunnel depth. The early strength gain is typically monitored using destructive tests, such as needle penetration, stud driving or coring samples for uniaxial compressive strength testing in the laboratory. Being destructive, these tests cannot be directly performed onto the lining without causing damage that must be repaired, which is a particular problem for permanent linings. For this reason and to avoid the need for operatives to work near exposed ground and/or fresh shotcrete, these destructive tests are often performed on panels, which are sprayed at the same time as the tunnel lining. All current testing methods are also very local, testing only a small part of the lining or a panel, which may not be representative because the temperature history could be significantly different. Therefore, these tests do not provide an accurate or complete picture of the lining strength gain. New testing methods that are non-destructive and can scan the whole lining remotely would be extremely desirable. This paper describes a new method, using thermal imaging techniques, that achieves these aims. It also discusses the real-time on-site application of the method, providing insight into the experience gained and conclusions derived.

Shotcrete

Shotcrete used for tunnel linings requires immediate strength development. The strength development is a direct result of the hydration reaction of cementitious materials present in it. A progressive sequence of the hydration reaction changes it from a solid suspension (typically referred to as fresh concrete) to a solid skeleton with a porous network and thereafter into a solid with predominantly discontinuous pores (Byfors 1980). In the case of shotcrete, early strength is needed to support the self-weight and then continuing early age strength gain is required to begin to support ground loads. These strength requirements, along with other workability needs, are met by careful concrete mixture design, the use of admixtures, such as accelerator and superplasticizer (BS EN 934-5 2007), and supplementary cementitious materials, such as silica fume.

Strength Development

The strength gain in concrete is known to be linearly proportional to the amount of cement hydration reactions that have taken place (Byfors 1980) and can be represented as shown in Fig. 1. If this relationship is known for a given concrete mixture, then concrete compressive strength (f_c) may be estimated if degree of hydration (ξ) is known.

Like many other chemical reactions, the rate of hydration ($d\xi/dt$) for a given concrete mixture is dependent on temperature as well as the degree of hydration, as shown in Fig. 2. Thus, it is widely accepted that the degree of hydration and, in turn, strength development is dependent on its temperature history (Byfors 1980). Various maturity functions have been developed, such as those presented in ASTM C1074 (2011), which can be used to estimate strength development from time-temperature histories. Out of the various available functions, the Arrhenius equation-based maturity function is the most widely accepted. This relationship between rate of hydration, temperature and degree of hydration was first demonstrated to be appropriate for concrete in works of Freiesleben Hansen and Pedersen (1977) and is formulated as shown in Equation (1), where $\tilde{A}(\xi)$ is normalised affinity (s^{-1}), E_a is activation energy (J.mol^{-1}), R is the ideal gas constant (= 8.314 J.mol^{-1}.K^{-1}), and T is absolute temperature (K). This function is useful while the activation energy is not varying. For cement hydration, it is applicable while the reaction is propelled through exothermic heat and is not diffusion based. This means this relationship is best applied in the ranges of $0.05 < \xi < 0.5$ (Kada-Benameur et al. 2000). The activation energy and normalised affinity are dependent on the cement type, the chemical admixtures and the supplementary cementitious materials. Therefore, they must be determined for each shotcrete mixture used on site.

$$\frac{d\xi}{dt} = \tilde{A}(\xi)\exp\left(-\frac{E_a}{RT}\right) \quad (1)$$

Early Age Strength Determination for Shotcrete

Currently accepted early age strength tests include needle penetrometer and stud driving and are conducted on site as described in BS EN 14488-2 (2006). At very early ages, these tests cannot be directly performed on the lining due to the danger of freshly sprayed shotcrete falling down. For this reason, shotcrete panels are used for these tests and are sprayed immediately after the lining has been sprayed. Assuming that the shotcrete for both the lining and the panels is placed in identical conditions, the lining strength development may be assessed. This indirect assessment approach, though widely accepted, does not present a complete picture since the panel and the lining may have a very different temperature history due to the different size, time of spraying and environmental conditions.

New Testing Approach

The proposed approach is based on developing temperature histories for the shotcrete lining using on-site thermal imaging. These histories can be applied to the maturity function, as shown in Equation (1), and a stepwise calculation can help determine degree of hydration and, in turn, the

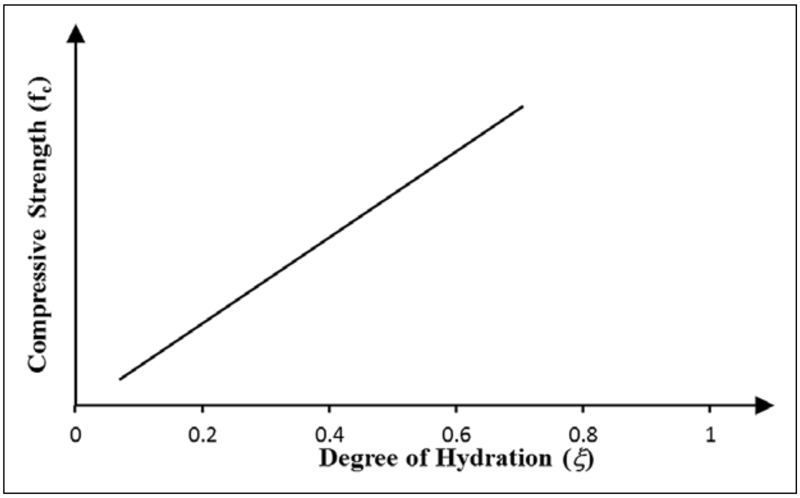

Fig. 1: Representation of linear relationship between concrete compressive strength and degree of hydration

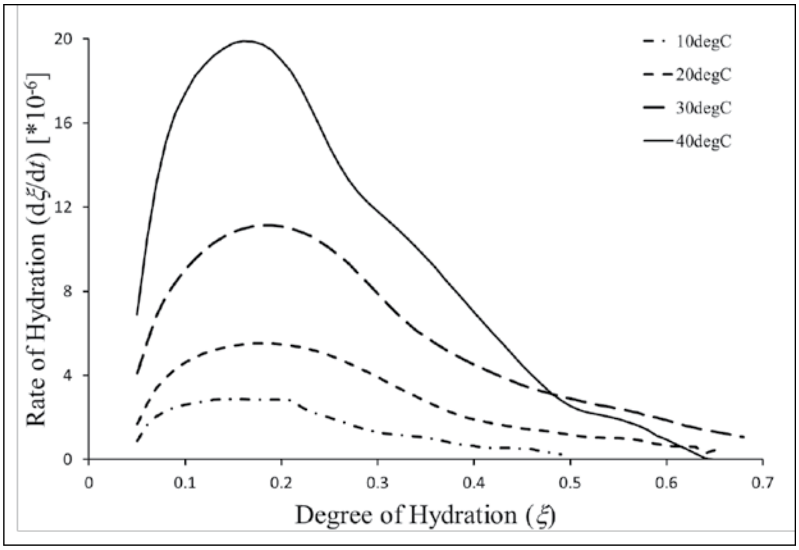

Fig. 2: Representation of change in rate of hydration versus degree of hydration development

compressive strength development. Currently, this patented approach is under further development at the University of Warwick and is being referred to as Strength Monitoring Using Thermal Imaging™ (SMUTI). Jones and Li (2013) and Jones et al. (2014) discuss various aspects of this approach in detail. Before using Equation (1), input parameters, such as $\tilde{A}(\xi)$ and E_a, are needed. Since these parameters are unique to a concrete mixture, they need to be re-evaluated if any major change is made, through lab testing such as isothermal calorimetry. Similarly, the linear relationship between f_c and ξ is also unique to a given mixture and must be determined independently for each mixture type. Due to the method of application, it is not realistic to conduct any strength testing inside a lab and so this requires real time field testing.

Field Application

Field trials were undertaken during primary shotcrete lining works at Whitechapel station, being constructed by BBMV, a joint venture of Balfour Beatty, BeMo Tunnelling, Morgan Sindall and Vinci Construction. The scope of field application was limited to collecting real-time thermomechanical data.

Mechanical Testing

Due to the importance of early age strength development, stringent testing criteria requiring in-situ testing, such as needle penetrometer and stud driving (BS EN 14488-2 2006), were specified. These tests were conducted separately on the panels sprayed immediately after the lining spray was finished. Table 1 describes the typical details of the testing methods used during the field testing.

Thermal Imaging

The temperature variations in the early age of concrete, mainly caused by hydrating portland cement, can be measured by thermal imaging using a camera with the capability of detecting infrared (IR) radiations. A FLIR E60bx camera was used. Figures 3(a) and (b) show digital and thermal images, respectively, of a shotcrete lining section demonstrating how thermal imaging can measure the temperature remotely. For the shotcrete panels only the top surface was imaged whereas for the lining, surface areas of key locations such as crown, shoulders, and axis level are monitored.

Site Testing

The following testing procedure was adopted for the field trials in order to validate the method (this will not be the procedure when SMUTI is used for systematic monitoring):

1. Select appropriate lining section;
2. Prepare five shotcrete panels, corresponding to lining section, for mechanical testing and thermal imaging purposes; and
3. Thermal imaging of lining section.

The shotcrete mixture design is shown in Table 2.

Results and Discussion

The following section discusses results corresponding to testing and thermal imaging of a

Table 1: Tests Performed on Shotcrete Panels

Stage	Test Type	Strength Range (equivalent cylinder compressive strength)	Time and Frequency	Typical Test Apparatus
1	Penetration needle (panels only)	14.5 to 145 psi (0.1 to 1.0 MPa)	Up to 1 hour Minutes – 15, 30, 60	Meyco Penetrometer
2	Stud driving (panels only)	290 to 2320 psi (2.0 to 16.0 MPa)	Up to 24 hours Hours – 3, 6, 12, 24	Hilti DX 450-SCT

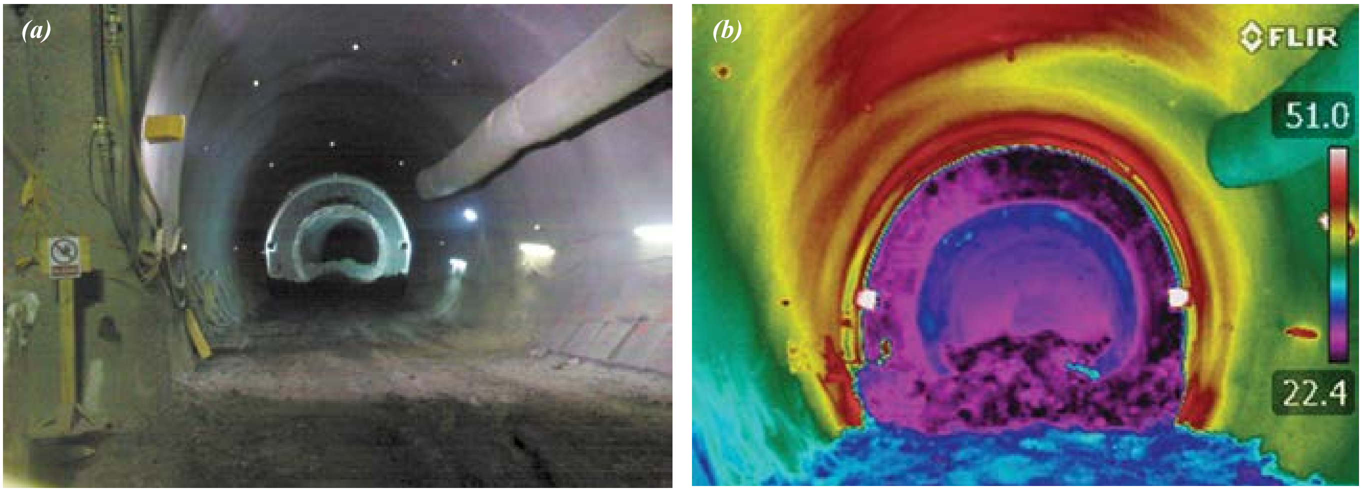

Fig. 3: (a) Digital and (b) thermal images taken during the early age of shotcrete lining demonstrating the ability of thermal imaging to measure temperatures remotely

Table 2: Primary Shotcrete Mixture Design P1

Content	Type	Quantity, kg/m³ (lb/yd³)	Ratio/dosage*
Cement	CEM I 52.5 N	420 (708)	—
Water	—	173 (292)	0.41
Aggregate	Limestone (0/4)	590 (995)	—
Aggregate	Marine Sand (0/4)	590 (9950	—
Aggregate	Limestone (2/6)	505 (851)	—
Microsilica slurry	EMSAC 500 S	52 (88)	12.38%
Retarder	Pantarhol 85 (VZ)	6 (10)	1.43%
Superplasticizer	Pantarhit T100CR (FM)	4.8 (8)	1.14%
Accelerator	Gecederal F 2000 HP	Added at spray	5.50% (averaged)
Steel fibers	Steel HE 55/35	35 (59)	—

*Dosage in percentage (%) of cement weight basis

lining section in the Eastbound Rail Tunnel – West (EBRT-W) pilot tunnel.

EBRT-W Pilot Tunnel Primary Shotcrete Lining Section

Five shotcrete panels were tested using a needle penetrometer and stud-driving as described in Table 1. Concurrently, thermal imaging was performed. Figure 4 shows real time strength (dashed lines) and temperature (dotted lines) histories. The strengths of up to 14.5 psi (1.0 MPa) were determined using the needle penetrometer while the rest were determined using standard-method green cartridge stud-driving using Hilti DX 450 SCT as described in its operating instructions (Hilti, 2009).

It can be seen that the panels have achieved strengths of around 2180 psi (15.0 MPa) at the age of 12 hours and have approached the upper limit of the stud-driving test. Therefore, further mechanical testing was not useful. In the case of the temperature histories, a typical temperature variation pattern was observed with initial lowering of temperature, approaching 84°F (29°C), during the first hour after spraying and increasing thereafter, peaking at more than 88°F

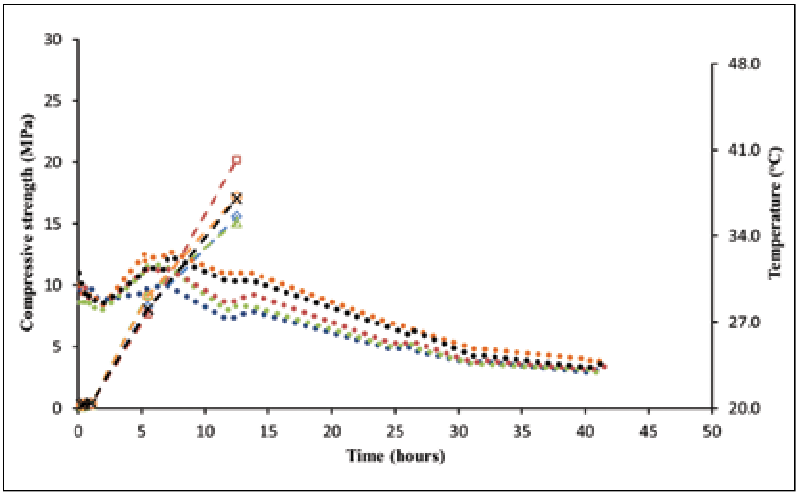

Fig. 4: Shotcrete panel strength and temperature histories for EBRT-W section

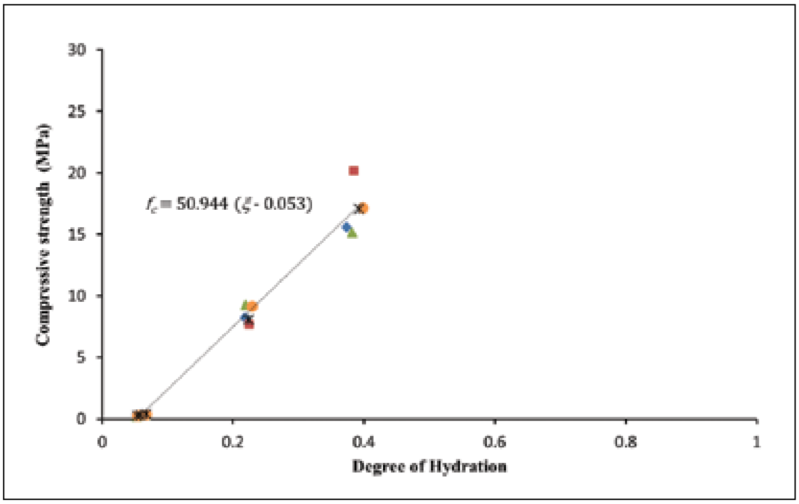

Fig. 5: f_c-ξ relationship from shotcrete panels corresponding to EBRT-W lining section

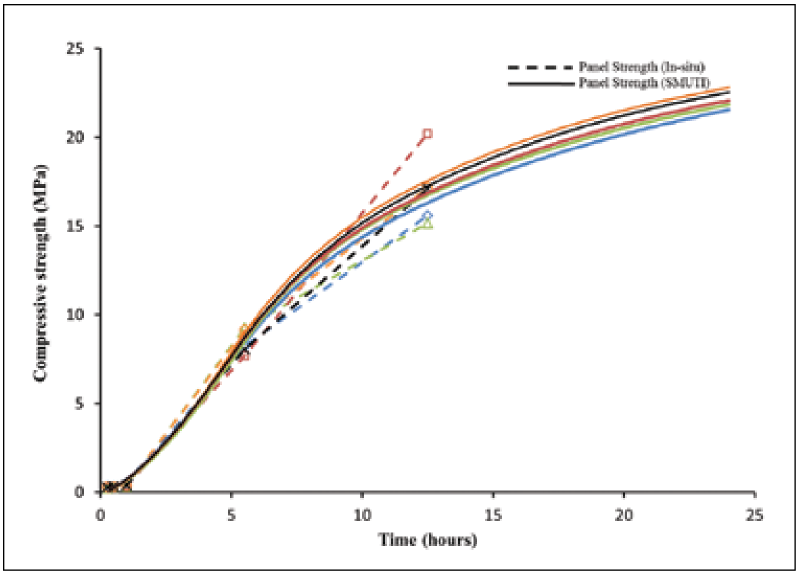

Fig. 6: Panel strengths—in-situ measurements and SMUTI estimation

(31°C). Afterwards, a consistent decrease was observed, stabilising at around 73°F (23°C) at the age of 40 hours.

The panel temperature histories in conjunction with Equation (1) were used to estimate the degree of hydration and are correlated to the strength histories. The input parameters for the rate of hydration equation were determined by isothermal calorimetric testing using an I-Cal 4000, manufactured by Calmetrix. The detailed results will be published in later publications. In the analysis, it was assumed that the shotcrete had achieved initial degree of hydration of 0.05 by the end of spray and started gaining strength immediately.

Figure 5 shows the f_c-ξ relationship deduced from the panel strength and temperature histories.

Using the f_c-ξ relationship shown in Fig. 5, the panel strength development was obtained from the calculated degree of hydration. Figure 6 provides a plot comparing strengths measured by in-situ tests and the strengths calculated using SMUTI. The average error between the in-situ and calculated strengths was approximately 7% while the maximum error was less than 17%. This may be due to the variability of the in-situ strength tests rather than inaccuracy of the SMUTI calculation. The maximum error occurred for the panel achieving the strength of 2900 psi (20 MPa). Since this strength was measured beyond the limit of the stud-driving range, it may not be reliable.

Next, the lining hydration was calculated using its temperature history. Figure 7 and Fig. 8 are comparative plots showing temperature histories and calculated degree of hydration, respectively, for the panels and lining section. It can be observed that as the temperature histories of the panels and the lining section were very different, so were the hydration developments. Further, the lining strength development was estimated using the f_c-ξ relationship and calculated degree of hydration shown in Fig. 5 and Fig. 8, respectively. These estimates are shown in Fig. 9, which is a comparative plot for strength histories of the five panels and three key locations of the lining (calculated using SMUTI).

Discussion

Figure 7 shows the lining surfaces were warmer than the panel surfaces, which means the lining experienced higher rate of hydration in its early age than the panels. Thus, the degree of hydration of the lining is always greater than that of the panels, in this case. This higher degree of hydration is shown in Fig. 8. It can be observed that the panels have an average degree of hydration of 0.12, 0.24, 0.38 and 0.49 at the ages of 3 hours, 6 hours, 12 hours, and 24 hours, respectively. On the other hand, the lining areas achieve an average degree of hydration of 0.15, 0.29, 0.44, and 0.61 at the ages of 3 hours, 6 hours, 12 hours, and 24 hours, respectively. The lining also experienced faster strength gain as while the panels had an average compressive strength of 16.6 MPa at 12 hours, the average lining strength was 2860 psi (19.7 MPa).

Additionally, with an average degree of hydration of 0.61 at 24 hours, the lining had achieved an average compressive strength of 4120 psi (28.4 MPa). It must be pointed out that from the f_c-ξ relationship shown in Fig. 5, it could be asserted that the shotcrete can achieve an average long-term strength of more than 6960 psi (48 MPa). This relationship was reasonably verified as the mean 90-day strength of the lining cores was determined to be 6860 psi (47.3 MPa).

Conclusions and Future Works

From the results shown in the previous section, the following can be concluded:

1. The Arrhenius equation-based temperature-sensitive maturity function is a useful tool to estimate shotcrete strength through the remote and nondestructive approach adopted in SMUTI.
2. With an average variation of 7% between the measured and calculated panel strengths, SMUTI appears to provide useful estimates that are in close agreement with the in-situ tests.
3. The f_c-ξ relationship deduced from the panel testing was reasonably verified by available 90-day lining core strengths averaging to 6860 psi (47.3 MPa).

While a promising step has been taken, further laboratory testing and on-site application is the most logical next step. This will improve understanding of degree of hydration development of shotcrete, especially when various admixtures, such as accelerator and superplasticizer, are key participants in its application. It will also enable the reliability of the method to be assessed.

SMUTI has the potential to provide the strength gain of the whole shotcrete lining (as against local tests on a panel) from a remote location. This is a step-change in safety and quality control of shotcrete tunneling.

As a final remark, the authors envisage that integration of the thermal imaging capability into tunnel setting out and convergence monitoring survey systems will further simplify the workflow

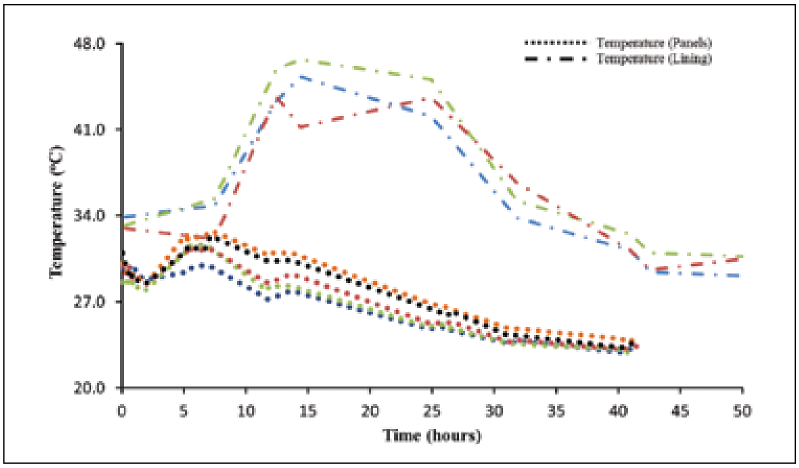

Fig. 7: Temperature histories for tested panels and corresponding EBRT-W lining section

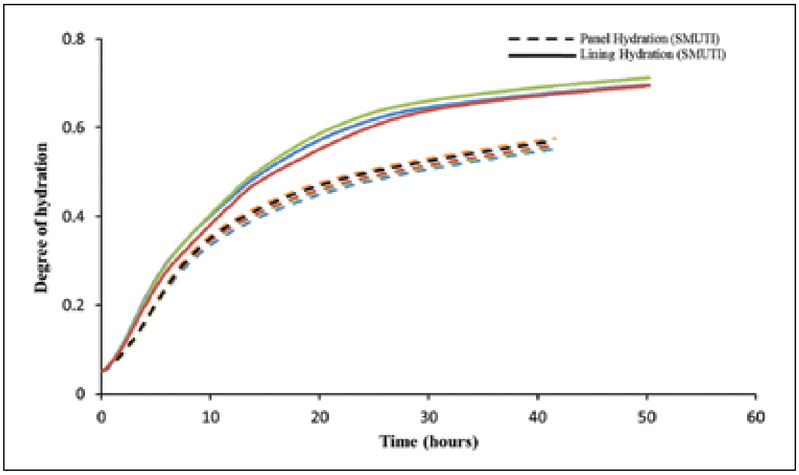

Fig. 8: Degree of hydration determination using temperature histories of EBRT-W section

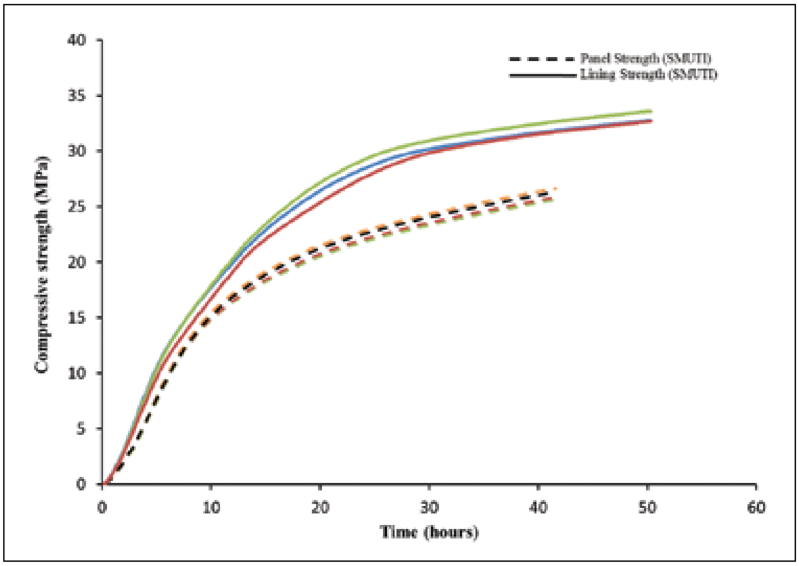

Fig. 9: Comparative plot showing in-situ panel strength and estimated strength for EBRT-W lining section

and provide an integrated and powerful tool for the engineer to make informed decisions about the safety of the tunnel.

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***Benoit Jones** has worked for 15 years in the tunneling industry for Mott MacDonald, Morgan Sindall, OTB Engineering, and until recently, the University of Warwick, where he retains a position as an Honorary Fellow. He has worked on major projects such as Heathrow Terminal 5 tunnels, High Speed 1, Crossrail, King's Cross Underground Station Redevelopment, and Tottenham Court Road Station Upgrade. In 2007, he received his engineering doctorate for research on stress measurement in sprayed concrete linings and numerical modeling of tunnel junctions. He has won the ICE's Telford Premium Award for a paper on the interpretation of tunnel monitoring, has twice given the prestigious ICE Geotechnical Engineering Lecture, and has written a large number of popular articles on advances in tunneling. He is the inventor of Strength Monitoring Using Thermal Imaging (SMUTI) and is Managing Director of Inbye Engineering, a spin-out company of the University of Warwick set up to enable the adoption of SMUTI by the tunneling industry. The patent and trademark for SMUTI are owned by Inbye Engineering.*

Convert Peanuts into Gold with the Right Pump or Gunite Machine

By Jim Farrell

A concrete pump and a gunite machine are work tools that can help a contractor turn a nickel's worth of concrete material into a dime, a quarter, or even a dollar using the wet- or dry-mix shotcrete process.

The odds of being successful are greatly enhanced with the selection of the correct tool and the correct material, combined with the knowledge and experience to properly use both. There are several types of pumps and gunite machines that can be used for the shotcrete process. Shotcrete is defined by ACI CT-13, "Concrete Terminology," as "concrete placed by a high-velocity pneumatic projection from a nozzle." Concrete material can also be air-placed using a lower velocity of compressed air combined with a smaller orifice nozzle. This technique is not recognized as shotcrete by the American Concrete Institute (ACI) or the American Shotcrete Association (ASA). In Europe, this low-velocity process has been referred to as "spray-up"; however, in the United States, spray-up is used in many concrete applications.

The four types of pumps for the wet-mix shotcrete process include:

- Hydraulic swing tube;
- Hydraulic peristaltic or squeeze;
- Rotor stator; and
- Hydraulic ball valve or ball seat pumps.

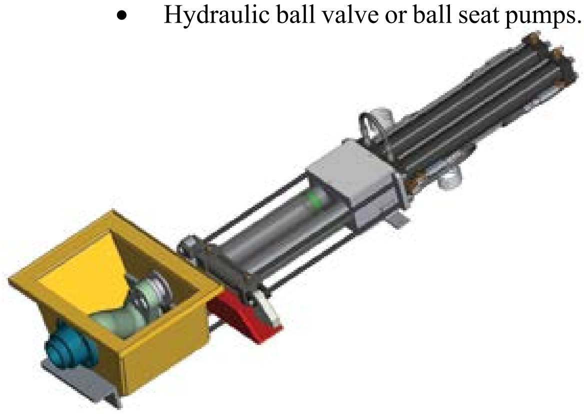


Fig. 1: The swing tube pump is a combination of two hydraulic cylinders that act as differential cylinders that are connected to and shift two material-pumping cylinders that come in direct contact with the material

The most popular type of gunite machine for the dry-mix process is a rotary gun.

Hydraulic Swing Tube Pump

The swing tube pump (refer to Fig. 1) is a combination of two hydraulic cylinders that act as differential cylinders that are connected to and shift two material-pumping cylinders that come in direct contact with the material. A single "S" tube shifts from one material cylinder to the other, activated by a hydraulic cylinder, so that each cylinder that is full of material can be discharged through the "S" tube and into a delivery line that is connected to the outlet of the pump. Each differential cylinder includes a proximity switch that sends an electrical signal to the hydraulic cylinder, which shifts the "S" tube. This pumping process is controlled by a sealed electrical control box and is synchronized.

Swing tube pumps recommended for shotcrete come in sizes with 3 and 4 in. (75 and 100 mm) outlets. The 3 in. (75 mm) pump would be recommended for jobs from 2 to 8 yd^3/h (1.5 to 6 m^3/h), and the 4 in. (100 mm) pump for jobs that require 9 to 20 yd^3/h (7 to 15 m^3/h). Swing tube pumps with outlets larger than 4 in. (100 mm) will result in significant surging at the nozzle because the speed of the pump must be reduced so that the nozzleman will not be overwhelmed with material, which is unacceptable.

The output or material pressure at pump discharge from a swing tube pump can vary from 750 to 2100 psi (5.2 to 14 MPa). The size of the delivery line is typically reduced down to 2 in. (50 mm) or even 1.5 in. (38 mm) at the nozzle. Trying to handle a delivery line in excess of 2 in. (50 mm) is almost impossible for a nozzleman because of the weight of the hose and nozzle. The higher pumping pressure capabilities of the pump typically results in the ability of the pump to convey harsh, lower-slump materials and to pump longer distances vertically and horizontally. The swing-out receiving hopper is very helpful in cleaning and servicing the pump.

Advantages of a swing tube pump:
- Highest pumping pressure for harsh materials and long distance pumping;
- Pump will run in reverse for safety in case of hose plug; and
- Infinitely variable pumping speed for high and low output.

Disadvantages of a swing tube pump:
- Higher cost to purchase; and
- Requires a trained and experienced operator.

Squeeze Tube or Peristaltic Pumps

A squeeze pump (Fig. 2) operates on the same principal as filling a straw with a milkshake and using your thumb and index finger to squeeze the milkshake out of the straw. Two squeeze rollers are mounted on a roller assembly inside a drum. Pairs of "following rollers" are mounted between the two squeeze rollers to keep the pumping tube in alignment. A rubber pumping tube is mounted on the inside circumference of the drum housing. A heavy-duty shaft is connected to the assembly that holds the squeeze rollers and follower rollers in place, and this shaft is held in place by the pump housing. A heavy-duty gear box powered by a hydraulic motor turns the rotor shaft, which turns the squeeze roller assembly. As the rollers turn and make contact with the tube, the rollers squeeze the tube closed, which causes the material to fill the tube on the suction side and discharge from the tube on the discharge side. The speed the rollers turn is directly related to the pump output, which is infinitely variable from 0 to 30 rpm. The pump can be reversed to pump in either direction. The pump also can be run dry without damage to the pump.

Squeeze pumps come in three sizes: 2 x 22 in. (50 x 560 mm) diameter with an output of 0 to 5 yd^3/h (0 to 3.8 m^3/h); 3 x 28 in. (75 x 710 mm) diameter with an output of 0 to 12 yd^3/h (0 to 9 m^3/h); and 3 x 36 in. (75 x 910 mm) diameter with an output of 0 to 25 yd^3/h (0 to 19 m^3/h). A roller-driven pump, where the squeeze rollers are under power rather than the rotor being under power, is also available in a 3 x 36 in. (75 x 910 mm) pump with 0 to 25 yd^3/h (0 to 19 m^3/h) output.

Squeeze pumps provide the lowest output pressure when compared to swing tube, rotor stator, or ball seat pumps. The maximum output pressure at pump discharge is 500 psi (3.4 MPa). As a result, squeeze pumps would not be recommended for pumping larger than 0.5 in. (13 mm) aggregate, exceeding 50 ft (15 m) vertically and 250 ft (76 m) horizontally. The slump of the material should not be less than 3 in. (75 mm). Squeeze pumps are preferred for cellular concrete because the lower pressure does not damage the bubbles in this material. Squeeze pumps have also been used successfully to pump shotcrete with steel and synthetic fibers.

Fig. 2: A squeeze pump operates on the same principal as filling a straw with a milkshake and using your thumb and index finger to squeeze the milkshake out of the straw

The lower pumping pressure makes a squeeze pump the safest to operate and, in many cases, customers with no concrete pumping experience can safely operate a squeeze pump.

The squeeze pump's wear part is the rubber pumping tube, and the tube can be replaced in about 30 minutes. The pumping tube should be lubricated on the underside where the squeeze rollers make contact with the tube to reduce friction and improve the life of the tube. The squeeze pump is the only concrete pump that is available as a skidsteer work tool. The squeeze pump work tool is the least expensive concrete pump on the market.

Advantages of the squeeze pump:
- Lowest cost to purchase and maintain;
- Low pumping pressure friendly to cellular concrete and low-velocity spray-up as well as standard shotcrete;
- No nozzle blowback, which is much less stressful to a nozzleman;
- Most simple and safe to operate and available as skidsteer work tool; and
- Pumps in both directions without priming.

Disadvantages of the squeeze pump:
- Limited to 50 ft (15 m) vertical, 250 ft (76 m) horizontal, and over 3 in. (75 mm) slump material.

Hydraulic Ball Valve Pump

The hydraulic ball valve (also known as ball seat) (refer to Fig. 3) is similar to the swing tube or "S" tube pump in that both use two hydraulic cylinders as differential cylinders to load and unload the material inside two 24 in. (610 mm) long by 4 in. (100 mm) diameter pumping cylinders. The hydraulic cylinders are attached to the pumping cylinders on end and the pumping cylinders are attached with a heavy-duty clamp to a pump manifold. The manifold is bolted to the material hopper. The pump manifold includes four balls and four seats. Each hydraulic cylinder has a proximity switch that leads to an electrical control box to automatically shift the cylinder to load and unload the pumping tube. When the pump is loading with material from the material hopper, the suction causes the ball to move to a stop to allow material to be sucked inside the pumping tube. When the hydraulic cylinder reverses to unload the pumping tube, the pressure of the material moves the ball into the seat and the material in the pumping cylinder is pushed up and out of the manifold, which serves as a housing for the balls and seats. The discharge outlet is reduced from 5 in. (125 mm) to 4 in. (100 mm) to 3 in. (75 mm) at the pump outlet, where the 3 in. (75 mm) delivery line is attached.

The manifold is attached to the pumping cylinders with heavy-duty clamps. The manifold is bolted to the receiving hopper on the opposite side of the manifold where the material loads into the manifold from the receiving hopper. When the clamps are removed from the pumping cylinders, the manifold becomes a part of the receiving hopper assembly. A hydraulic cylinder attached to the receiving hopper moves this entire assembly

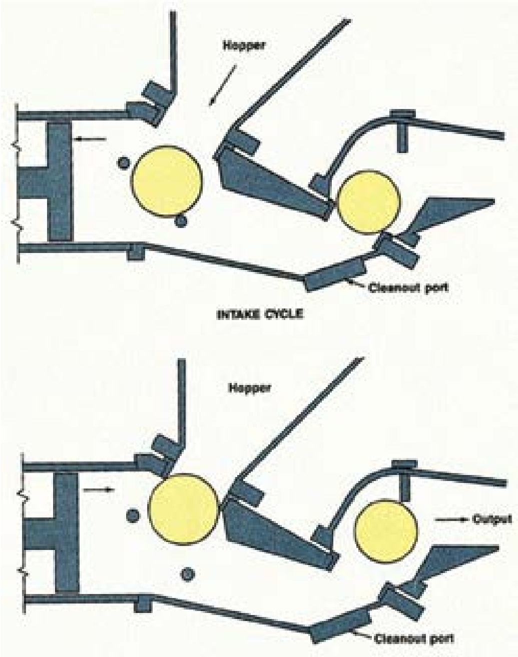


Fig. 3: The hydraulic ball valve, or ball seat, uses two hydraulic cylinders as differential cylinders to load and unload the material inside two 24 in. long by 4 in. diameter pumping cylinders

up and away from the pumping cylinders for easy access for cleaning and maintenance.

The ball valve pump delivers up to 1100 psi (7.6 MPa) pumping pressure; however, it is limited to 3/8 in. (10 mm) aggregate and a slump that is not less than 3 in. (75 mm). The ball valve pump will not run in reverse; therefore, extreme caution must be taken to relieve the pressure on the delivery line should the line plug. There is a small ball valve on the discharge pipe of the manifold to manually relieve this pressure. Materials such as gypsum flooring materials, which are very plastic in nature, tend to build up over time in the receiving hopper and manifold. Shotcrete materials do not have these same characteristics and will work well provided the aggregate does not exceed 3/8 in. (10 mm) in diameter.

Advantages of a ball seat pump:

- Lower cost to purchase than swing tube pump; and
- Simple and quick to maintain.

Disadvantages of ball seat pump:

- Cannot run in reverse so caution must be taken with hose plugs; and
- Oversized aggregate will not pass between ball and seat.

Rotor Stator, Screw, Progressive Cavity, or Worm Pump

Rotor stator pumps (refer to Fig. 4) are available in many sizes. The eccentric screw pump or rotor stator is a progressive cavity pump. The design of the progressive cavity pump consists of a single-threaded screw or rotor, turning inside a double-threaded stator. The rotor seals tightly against the rubber stator during rotation, forming a set of fixed-size cavities in between. The cavities move when the rotor is rotated but their shape or volume does not change. As the rotor rotates inside the stator, cavities form at the suction end of the stator, with one cavity closing as the other opens. The cavities progress axially from one end of the stator to the other as the rotor turns, moving mortar through the pump. New spaces/cavities are created when the rotor is turning that move axial from the suction side toward the pressure side. The suction side and the pressure side are always sealed off, and a continuous flow of material is created. The material exits the pump and is conveyed hydraulically, under pressure through a rubber hose or steel pipe, to the point of placement.

The benefit of a rotor stator pump is there is no pulsation when material is continuously fed. Most applications for rotor stator pumps use the low-velocity or spray-up method. A rotor stator pump can generate up to 600 psi (4.1 MPa) of pumping pressure. These pumps are commonly used for pumping highly flowable materials, but they can tolerate small aggregate. Too sharp of aggregate may result in premature wear of the stator.

Advantages of rotor stator pump:

- No pulsation;
- Low cost to purchase; and
- Good mid-range pumping pressure.

Disadvantages of rotor stator pump:

- Aggregate will affect rotor stator wear; and
- Rotor stator costs.

Rotary Gunite Machine

A rotary gunite machine (refer to Fig. 5) is recommended for the dry-mix shotcrete process. In the rotary barrel-type gun, a rotor, available with rotor openings of various shapes and sizes, is sandwiched between a top plate and a bottom plate that has been machined flat. Rubber wear pads are mounted to the underside of the top plate and the top of the bottom plate. Case-hardened metal wear plates are mounted to the top and bottom of the rotor. A single, self-leveling bolt tightens the top plate to the bottom plate and seals the rotor between the two rubber wear pads to guarantee a seal. A high volume of compressed air is connected to an inlet on the top plate and this compressed air is used to convey the material from the pockets of the rotor that are full of material through a 90-degree fitting attached to the underside of the bottom plate and into the delivery line. Additional compressed air is connected to the delivery line. The speed the rotor turns is directly related to the amount of material that will pass through the rotor section. A nozzle with a water ring is attached to the end of the delivery line to hydrate the material. A water valve adjusted by the nozzleman provides control of the level of water injected into the dry-mix materials flowing through the nozzle. Standard delivery lines vary from 2.5 in. (62 mm) down to 1.25 in. (30 mm) in diameter. Acceptable hydration has occurred when the material has been hydrated to 10 to 12% by weight of the concrete materials.

The power supply is available with an electric motor, air motor, gas or diesel engine, and hydraulics. The rotary gun is also available as a skidsteer work tool. The dry-mix shotcrete process means that the material remains "dry" until it is properly hydrated at the nozzle. Best results occur if the material has 3 to 5% moisture when loaded into the hopper of the gunite machine. To accomplish this, preparation should be made to pre-dampen the material, if needed.

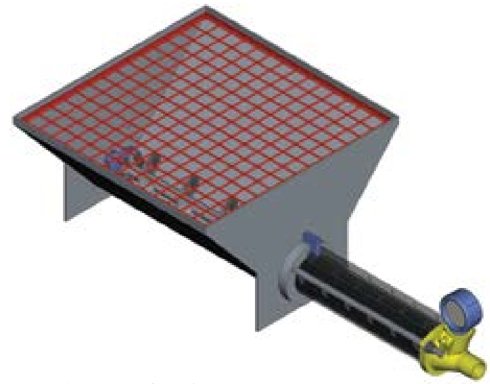


Fig. 4: The benefit of a rotor stator pump, such as this one, is there is no pulsation when material is continuously fed

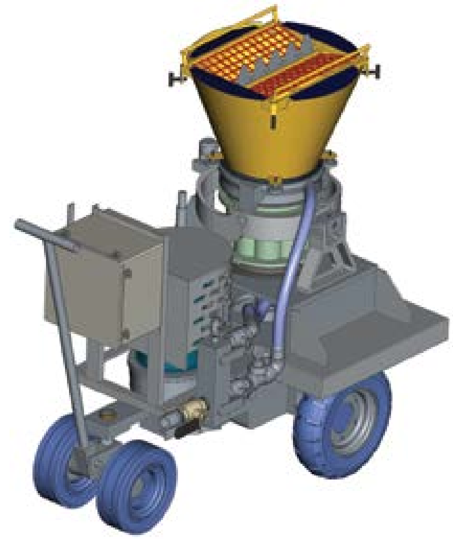


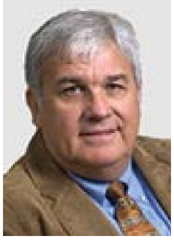
Fig. 5: A concrete pump and a gunite machine, such as the one pictured, are work tools that can help a contractor turn a nickel's worth of concrete material into a dime, a quarter, or even a dollar using the wet- or dry-shotcrete process

Advantages of rotary gun for dry-mix shotcrete process:

- Precise control of material flow for low or high output;
- Easy stop and start with no cleanup; and
- More forgiving to variations in aggregate size.

Disadvantage of rotary gun for dry shotcrete:

- Generates more dust and waste, particularly if not properly hydrated; and
- Requires more compressed air to convey material.



***Jim Farrell**, CEO of Blastcrete Equipment Company, has nearly 40 years of experience in specialty refractory products, including shotcrete and gunite equipment. He heads the family-owned company based in Anniston, AL, and serves customers around the world.*

Confined Space—In the Shotcrete World

By Mike Munyon and Frank E. Townsend III

In life, learning from practical experiences often requires learning from our misunderstandings and mistakes. In many cases, this can be an effective way of developing greater levels of competence and understanding in the workplace. Unfortunately, when mistakes or misunderstandings are made in a confined space, the cost of this education is often measured in the number of lives lost due to tragedy.

The deadly nature of confined spaces leaves little to no room for error, and even less opportunity to "learn as you go" or accept the "this is how we have always done it" thought process. Understanding the requirements, hazards, and common mistakes will go a long way toward establishing a confined space safety program based on industry best practices, as well as the requirements of the Occupational Safety and Health Administration (OSHA) rules.

Working in confined spaces merits its own considerations and safety precautions

We must make every effort to ensure the safety of our employees through training and monitoring of our jobsites in the shotcrete industry. It is no different regardless of project or industry; the employer must provide training to each employee whose work is regulated by this standard. It should come at no cost to the employee, and ensure that the employee possesses the understanding, knowledge, and skills necessary for the safe performance of the duties assigned under this standard.

What questions must we ask? Understanding if any employee is claustrophobic prior to training is important and if so, do not place the worker in this position. Understand your ventilation plan and backup plan. Are respirators required? What kind? What is the lighting plan? Are there backup lights? A communication plan is essential: hard line and backup radios? Do the radios work in that environment, and have they been tested in that environment previously? What are the ways in and out of that section of work and other adjacent ways? In case of an accident, what is the response plan? Has the fire department toured the job? Who is the attendant? Who is the supervisor in charge of the operation? Know who will be in the space. Everyone on the team should know all this information prior to entering the project site. Training is then reinforced by checking to ensure that it has sunk in and is being followed.

Some important rules the training must include are:

- The hazards in the permit space;
- The methods used to isolate, control, or in other ways protect employees from these hazards; and
- The dangers of attempting such rescues for employees not authorized to perform entry rescues.

OSHA's Confined Space Standard 29CFR1910.146

This OSHA document, published in 1999, establishes requirements for confined and permit-required spaces in general industry. It specifically discusses general and program requirements for permit-required confined spaces, as well as training requirements and the duties of entrants, attendants, and the entry supervisor. Underground construction activities must also comply with the requirements of tunnel and shaft construction. Many tunnels are classified as "confined spaces" and others are "permit-required confined spaces." Before entry into a tunnel, employees must be informed of the requirements of the confined space program, and address the specific hazards associated with distance, communication, physical demands, and emergency rescue.

The determination of whether a space is a permit-required confined space is contingent upon two factors. The first factor is solely based on physical characteristics of the space itself. A confined space must be large enough and so configured that an employee can physically enter and perform assigned work, have limited or restricted means for entry or exit, and not be designed for continuous employee occupancy. If the space is so configured, then the second factor is whether the space contains or the activities introduce any hazard capable of causing death or serious physical harm. A space would be classified as a "permit-required confined space" if it either contained or has a potential to contain a hazardous atmosphere—a material which has the potential to engulf an entrant, an internal configuration such that an entrant could be trapped or asphyxiated, or contain any other recognized serious safety or health hazard.

OSHA Issues Final Rule for Confined Spaces—Change

OSHA issued the final rule, designated 29CFR1926, to specifically increase protections for construction workers in confined spaces. The final rule was released on May 1, 2015, and took effect on August 3, 2015. The change does a good job of assigning roles and responsibilities on jobsites with a general contractor and multiple subcontractors. Compliance assistance material and additional information is available on OSHA's Confined Spaces in Construction web page: **www.osha.gov/confinedspaces/index.html**. Employers must be in compliance with the training requirements of either the new or previous standard. Employers who fail to train their employees with either of these two standards consistently will be cited. **Failure to recognize the triggering conditions or implement required safeguards can result in stiff civil or even criminal penalties, including fines up to $70,000 for each violation.**

Factors that indicate employers are making good-faith efforts to comply include:

- Training for employees as required by the new standard;
- Ordering the equipment necessary to comply with the new standard; and
- Taking alternative measures to educate and protect employees from confined space hazards.

OSHA estimates the new confined spaces rule could protect nearly 800 construction workers a year from serious injuries and reduce life-threatening hazards. A few key notes from the new standard follow.

There are five key differences from the original rule and several areas where OSHA has clarified existing requirements. The five new requirements include:

1. More detailed provisions requiring coordinated activities when there are multiple employers at the worksite. This will ensure hazards are not introduced into a confined space by workers performing tasks outside the space. An example would be a generator running near the entrance of a confined space, causing a buildup of carbon monoxide within the space;
2. Requiring a competent person to evaluate the worksite and identify confined spaces, including permit-required spaces;
3. Requiring continuous atmospheric monitoring whenever possible;
4. Requiring continuous monitoring of engulfment hazards. For example, when workers are performing work in a storm sewer, a storm upstream from the workers could cause flash flooding. An electronic sensor or observer posted upstream from the worksite could alert workers in the space at the first sign of the hazard, giving the workers time to evacuate the space safely; and
5. Allowing for the suspension of a permit, instead of cancellation, in the event of changes from the entry conditions list on the permit or an unexpected event requiring evacuation of the space. The space must be returned to the entry conditions listed on the permit before re-entry.

In addition, OSHA has added provisions to the new rule that clarify existing requirements in the general industry standard. These include:

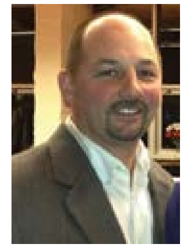
1. Requiring that employers who direct workers to enter a space without using a complete permit system prevent workers' exposure to physical hazards through elimination of the hazard or isolation methods, such as lockout/tag-out; and
2. Requiring that employers who are relying on local emergency services for emergency services arrange for responders to give the employer advance notice if they will be unable to respond for a period of time (because they are responding to another emergency, attending department-wide training, and so on).

Exclusion Criteria

Enclosed spaces that are not confined spaces for the purposes of the application of the new standard must satisfy specific exclusion criteria.

To determine that a space is not a confined space, it must be identified as a space described in Column A and must meet all the criteria in Column B (refer to Table 1).

The Exclusion Criteria table does a nice job of defining what constitutes permit-requiring confined spaces. It highlights the risks involved in working in confined spaces that should not be ignored.



Mike Munyon is a Senior Project Manager for Superior Gunite for the East Side Access Project in New York City. He has been with Superior Gunite East Coast for 3 years.

Frank E. Townsend III is the East Coast Region Manager for Superior Gunite. He is a civil engineer graduate of Worcester Polytechnic Institute, Worcester, MA, and received his master's degree from the University of Missouri, Columbia, MO. Townsend is an active member of ACI Committee 506, Shotcreting, and serves on the ASA Board of Directors. He has been awarded the U.S. Army Corps of Engineers deFluery Medal and Engineering News-Record *New York's "Top 20 Under 40" design and construction leaders in 2016. Townsend is also an active member of the New Jersey Chapter – ACI; the Concrete Industry Board, an ACI New York City Chapter; The Beavers (a Heavy Engineering Construction Organization); American Society of Concrete Contractors; American Society of Civil Engineers (ASCE); AREMA; and Society American Military Engineers (SAME), remaining a lifelong soldier.*

Table 1: Confined Spaces Exclusion Criteria

Column A	Column B
Spaces that may be excluded from Part 9, provided that **all** the criteria in Column B are met	Exclusion criteria
Swimming pools Crawl spaces under school portables or other non-industrial buildings Excavations Attic space Open, unconnected wet wells, or dry wells for storm or sewer hookups at new construction sites Elevator shafts	1. The design, construction, location, and intended use of these spaces will ensure these spaces are characterized by clean respirable air at all times. 2. The space must have an interior volume of not less than 64 ft^3 (1.8 m^3) per occupant. 3. The space must have openings to the atmosphere that are known to provide natural ventilation. 4. There must be no potential for a high or moderate hazard atmosphere, as defined in Section 9.1 of the *Regulation*, to exist or develop immediately prior to any worker entering the space or during any work within the space. 5. There must not be a need to mechanically ventilate, clean, purge, or inert the space prior to entry for any reason. 6. There must be no potential for a hazardous substance to migrate through any media (for example, air, soil, conveyance, piping, or structure) to infiltrate the space. 7. The space must be free of residual material (for example, waste, sludge, debris) that, if disturbed, could generate air contaminants that could immediately and acutely affect a worker's health. 8. There must not be any risk of entrapment or engulfment to workers entering the space. 9. The space must not contain, have introduced, or be adjacent to tools, equipment, or involve processes that could generate air contaminants that could immediately and acutely affect a worker's health.

LRutt Contracting Ltd

LRutt Contracting Ltd. focuses on unique solutions for shotcrete projects. LRutt has been providing both wet- and dry-mix shotcrete services to clients since 2004. Their main objective is to provide solutions to the challenges faced on their clients' projects and execute the work involved safely and diligently. With their qualified staff of shotcrete personnel and management, they can analyze project requirements and effectively offer their clients the experienced technical and practical approach to complete their projects on time and within budget.

LRutt Contracting uses its experience in structural shotcrete application on a wide variety of projects. The company has a number of ACI-certified wet-mix and dry-mix nozzlemen, and experienced support staff.

Structural Shotcrete Installation

LRutt uses shotcrete to complete many different projects, such as blind foundation walls and single-sided formed architectural walls, retaining walls, and seismic upgrade elements.

Concrete Repair

LRutt has completed shotcrete and concrete installations to repair and restore structures for seismic upgrades. Structural upgrades to heritage or other buildings can be challenging and LRutt uses shotcrete as a means of reducing time and materials on site to expedite the upgrades. They work with owners, contractors, consultants, and engineers on each upgrade project with the preplanning required to ensure the most effective technology for each aspect of the work.

Infrastructure

LRutt Contracting has completed projects related to rapid transit and highway improvement.

Most recently, LRutt completed a Light Rapid Transit tunnel separation wall 1.25 miles (2 km) in length and 21 ft (6.3 m) in height. The client required a quick turnaround time and LRutt completed the wall using wet-mix shotcrete in 40 days.

Highway project repairs are another service provided by LRutt. Some of the unique projects completed include shotcrete relining of deteriorated water culverts below major highways. By using the shotcrete process, costly removal of existing failing culverts and traffic interruption were avoided. Other highway work includes slope stabilization shotcrete and anchors, and permanent retaining walls.

Hydro Projects

LRutt has worked on several large hydro projects using both dry- and wet-mix shotcrete. In northern British Columbia, Canada, LRutt completed the installation of 1635 yd^3 (1250 m^3) of Grade No. 2 dry shotcrete with silica fume and steel fibers to stabilize a degraded rock slope up to 197 ft (60 m) high above an active dam spillway.

Vancouver, BC, Canada. LRT tunnel shotcrete separation wall, before and after shotcrete

Vancouver, BC, Canada. LRT tunnel setup to install shotcrete wall

Northern British Columbia Hydro Dam. Spillway rock slope stabilization. Custom crane basket with wheels allowed the crew to stay in contact with the irregular rock profile while applying dry-mix shotcrete

Shotcrete was placed out of a custom crane basket.

Most recently, LRutt worked on an upgrade to an active dam concrete spillway surface near Vancouver, BC, Canada. The challenges here were installing a wet mix with silica fume and steel fibers to an existing prepared spillway face up to 131 ft (40 m) high. The spillway surface shotcrete averaged 6 in. (150 mm) thick and had to be placed from a custom swing stage on elevated rails above the finished shotcrete surface profile. The spillway profile varied from 38 degrees off vertical to near horizontal. The tolerances of the finished face of the shotcreted profile was one of the many project challenges. Other hydro projects include penstock shotcrete repairs.

Mining Underground

In mining, some of the shotcrete projects LRutt has worked on include portal stabilization work and mine tunnel abandonment. For the latter, LRutt produces shotcrete and concrete plug installations as well as providing drilling and grouting services.

Experience Advantage

LRutt has diverse shotcrete project experience. Their staff, along with a network of engineers and other industry contacts, provides their clients with the professional approach they are looking for. “Quality Counts.”

Northern British Columbia Hydro Dam. Rock slope stabilization shotcrete was completed in two layers of 3 in. (75 mm) each. This provided safety to the crew as they worked to the bottom of the rock face slope

Hydro Dam Spillway Project. Spillway shotcrete resurfacing work had to be completed in three phases to maintain operation of the existing hydro facility

Hydro Dam Spillway Project. Spillway shotcrete resurfacing working off of a custom swing stage, before and after shotcrete

Contact us if you would like more information on how we may assist you on your next project.

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2017 *Shotcrete* Magazine Media Kit

With our continued efforts in rebranding, ASA's *Shotcrete* magazine will see a facelift starting with our 2017 series! Media kits will be available in September. Like us on Facebook (**www.facebook.com/AmericanShotcreteAssociation**) and sign up for our complimentary eNewsletter, What's In the Mix (**www.shotcrete.org/pages/news-events/e-news-subscribe.htm**), to hear when it is available!

ASA Fall 2016 Committee Meetings

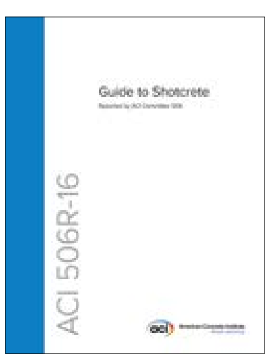
October 22, 2016 | Philadelphia Marriott Downtown | Philadelphia, PA

Make plans to attend the ASA fall meetings in Philadelphia, PA. ASA will be introducing a dual meeting track for the morning this year. Please refer to the following schedule:

Time	Room 414-415	Room 406
7:30 am–8:30 am	Education	Underground
8:30 am–9:30 am	Membership	Pool & Rec
9:30 am–10 am	Break	
10:00 am–11:00 am	Marketing	Safety
11:00 am–12:00 pm	Publications	CQC
12:00 pm–1:00 pm	Lunch	
1:00 pm–3:30 pm	Board	—

No registration required. All are welcome. Please come and contribute to the many initiatives ASA is advancing for the shotcrete industry!

Revision of ACI 506R, "Guide to Shotcrete"



The American Concrete Institute (ACI) announced the availability of an invaluable new publication for concrete industry professionals—ACI 506R-16, "Guide to Shotcrete."

The new guide provides information on materials and properties of both dry- and wet-mix shotcrete. Most facets of the shotcrete process are covered, including application procedures, equipment requirements, and responsibilities of the shotcrete crew. Other aspects, such as preconstruction trials, craftsman qualification tests, materials tests, finished shotcrete acceptance tests, and equipment, are also discussed.

"The guide is an excellent primer with numerous pictures and figures covering the entire shotcrete process for engineers, architects, contractors, inspectors, testing firms, material and equipment suppliers, educators, and students," stated Charles Hanskat, Executive Director of the American Shotcrete Association (ASA) and voting member of ACI Committee 506, Shotcreting. "A wide variety of applications and details of the shotcrete placement process are covered, including history, equipment selection, material requirements, formwork, crew composition and qualification, proper placement techniques, types of finishes, QA/QC testing, and sustainability."

According to Michael Tholen, Managing Director of Engineering and Professional Development, the new guide, together with ACI 506.2-13, "Specification for Shotcrete," provides the most up-to-date information available today, enabling the shotcrete specialist to complete projects in an efficient and safe manner. "ACI Committee 506, Shotcreting, worked very hard to incorporate all the latest innovative practices into this document," stated Tholen. "ACI's role as a recognized leader in concrete knowledge dissemination is highlighted with this new guide."

Also of note, because the new ACI 506R-16 Guide is intended to serve as a commentary for the current 506.2-13, "Specification for Shotcrete," ACI and ASA have provided a special, reduced price when purchasing both the documents together.

Learn more and purchase from ACI: **www.concrete.org** or (248) 848-3700 or from ASA: **www.shotcrete.org** or (248) 848-3780.

SPACE Shotcrete Annual Short Course

September 7-9, 2016 | Colorado School of Mines, Golden, CO

ASA is again a co-sponsor for this annual 3-day course on effective and sustainable uses of shotcrete. This course is intended for owners, engineers, contractors, consultants, and equipment suppliers involved in the design and implementation of aboveground structures, support of excavation, tunneling, mining, shaft construction, and heavy civil and architectural projects. The optional third day, Hands-On Lab & Demo, is a recent addition to this event.

SDC Technology Forum #40—Fall 2016

ASA is an active member of the ACI Foundation's Strategic Development Council (SDC). The SDC Technology Forum #40 will take place September 8-9, 2016, in Salt Lake City, UT. This technical conference brings the concrete industry, government, and academia together to collaborate on industry-critical issues and accelerate new technology acceptance. The forum provides a platform for examining and incrementally addressing challenges facing the concrete industry.

Forum #40 will explore recent advances in concrete wind turbine tower technology, sustainability technologies, repair and crack reduction, and will look toward the future with presentations on innovative approaches to improving concrete construction industry. Presentations and Technology Showcases include:

- Construction of the tallest concrete wind turbine tower in the United States;
- NASA's approach to CO_2 reduction in cement plant emissions;
- NIST program on 3-D printing;
- Viability of using post-consumer glass as a fly ash replacement;
- Slip-formed concrete wind turbine towers;
- Self-assembling concrete forms;
- Crack reduction technology research;
- Commercialization of Hexcrete—precast concrete for concrete wind turbine towers;
- A novel route toward CO_2 neutral cementation; and
- Magnesium-based repair materials.

Breakout sessions include:

- Discussion of the next steps to move the concrete wind turbine tower technological concept forward. The session will include an overview of the soon-to-be-released ACI technical document ITG-9R, "Report on Design of Concrete Wind Turbine Towers";
- More detailed discussion on the viability of using post-consumer recycled glass in concrete; and
- Recap of the Concrete 2029 Roadmapping Workshop 1 and a planning meeting for the "Special Code-Related Workshop."

For more information, visit **www.concretesdc.org/meetings/session40/SDC40_generalinfo.htm**.

Tunneling Short Course

September 12-15, 2016 | University of Colorado at Boulder, CO

ASA is a co-sponsor for this Short Course. Breakthroughs in Tunneling covers all aspects of conventional and mechanized tunnel design and construction in hard rock, soft ground, and soils. This 3.5-day intensive Short Course brings experts together to present lectures on every aspect of mechanized and conventional tunneling. Use "network" for discounts when registering.

*Visit **www.shotcrete.org/pages/products-services/shotcrete-magazine-authors.htm**, contact ASA via e-mail at info@shotcrete.org, or call (248) 848-3780 to submit your News items.*

New ASA Members

CORPORATE MEMBERS

Abbott Shoring & Foundations Ltd.
Coquitlam, BC, Canada
www.abbottshoring.com
sylvia@abbottshoring.com
Primary Contact: Sylvia Bourgeois

DMB Construction Corp.
Islandia, NY
erinegan@dmb-construction.com
Primary Contact: Erin Egan

The Euclid Chemical Company
Poplar Grove, IL
www.euclidchemical.com
hmorrall@euclidchemical.com
Primary Contact: Heath Morrall

Madole Construction Co., Inc.
Washoe Valley, NV
www.madoleconstruction.com
seanm@madoleconstruction.com
Primary Contact: Sean Madole

Montana Manroc Developments
Columbus, MT
www.montanamanroc.com
mikehare.manroc@yahoo.com
Primary Contact: Mike Hare

Promiz, LLC
Junction City, IL
kevin@promizllc.com
Primary Contact: Kevin L. Hickman

Proshot Structures
Surrey, BC, Canada
http://pro-shot.ca
dsmith@pro-shot.ca
Primary Contact: Doug Smith

Specialty Concrete Services LLC
Austintown, OH
john@specialty-concrete.com
Primary Contact: John Lucci

Summit Shotcrete
Lehi, UT
http://summitshotcrete.com
therin@summitshotcrete.com
Primary Contact: Therin Ramos

TBH & Associates LLC
Vancouver, WA
www.tbhdrill.com
rlarson@tbhdrill.com
Primary Contact: Peter A. Tapio

Wagman Heavy Civil
York, PA
www.wagman.com
erlaczynski@wagman.com
Primary Contact: Ed Laczynski

Western Materials & Design, LLC
Harrisonville, MO
www.wmdus.com
creeves@wmdus.com
Primary Contact: Clint Reeves

CORPORATE ADDITIONAL INDIVIDUAL MEMBERS

Jake Ipema
American Concrete Restorations
Lemont, IL

STUDENTS

Dave R. Rushangkumar
Winnipeg, MB, Canada

Hau (Howard) Yu
University of Alberta
Edmonton, AB, Canada

Read more about the benefits of being an ASA member and find a Membership Application under the ASA Membership tab at **www.shotcrete.org**.

american shotcrete association | asa

APSP and NSPF Boards Agree to Unify

The boards of the Association of Pool & Spa Professionals (APSP) and National Swimming Pool Foundation® (NSPF®) met recently and agreed in principle to merge the two organizations. Both boards believe that the merger will better support the present and future needs of the aquatics industry. Rich Garbee, APSP Chairman of the Board, and G. Bruce Dunn, NSPF Chairman of the Board, jointly stated, "The aquatics industry has seen dramatic changes over the past 10 years. APSP and NSPF each have a distinguished history of service to our industry. We are excited to build a vision where we can achieve even more together." A process is underway to plan and implement this merger of equals. For more information, or to arrange an interview with Bruce Dunn, President of NSPF's Board of Directors, please reach out to Jacki Krumnow at (719) 540-9119 or jacki.krumnow@nspf.org.

APSP is the world's oldest and largest association representing swimming pool, hot tub, and spa manufacturers, distributors, manufacturers' agents, designers, builders, installers, suppliers, retailers, and service professionals. Dedicated to the growth and development of its members' businesses and to promoting the enjoyment and safety of pools and spas, APSP offers a range of services, from professional development, to advancing key legislation and regulation at the federal and local levels, to consumer outreach and public safety. APSP is the only industry organization recognized by the American National Standards Institute to develop and promote national standards for pools, hot tubs, and spas. For more information, visit **www.apsp.org** or the Association's consumer site, **www.escapetowater.com**. Connect with APSP on Twitter, Facebook, YouTube, and Houzz.

NSPF believes everything they do helps people live healthier lives. They believe they can make a difference by making pools safer; keeping pools open; and attracting more people to use pools, spas, and aquatic facilities. They do this by offering the world's leading NSPF and Genesis educational products and programs that are technically sound, convenient, and beautifully designed. As a 501(c)(3) nonprofit, proceeds from all of NSPF's educational products fund research and help create swimmers through their Step Into Swim campaign with a goal to create 1 million more swimmers within 10 years. To find ways NSPF can serve you, visit **www.nspf.org**, e-mail service@nspf.org, or call (719) 540-9119.

Allen Named Sales Manager for Blastcrete Equipment Company

Blastcrete Equipment Company, manufacturer of mixing and pumping equipment for the refractory and shotcrete industries, announced Bill Allen as its new Sales Manager. Allen is responsible for helping customers around the world automate their processes with Blastcrete equipment.


Bill Allen

"We've known Bill for nearly 25 years and his familiarity with the industry and our equipment is a great asset to our team," said Jim Farrell, Blastcrete CEO. "We are a family-owned company and Bill shares our values of working with customers one-on-one to determine the equipment that meets their needs."

Allen is no stranger to concrete and refractory after more than 30 years in the construction business. He worked as a Sales Manager for BASF, the world's largest chemical company, for 7 years and managed its global sales of dry- and wet-process shotcrete equipment. He also served as BASF Construction Polymers' North American Sales Manager for more than 6 years. It was during his time at BASF that Allen gained familiarity with Blastcrete and the refractory industry. He spent more than 2 years working as the International Business Development Manager for Putzmeister America.

"Refractory and shotcrete customers require customized solutions, and Blastcrete is unique in its ability to cater to individual customer needs," Allen said. "My goal is get the message out there that Blastcrete is one of the few remaining manufacturers with this approach."

As Blastcrete's Sales Manager, Allen plans to travel regularly to meet with customers in the field.

Allen also holds extensive experience in the flooring industry as a formulator of self-leveling underlayment. He started a company, Sub-Floor Science, which tested concrete slabs, sub-floors, and floor coverings as well as evaluated floor failures, diagnosed problems, and recommended solutions. Allen served as a Blastcrete distributor with Sub-Floor Science and plans to use his experience to help Blastcrete expand in this market.

Allen studied business at the University of North Texas, Denton, TX. He earned a Concrete Slab Moisture Testing Technician—Grade 1 certification from the International Concrete Repair Institute as well as a Concrete Field Testing Technician Grade 1 license and an Aggregate Testing Technician Level 1 license from ACI. He is an associate member of ACI Committee 302, Construction of Concrete Floors, and a member of the International Association for Testing Materials' Committee F06 on resilient flooring.

Formerly a Texas resident, Allen relocated to Anniston, AL, Blastcrete's headquarters, in April.

Blastcrete has been manufacturing safe, reliable, and user-friendly solutions for the refractory and shotcrete industries for more than 60 years. With a complete product line that consists of concrete mixers, pumps, and related products, the company serves the commercial and residential construction, insulated concrete form and structural concrete insulated panel building systems, refractory, and underground markets. More information: Blastcrete Equipment Company, 2000 Cobb Ave., Anniston, AL 36202; (800) 235-4867; fax (256) 236-9824; info@blastcrete.com; **www.blastcrete.com**.

Airplaco and Gunite Supply Announce Launch of New Combined Website

Airplaco Equipment and Gunite Supply, specializing in the design and manufacturing of grout pumps, mining equipment, and wet- and dry-mix gunite machines, is pleased to announce the launch of their new website, located at **www.airplaco.com**. The new website has a clean uncluttered design and improved functionality for ease of use. The website was designed to meet the requirements of an increasingly digital customer base and can be viewed on smartphones, tablets, and other mobile devices without loss of functionality.

The new website will merge the current Airplaco site with the existing Gunite Supply site into one easy and central location. Additionally, the new website will have a customized eCommerce store allowing customers a new method of purchasing parts and accessories; the refreshed store is more customer-oriented and offers the ability to routinely reorder parts and accessories more efficiently as the site can store previous customer orders.

"We are very pleased with the redesign of Airplaco's website," said Ken Segerberg, Director of Sales at Airplaco. "The functionality of the new site makes it easy for our customers to navigate, research equipment, and purchase accessories and parts. We're excited to have our customers explore all of our products in one convenient location."

Concrete 2029 Continues Building to Future

Spearheaded by the American Society of Concrete Contractors (ASCC) and facilitated by the ACI Foundation's Strategic Development Council (SDC), Concrete 2029 was recently launched as a strategic initiative to develop a vision and roadmap for the future of the concrete construction industry.

"The motivation for this endeavor is to secure the future of the concrete construction industry by getting in front of issues such as the misconstrued image of concrete, code struggles, loss of market share to other building materials, declining productivity, and a shortage of workers in concrete construction," opined Bev Garnant, Executive Director, ASCC.

The initial workshop, held prior to SDC Technology Forum #39, took place on May 10, 2016, in San Antonio, TX. The meetings focused on issues such as defining and improving in-place concrete quality, increasing workplace productivity, and improving industry promotion and perception. Presentations included:

- The Misconstrued Image of Concrete;
- Consequences of Poor Design;
- The Owner's Mindset;
- What Must Happen to Improve Productivity; and
- Attracting and Training the Right People.

Participants acknowledge that a clear vision and excellent strategy are vital for the concrete construction industry to thrive in the future. With this in mind, SDC announces Concrete 2029's second workshop, which will further define and prioritize the goals to populate a roadmap for the concrete construction industry. "The industry has pulled together to identify the trends that are affecting it," stated Doug Sordyl, Managing Director of SDC. "Continued vigilance and unified industry action can turn our challenges into an immense opportunity."

Concrete 2029's second workshop will be held on September 7, 2016, in Salt Lake City, UT, preceding SDC's Technology Forum #40. Registration information for Concrete 2029, as well as the May workshop speaker presentations and agenda, are available at **www.concretesdc.org**.

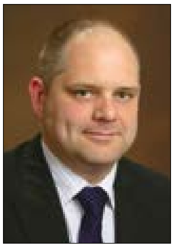
The ACI Foundation was established in 1989 to promote progress, innovation, and collaboration and is a wholly owned and operated non-profit subsidiary of the American Concrete Institute (ACI). Three councils make up the ACI Foundation: the Strategic Development Council, committed to accelerating technology acceptance within the concrete industry; the Concrete Research Council, which funds and assists in the research of new concrete technologies; and the Scholarship Council, which facilitates student fellowships and scholarships.

ASCC is a nonprofit organization dedicated to enhancing the capabilities of concrete contractors and those who build with concrete, and to providing a unified voice in the construction industry. Members include concrete contractors and contracting firms, manufacturers, suppliers, and others interested in the concrete industry such as architects, engineers, and educators. ASCC has approximately 550 member companies in the United States and 12 foreign countries. For more information, go to **www.ascconline.org**.

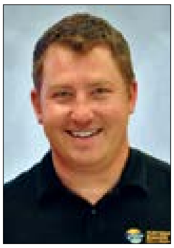
Hayward Baker Announces Staff Promotions and New Hires in Atlanta Office

Hayward Baker Inc. (HBI), North America's leader in geotechnical construction, announces that James Dickinson has joined the company as the Southern States Shoring Division Manager in its Atlanta, GA, office. In addition, Michael Morello has been promoted to Operations Manager, and James Weldon, PE, joins Hayward Baker as a Project Manager within the Southern States Ground Improvement Division.

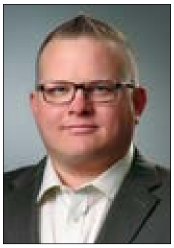
James Dickinson received his master's degree in civil and structural engineering from the University of Liverpool, Liverpool, England. He has over 15 years of experience in the geotechnical construction industry with particular specialization in earth retention, anchors, bracing, auger cast piling, micropiles, and related technologies. Prior to joining Hayward Baker, he was employed by a national geotechnical contracting company over a 13-year period holding positions of progressive responsibility encompassing all aspects of the sheeting and shoring operations throughout the Mid-Atlantic and Southeast United States. He will be HBI's primary point of contact for shoring projects in the southern states.


James Dickinson

Michael Morello received his BS in civil engineering from the Georgia Institute of Technology, Atlanta, GA. He has over 10 years of experience with Hayward Baker, specializing in ground improvement engineering and construction. Morello started with Hayward Baker as an intern and has since gained progressive responsibility in the southern states based in Atlanta. As Operations Manager, Morello will coordinate resources and shop activities for the Southern States Ground Improvement Division.


Michael Morello

James Weldon, PE, comes to Hayward Baker with 5 years of experience with a California-based shoring company. He received his BS in civil engineering from California State University, Fullerton, Fullerton, CA. He has wide-ranging experience in design-build shoring, foundation drilling, mass excavation, and structural shotcrete. Weldon will manage geotechnical construction projects in the southern states.


James Weldon

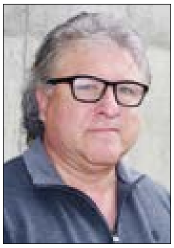
Commenting on the recent appointments, Joe Persichetti, Vice President, stated, "We are delighted to welcome James Dickinson and James Weldon, our two newest team members, to HBI's Southern States business. We are also proud to recognize Michael Morello's contributions to the company through his promotion. All three have strong construction experience and engineering competence to push Hayward Baker's growing Southern businesses to the next level in today's exciting design-build construction market."

Hayward Baker is a North American leader in geotechnical construction, annually ranked by *Engineering News-Record* (ENR) magazine No. 1 in foundation construction. With a 60-year record of experience, Hayward Baker offers geotechnical construction technologies through a network of more than 30 company-owned offices and equipment yards across the continent. Project applications include foundation support, settlement control, site improvement, slope stabilization, underpinning, excavation shoring, earth retention, seismic/liquefaction mitigation, groundwater control, and environmental remediation. Visit **www.haywardbaker.com**.

Hayward Baker Inc. is part of the Keller Group of companies, a multinational organization providing geotechnical construction services throughout the world. Visit **www.keller.co.uk**.

Kryton Welcomes New Central US Territory Manager

Kryton International Inc. is proud to welcome William Dauphin to its growing team as Territory Manager – Central US. Dauphin has over 18 years of experience in the construction waterproofing, building envelope, and adhesive/coating manufacturers industries. His local market acumen has driven the development of markets in Texas and the Central United States.


William Dauphin

CCS Launches New Division and Website

CCS is pleased to announce its new division and the launch of its new shotcrete supply website, **www.shotcretesupply.com**.

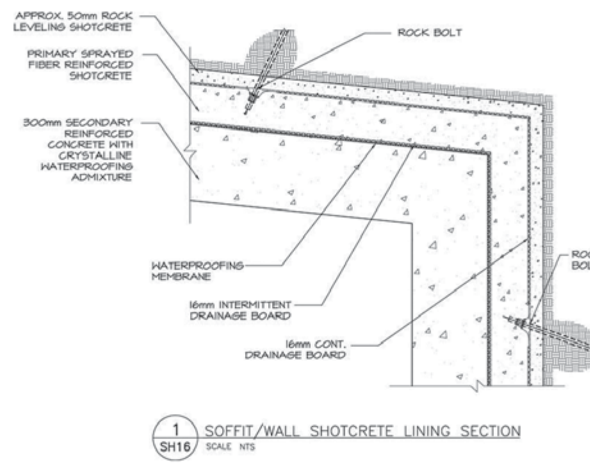
The site was designed with user-friendly navigation, brochures for REED equipment, a request a quote section, and it has been updated with the latest information about all their services and products. Visitors will find everything they're looking for in a few easy clicks.

Contact sales@ccsgrouponline.com or call (618) 476-7224.

HCM Innovation—Ottawa West Block Tunnels

HCM is currently completing shotcrete placement for tunnels at the West Block of Parliament Hill in Ottawa, ON, Canada. Work consists of the installation of a 2 to 4 in. (50 to 100 mm) shotcrete regulating layer followed by a 6 in. (150 mm) thick waterproofing preparation layer. HCM will install regulating and waterproofing preparation shotcrete for approximately 11,500 ft^2 (1068 m^2) of tunnel area, including 3500 ft^2 (325 m^2) of overhead work.

HCM is using nozzle-added accelerator to achieve high early strength and increased cohesiveness, allowing the shotcrete to be effectively applied overhead.



Shotcrete Calendar

AUGUST 28-31, 2016
AREMA 2016 Annual Conference & Exposition
Visit ASA's Booth #1002
Hilton Orlando
Orlando, FL
www.arema.org

SEPTEMBER 7-9, 2016
SPACE Shotcrete Annual Short Course
Cosponsored by ASA
Colorado School of Mines
Golden, CO
www.csmspace.com/events/shotcrete

SEPTEMBER 8-9, 2016
SDC Technology Forum #40
DoubleTree Salt Lake City Airport
Salt Lake City, UT
www.concretesdc.org

SEPTEMBER 12-15, 2016
Breakthroughs in Tunneling Short Course
Cosponsored by ASA
Use discount code: "network"
University of Colorado in Boulder
Boulder, CO
www.tunnelingshortcourse.com

OCTOBER 3, 2015
Deadline for ASA 2016 Outstanding Shotcrete Project Awards Program Entries
www.shotcrete.org/asaoutstandingprojects

OCTOBER 22, 2016
ASA Fall 2016 Committee Meetings
Philadelphia Marriott Downtown
Philadelphia, PA
www.shotcrete.org

OCTOBER 23-27, 2016
The ACI Concrete Convention and Exposition
Theme: "Revolutionary Concrete"
Philadelphia Marriott Downtown
Philadelphia, PA
www.concrete.org

NOVEMBER 2-4, 2016
International Pool | Spa | Patio Expo
Theme: "Where It All Comes Together"
Ernest N. Morial Convention Center
New Orleans, LA
www.poolspapatio.com

NOVEMBER 9-11, 2016
ICRI 2016 Fall Convention
Theme: "Urban Reconstruction"
The Westin Cleveland Downtown
Cleveland, OH
www.icri.org

DECEMBER 4-9, 2016
ASTM International Committee C09, Concrete and Concrete Aggregates
Renaissance Orlando at SeaWorld
Orlando, FL
www.astm.org

JANUARY 16, 2017
ASA Meetings at World of Concrete
Las Vegas Convention Center
Las Vegas, NV
www.shotcrete.org

JANUARY 17-20, 2017
World of Concrete 2017
Visit ASA's Booth #S10839
Las Vegas Convention Center
Las Vegas, NV
www.worldofconcrete.com

MARCH 15-17, 2017
ICRI 2017 Spring Convention
Theme: "Bridges and Highways"
Le Westin Montreal
Montreal, QC, Canada
www.icri.org

MARCH 25, 2017
ASA Spring 2017 Committee Meetings
Marriott Detroit at the Renaissance Center
Detroit, MI
www.shotcrete.org

MARCH 26-30, 2017
The ACI Concrete Convention and Exposition
Theme: "Driving Concrete Technology"
Marriott Detroit at the Renaissance Center
Detroit, MI
www.concrete.org

See this full list online with active links to each event: visit www.shotcrete.org and click on the Calendar link under the News & Events tab.

Atlas Copco New RTEX Pneumatic Breaker Focuses on Big Power with Less Airflow and Fewer Vibrations

Atlas Copco's new RTEX pneumatic breaker offers rental centers and contractors a cost-effective and powerful solution for a variety of demolition projects. The RTEX requires just 37 cfm to operate—about 50% less air energy than conventional breakers in the same weight class. This gives contractors the option to run multiple breakers off of a compact air compressor, resulting in greater efficiency and a high return on investment.

"Contractors will notice the RTEX difference after one use. Since the RTEX air consumption is essentially cut in half, contractors are able to run two 60 lb (27 kg) RTEX breakers off a 90 cfm compressor," said Gus Armbruster, Atlas Copco Handheld Construction Tools product manager. "This not only saves on rental or ownership costs on a small compressor but also on fuel consumption without sacrificing breaking power."

The RTEX has the breaking capacity of a 66 lb (30 kg) breaker or greater, but weighs only 55 lb (25 kg). Its Sofstart™ two-step trigger lets the operator start the breaker slowly for full control over the chisel's starting position and placement.

The RTEX operates with a constant pressure control that features improved energy transfer from the breaker to the new RHEX power chisel. The RHEX chisel generates a powerful breaking force and features a concave tip profile to significantly reduce jamming and promote operator productivity. The constant pressure chamber sits at the top of the breaker and serves as an advanced pneumatic suspension, which minimizes vibrations. Because the constant pressure chamber sits at the top of the breaker, there is no need for ergonomic handles—vibration values are comparable to a conventional breaker with flexible and vibration-reducing handles. This enhances operator comfort and allows the operator to work as much as eight times longer than with conventional breakers.

The breaker's minimal vibrations also minimize stress on its internal components, which means fewer spare parts replacements and less maintenance.

The RTEX features a long piston design that delivers double the interaction time—100 milliseconds—of the tool with the surface than conventional pistons. This results in higher impact energy per blow and faster results than what can be achieved with conventional breakers in the 60 lb (27 kg) weight class.

In a conventional breaker, air discharges each time the acting piston moves up or down. In the RTEX breaker, the air discharges only once—on the piston's return stroke, in which the constant pressure from the chamber pushes the piston down. Minimum valuable air is consumed, contributing to the high efficiency of the stroke mechanism.

To learn more about the RTEX breakers, visit **www.atlascopco.us/usus/products/demolition-equipment/product/3590230**.

Schwing Adds Tier IV Engine: SP 500 Stationary Pump

Schwing is now providing their popular SP 500 stationary concrete pump with a Tier IV-compliant Caterpillar diesel engine. This is a response to government-mandated reductions in harmful exhaust gases from diesel-powered equipment. The California Air Resource Board (CARB) requires Tier IV compliance for stationary pumps used on public and private projects. Other parts of the country are also requiring Tier IV compliance depending on the locale and project. The CAT® C3.4B diesel is rated at 74.5 hp while providing durability and fuel efficiency. Customers will enjoy unprecedented global parts, service, and repair options through the CAT dealer network.

The SP 500 is a versatile machine with up to 45 yd^3/h (34 m^3/h) output and 1100 psi (8 MPa) maximum pressure on the material. The machine excels in pumping grout, shotcrete, or concrete. The twin-cylinder, all-hydraulic pump handles up to 1.5 in. (38 mm) aggregate with its 6 in. (152 mm) diameter pumping cylinders operating through a 39 in. (991 mm) stroke. Sequencing the concrete to the pumping cylinders is the Rock Valve that enjoys proven reliability on Schwing's largest concrete pumps. Besides pumping harsh mixtures, the Rock Valve cleans up faster using less water for high use on multiple projects in a day. Dual-shifting cylinders provide positive valve actuation for smooth discharge. The open loop hydraulic system combines with the CAT engine to provide all-day economy from the 20 gal. (76 L) fuel tank.

Schwing SP models can be provided as skid, truck, or trailer-mounted units. A convenient control panel on the side of the machine includes switches for on/off, forward/reverse, and hopper agitator. Electric power is also available. A cable remote is standard with optional radio remote control.

For more information on the Tier IV compliant SP 500 and the entire line of Schwing stationary pumps, visit **www.schwing.com**.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• Average savings of 25% or more compared to other leading trade association magazines
Get it TODAY!
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Call (248) 848-3780 or e-mail info@shotcrete.org.

Shotcrete FAQs

As a service to our readers, each issue of *Shotcrete* will include selected questions and provide answers by the American Shotcrete Association (ASA). Questions can be submitted to info@shotcrete.org. Selected FAQs can also be found on the ASA website, **http://shotcrete.org/pages/products-services/technical-questions.htm**.

Question: *Our company has been working on the design of a concrete pond for winery wastewater and the contractor proposed to replace the concrete liner with a geomembrane (canal 3) covered by shotcrete. Have you seen cases of this application being successful for wastewater holding?*

As an alternative, we are considering applying the shotcrete over a clay liner. Are there any concerns or recommendations for this approach?

Answer: Shotcrete is a placement method for concrete. Shotcrete has been successfully used for over 70 years in thousands of industrial wastewater treatment/storage tanks, as well as in replacement linings of sewers and manholes. Thus, exposure of the shotcreted pond to wastewater should be as good or likely even better than the original cast concrete liner. Long-term durability of the shotcreted section will be dependent on the concrete mixture design. Many contractors use supplemental cementitious materials (SCMs) such as silica fume or fly ash to improve the pumping or shooting characteristics of the mixture. These SCMs also help to reduce permeability, increase strength, and thus make the concrete more durable. Fly ash also has the benefit of adding some sulfate resistance that would be beneficial in wastewater exposure conditions. Shotcrete is often shot on geomembranes or directly on the subgrade soils if they are stable enough to hold the impact and weight of the shotcrete.

Question: *We have a backwash tank on a wastewater treatment plant, which is made by a secant wall. The lower area for this structure will receive a shotcrete liner approximately 12 ft (3.7 m) tall on average; the interior perimeter of the structure includes 104 ft (32 m) of unreinforced and 440 ft (134 m) reinforced sections, which are a 12 in. (300 mm) minimum thickness. The drawings call for vertical control joints with a waterstop approximately every 30 ft (9 m).*

We don't believe the control joints are necessary and could achieve the same desired performance with one monolithic installation of the shotcrete. Are the control joints really necessary when you are installing the shotcrete against a solid secant wall that does not contain any control joints?

Answer: By "control joints," we assume you mean contraction joints. Shotcrete is a placement method for concrete. All normal concrete experiences drying shrinkage that creates a volume change in the hardened concrete. Although shotcrete has a lower water-cementitious materials ratio (*w/cm*) than most form-and-pour concrete, it will still undergo shrinkage. In being shot on an existing concrete wall the shotcrete liner will be restrained by the bond to the substrate and the restraint of the horizontal volume change from shrinkage can create internal tensile stresses in the concrete. This is likely the reason the designer has specified contraction joints in the section. Spacing of 30 ft (9 m) between joints is common in new construction of concrete tanks. The question becomes whether the bond of the shotcrete to the existing substrate is high enough to restrain the volume change and prevent cracking along the hundreds of feet of wall you will be lining. The thickness of the lining, the type and duration of curing, the concrete mixture design, the strength of the concrete, the strength of the substrate, the quality of shotcrete application, proper surface preparation, and exposure to seasonal temperature changes will impact the effect of the volume change of the lining. With the many variables we've pointed out, you can see there isn't a clear answer that covers all situations. We recommend you discuss your opinion with the designer or consult with a professional engineer experienced in shotcrete repairs to fully evaluate the specific structural sections you're shotcreting.

Question: *What is the R-value per inch of shotcrete?*

Answer: Because shotcrete is simply a placement method for concrete, the *R*-value is the same as cast concrete. ACI 122R-14, "Guide to Thermal Properties of Concrete and Masonry Systems," would be a good reference.

Question: *I modified an existing pool and had a new 20 ft (6 m) wall built that was subsequently backfilled. The reinforcing bar was epoxied and tied into existing pool wall/floor. The wall is 4.5 to 6 ft (1.3 to 1.8 m) tall. Sixty days later, we have two vertical hairline cracks that run top to bottom. I watered the wall properly and there are no cracks in the other sections we shot (such as the spa). We backfilled 12 days after the wall was shot with hand equipment only. The sample test taken when shooting came back at 6500 psi (4.1 MPa). The original pool bottom is below the wall and has no issues.*

The wall appears to be 12 to 14 in. (300 to 350 mm) thick from top to bottom. My question is: If the wall was shot too thick, would the lack of additional reinforcing bar cause the wall to fail? And is the necessary course of action to demolish the entire wall and reinforce the reinforcing bar, then shotcrete again?

Answer: There are many variables that can cause cracking. Vertical cracking is often the result of drying shrinkage of the concrete. You said you cured (watered) the wall properly, but don't give any specifics. ASA recommends a minimum of 7 days of curing, with a wet cure preferred over a spray-applied membrane. You should have a licensed engineer evaluate the structural sections, and determine if there were any problems with the amount or placement of reinforcement in your wall section.

Shotcrete FAQs

Question: *I am a homeowner who is having a pool built in my backyard. The company used shotcrete last Thursday, but didn't tell us we needed to keep it wet for the next few days. We found out on the following Monday that we should have been keeping the shotcrete wet. The 4 days that passed before we began wetting the shotcrete were very windy and hot (temperatures in the low 80s [°F]). The pool company is now telling us that it's probably not a big deal that the shotcrete wasn't kept wet for 4 days. My question is this: How has the shotcrete been compromised by not keeping it wet for 4 days? What can I expect to happen to the shotcrete (cracks?) What would you recommend as far as a fix?*

Answer: ASA recommends a minimum of 7 days curing to help control shrinkage issues in young concrete sections. Lack of curing, and exposure to windy, hot, or dry conditions will certainly increase the potential for shrinkage and cracking of the concrete. Lack of curing will prevent the concrete from achieving its maximum potential strength. However, shotcrete generally exceeds the minimum 4000 psi (28 MPa) 28-day compressive strength ASA recommends, and required strength depends on the pool design. If you want to confirm the compressive strength of your in-place concrete, cores taken from the pool should be tested for compressive strength by a qualified testing lab. ASTM C1604, "Standard Test Method for Obtaining and Testing Drilled Cores of Shotcrete," gives guidance on taking cores from existing structures. A minimum 3 in. (76 mm) diameter core is recommended. Before coring, it is recommended to use ground-penetrating radar (GPR) or similar equipment to identify the location of reinforcement in the pool section, and then take cores to avoid cutting through the reinforcement wherever possible. The core holes would then need to be filled with a high-strength, non-shrink cementitious grout. Once you learn the actual strength, you would need to check with the pool design engineer to verify the strength is adequate for the design. If the strengths are not adequate, you should consult with the pool designer or a licensed professional engineer experienced in pool design for potential solutions.

Question: *A client of mine has requested an upgrade to their mine conveyor entrance, which is currently formed from natural earth and was initially covered with a geotextile. The wind has continuously blown the textile off and as a result the slope has kept eroding. There are areas of surface undulations but the general surface is sound. They have now requested a shotcrete solution. The entrance is a V-shaped valley with a conveyer running at the bottom. Slopes on either side are 1:1 and extend in a series of levels each about 33 ft (10 m) high. Each level has an interceptor ditch. Slope stabilization is not of concern but rather erosion control. I will be using polypropylene-reinforced fiber shotcrete.*

I have a few questions:

- *What thickness of shotcrete would be optimal over the large areas to prevent further erosion for a long service period of 10 years? The shotcrete is to act as a barrier and not to stabilize the surface specifically.*
- *How would I anchor the shotcrete onto the soil? Types of anchors and spacing? Is it possible to anchor onto soil without a type of surface preparation?*
- *At what spacing would joints need to be installed?*

Answer: These are all good questions. Shotcrete is an excellent solution for the proposed upgrade. However, these are really design questions that should be evaluated by a licensed professional engineer experienced in slope stabilization, soil nails, and shotcrete. You may want to consult our Buyers Guide for contacts with our consultant members: **www.shotcrete.org/pages/products-services/Buyers-Guide/index.asp**.

Although most of our members are in North America, several members consult on projects around the world.

Question: *Can you please provide me a technical recommendation on whether or not expansion joints should be used in a large shotcrete pool that is approximately 230 x 135 ft (70 x 41 m)? In my design I am calling for two expansion joints, which would break the pool into three approximately 75.5 ft (23 m) sections. The contractor is telling me that he typically does not use expansion joints in the pool and that they are unnecessary. I do not typically work with shotcrete and have limited pool design but given the size of the structure I would think it would be best to include expansion joints. Can you please recommend whether or not the expansion joints should be used? Any help would be greatly appreciated.*

Answer: Shotcrete is a placement method for concrete. All normal concrete experiences drying shrinkage that creates a volume change in the hardened concrete. Pools will also experience volume change in the concrete due to thermal changes, especially summer to winter seasonal swings. Contraction and expansion joints are common in all kinds of concrete liquid-containing structures, especially with walls of this length. Although we can't provide a firm design recommendation, you should consider these factors:

- What are the weather conditions when the pool is anticipated to be built? If during hot summer months, could there be enough seasonal temperature swing to require expansion joints?
- If expansion joints wouldn't be needed, would contraction joints be needed to handle anticipated temperature swings and drying shrinkage?
- Will the pool be empty for extended times? (This could lead to more shrinkage or direct exposure to solar gain or cold conditions.)
- Is the pool to be kept full or empty during the winter months? (If the pool is in a geographic region where extending freezing conditions are prevalent…)

Overall, the design for a shotcrete pool should be the same as one for a cast concrete pool.

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