shotcrete MAGAZINE

A quarterly publication of the American Shotcrete Association

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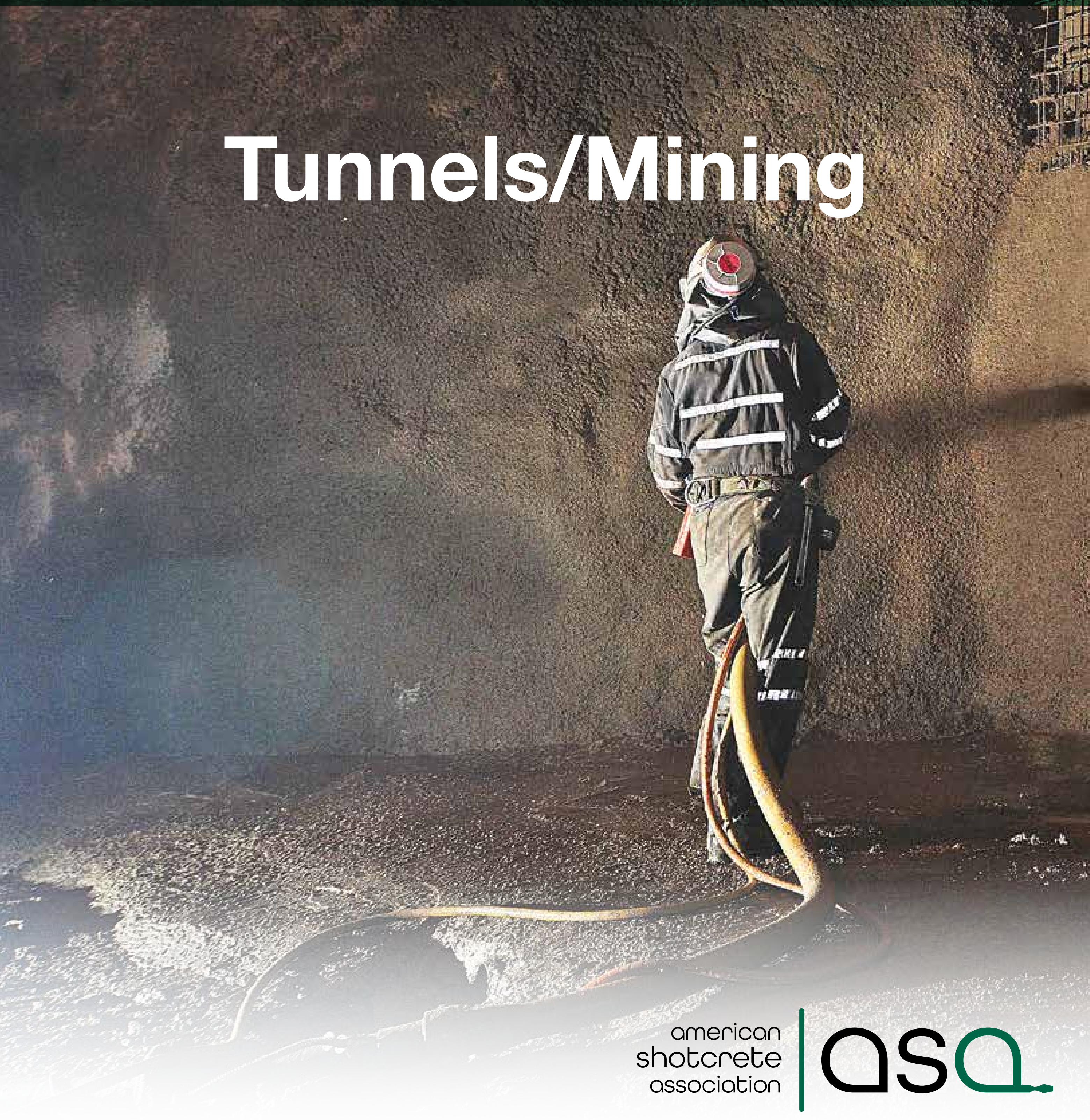
Tunnels/Mining



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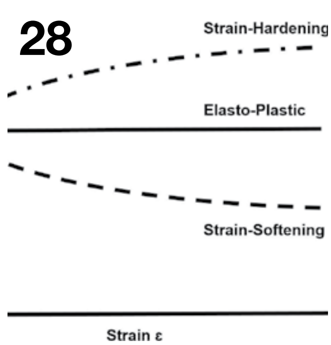
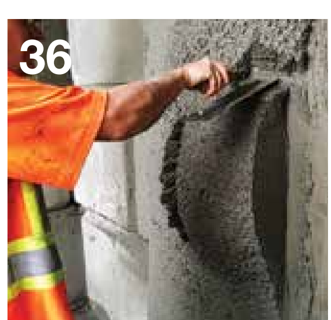
FEATURES





Shotcrete is a quarterly publication of the American Shotcrete Association. For information about this publication or about membership in the American Shotcrete Association, please contact ASA Headquarters at:

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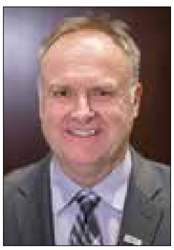
Editor's Note: Shotcrete is a placement method for concrete. However, for the sake of readability, the word "shotcrete" is often used either to identify the shotcrete process (method of placement) or the shotcrete mixture (product materials).

DEPARTMENTS

On the cover: Prepackaged dry-mix shotcrete is used at Vale's Creighton Mine in Sudbury, ON, Canada, for both ground support and underground construction applications. Photo courtesy of King Shotcrete Solutions.

Advancing the Mission

By Scott Rand



I am both honored and humbled to accept the challenge of being the 2017 ASA President. Spending two terms on the Board and evolving through the roles within the Executive Committee has furthered my education and appreciation of our industry with yet-to-be-defined future potential. Ironically, as we enter what is now our 20th year as an association, I pass the threshold of my 20th year at King Packaged Materials Company in this construction segment where many of us share our passion.

Echoing my January comments at our Outstanding Shotcrete Project Awards Program in Las Vegas, NV, I would like to take the time to acknowledge some people who have influenced my path. While there have been numerous people industry-wide that have both helped and taught me along the way (easily enough to fill an entire page), some people within our association deserve special mention. My involvement in the Executive Committee has consistently increased the appreciation I have for the incredible effort and dedication that both Charles Hanskat and Alice McComas bring daily to our organization. I am very indebted to our ever-growing list of Past Presidents whose direction, leadership, and example I have had the benefit of witnessing first-hand. I have had the pleasure of serving on the Executive Committee with five of them (Totten, Cotter, Hanskat, von der Hofen, and Drakeley) and, added to that list, two colleagues who I work with whose constant counseling can't be overstated (Hutter and Bridger). While I am extremely grateful for their collective participation and for sharing their wealth of experience, I would like to thank them again personally for not only giving back to our industry but also for their determined pursuit of raising the bar.

Michael Cotter not only was the first to recommend my name for the Board back in New Orleans (2002) but also the one who picked up the phone a few years ago to ask if I would consider serving as an ASA officer. Over the past year, Bill Drakeley has provided a great example of steering the ship and I am grateful for both his guidance and friendship. It's comforting to know that Bill retains a position as Past President on the Executive Committee for one more year. One other Past President who has influenced not just my career but many others', as well, is George Yoggy. I was first introduced to George 20 years ago while attending the NORCAT Nozzleman Training Course in Sudbury, ON, Canada. If you have any involvement in our industry, you understand that George was and is such a passionate leader and mentor.

Many years ago, when I started to pursue New York City's East Side Access, it was George who opened the doors for many of us to become involved. Patrick Bridger and I were fortunate enough to meet George for lunch late last year in Allentown, PA, and I was thrilled and inspired to see that his passion for shotcrete is still alive and well.

I am genuinely excited about the year ahead. Thanks to Charles Hanskat, who was our ASA President at that time, we sat down 3 years ago and updated our Mission and our Vision to match the growth and challenges in our industry that have evolved since we started as an Association in 1998. Then we went forward and developed our first ASA Strategic Plan. With some modifications along the way, we started tackling approximately 40 objectives. We truly began to gain momentum at that pivotal Denver, CO, meeting (November 2015) and the growth since has been tremendous. As those of you involved know, and for others simply following our progress, our plan involves two goals that are nearing completion: the development of our Shotcrete Inspector Education and Contractor Qualification programs. Overall, we are well past the halfway mark in our pursuit and are now at the point where we need to sit down to develop the roadmap for our next 3 years. By the time this issue goes to print, we will have already met in Detroit, MI, to do just that.

The scorecard approach that we are using to monitor our progress on the strategic planning items is direct and efficient. I met with one of Queen's University's Executive Professors who teaches Leadership, Strategy, and Execution last Fall and showed her what we were accomplishing. She loved it and agreed with the theory from the *4 Disciplines of Execution* that we have modeled our approach after. We are on a positive track and you can see increased momentum within every single committee.

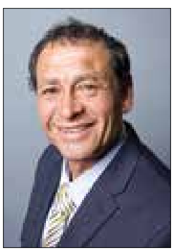
We have very strong leaders and volunteers throughout our Association. I applaud their efforts and especially our committee chairs. If you haven't been actively involved to date, but would like to be a part of our next 20 years, please approach one of our committee members or staff to start the process (**shotcrete.org/pages/membership/contact.htm** and **shotcrete.org/pages/membership/committees.htm**). The acceptance and use of shotcrete is growing tremendously and our product is proving to be one of the most versatile, creative, and efficient concrete construction methods available in the market.

Thank you for your support and allowing me the honor to serve as this year's ASA President. I look forward to doing my part to drive our new Strategic Plan and grow ASA to be of more value to our members and the shotcrete industry.

ASA Education Committee

By Oscar Duckworth

ASA's Vision: "Structures built or repaired with the shotcrete process are accepted as equal or superior to cast concrete."



If you have been in this business as long as I have, you have given similar passionate sermons on the virtues of shotcrete countless times. Years ago, compelling clients to use the shotcrete process required the persuasive skills of a Baptist minister. Is shotcrete strong? Durable? Why haven't I heard of it? Those predictable responses were repeated by clients like a skipping record.

We have come a long way since then. Decades of research, published documents, and the acknowledgment of thousands of successful shotcrete applications worldwide have helped the shotcrete industry gain a greater acceptance… Shotcrete **is** concrete. *We knew it all along, didn't we?*

So, is the shotcrete process universally accepted as equal or superior to cast concrete? Unfortunately, no. Many specifiers (primarily engineers and architects) and upcoming specifiers (university engineering or construction management students) know little about the shotcrete process. Improving acceptance of shotcrete can only come through improving the outreach of shotcrete knowledge.

Recently, ASA held a 1-day session to update our Strategic Plan. The session was held at ASA's office in Farmington Hills, MI. The day's topics focused on the ongoing efforts of ASA to increase the acceptance, quality, and safe practices of the shotcrete process. Like the previous strategic planning meeting held 3 years ago, **education and outreach** to specifiers and university students was identified as a key element to promoting the widespread acceptance of shotcrete.

With the exceptional volunteer work of the involved committee members, a revised and modernized "Introduction to Shotcrete" hour-long education session for this target market is complete and has been presented to groups across the country. This session is created so the base presentation can be customized with additional information for a specific audience. The most common format has been a lunchtime session at an engineer's or architect's office. Sessions have been given to student groups at their schools. Also, ASA has presented online webinars for reaching multiple offices with a single session, or a remote facility or country. These short educational sessions are ideal opportunities to promote shotcrete's many benefits. Promotion of the presentation can improve our educational outreach considerably.

We need your involvement! Outreach will not automatically occur. ASA members who have connections with organizations (engineers, architects, owners, universities) who could benefit from an educational session should take the initiative to speak with them and let them know how easy it is to schedule a session. All they need to do is contact ASA staff at info@shotcrete.org or (248) 848-3780 to arrange for an on-site informational presentation tailored for their group's needs.

Spreading the word and improving the acceptance of the shotcrete process is a constant effort. Let ASA help reach out to those who need to be more knowledgeable about shotcrete and it just might cut down on the need for your passionate sermons regarding shotcrete.

SHOTCRETE SAFETY

The recent Strategic Plan refresh meetings discussed the need for the Education Committee to team with the Safety Committee and focus on completion of a "Shotcrete Safety" educational program to support the current ASA Safety

ASA Education Committee

Oscar Duckworth, Chair | Valley Concrete Services
Andrea Scott, Secretary | Hydro Arch

Lars Balck | Consultant
Michael Cotter | MP Solutions
Roberto J. Guardia | Shannon & Wilson Inc.
Warren Harrison | WLH Construction Company
Marc Jolin | Laval University
Andy Kultgen | Construction Forms Inc.
Ron Lacher | Pool Engineering Inc.
Dudley (Rusty) Morgan | AMEC
Ryan Poole | Consultant
Raymond Schallom | RCS Consulting & Construction Co. Inc.
Ted Sofis | Sofis Company Inc
Frank Townsend | Superior Gunite
Marcus H. von der Hofen | Coastal Gunite Construction Co.
Ezgi Yurdakul | GCP Applied Technologies
Lihe (John) Zhang | LZhang Consulting & Testing Ltd.

Guidelines for Shotcrete document. It will be formatted to a 1.5- to 3-hour shotcrete-specific session focusing on the obvious and hidden hazards of both wet- and dry-mix shotcreting. Once completed, this program will be an important educational tool for member companies as well as a potential education component to the current ASA-sponsored ACI Nozzleman Certification education sessions. Adequate shotcrete specific safety training is important to all shotcrete workers however, Nozzlemen-in-Training (NIT) are often at the greatest risk of injury due to their lack of experience in holding and manipulating the nozzle in a variety of applications. Only a minimum of 25 hours of hands-on nozzling experience is required to qualify a participant to take the ACI Nozzleman Certification testing as a NIT. Thus, the NITs may particularly benefit from a comprehensive shotcrete-specific safety training prior to gaining the additional hours on the nozzle to reach the 500-hour minimum required for full certification. The best time to prevent an accident is before one occurs. It is our goal to dramatically increase the shotcrete safety resources available for all workers through ASA.

Moving Forward… Strategically

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

First, I note with sadness that one of the leaders in our industry, Chris Zynda, passed away in early March. Though I only knew Chris personally through his activities with ASA and ACI, I knew much more of him by his reputation. His active and enthusiastic involvement in all things related to shotcrete was infectious. His commitment to improving the safety for our shotcrete crews while increasing the quality and durability of the structures we build was unmatched. It is obvious from the projects Chris was involved in that he envisioned shotcrete placement as an opportunity to be efficient; cost-effective; and above all, creative.

In his various roles with ASA—serving and chairing committees, serving on the Board, and serving in various officer positions culminating as President, he set the example for what meaningful and productive service to ASA entails. The shotcrete industry has made major gains in the two decades since ASA was formed, and his involvement with ASA has been a significant factor in our pushing the industry forward in both quality and recognition.

He will be missed…by family, by friends, by co-workers, by ASA members past and present, and in truth the entire shotcrete industry.

ASA SPRING MEETINGS

We had great attendance at our Spring 2017 ASA meetings held here in our offices in Farmington Hills, MI, at the end of March. Our meetings included a special 1-day meeting to review and refresh our Strategic Plan. In the review, we confirmed the exceptional progress we've made from the original plan developed just 3 years ago. In revisiting our Vision and Mission statements, we found them to still be meaningful and provide a clear direction.

ASA's Vision

"Structures built or repaired with the shotcrete process are accepted as equal or superior to cast concrete."

ASA's Mission

"ASA provides resources, qualification, certification, education, networks, and leadership to increase the acceptance, quality, and safe practices of the shotcrete process."

The refreshed Strategic Plan was shared with the Board and Committees during the meetings the following day.

Through the active involvement of our committee chairs and members, made strides to move our programs and outreach ahead. This included:

- The **Underground Committee** (Chair: Axel Nitschke) is nearing completion of the 1-hour Underground Shotcrete on-site seminar. This was balloted to the Board shortly after the Spring meetings. This program is based on the content in ACI 506.5R, "Guide for Specifying Underground Shotcrete," and will be a valuable resource for engineers and specifiers to learn more about underground shotcreting.
- The **Pool and Recreational Shotcrete Committee** (Chair: Bill Drakeley) confirmed their position paper on Forming for Pool Construction. This was balloted to the Board shortly after the Spring meetings. They are also working on other position papers and hope to have one or more finalized later this year. Chair Drakeley informed the group that a pool subcommittee was established under ACI 506. This new subcommittee met at the ACI meetings in downtown Detroit the day after our committee meetings.
- The **Marketing Committee** (Chair: Joe Hutter) reviewed our tradeshow activity and recommended adding the Railway Interchange exhibition in September 2017 sponsored by AREMA/REMSA/RESI to the tradeshows we will exhibit at this year. Also, as 2018 is the 20th Anniversary of ASA, the group had much discussion and recommended holding an enhanced 20th Anniversary event in place of our traditional Awards Banquet held in conjunction with World of Concrete. You'll hear more about this soon, as the 20th Anniversary event was approved by the Board.
- The **Membership Committee** (Chair: Cathy Burkert) reviewed our membership statistics and made assignments for contacting recently dropped corporate members to remind them of the benefits of membership in ASA. The committee also discussed our membership dues that have not increased since our inception 20 years ago and established a task group to review our dues structure in comparison to other similar trade associations.
- The **Education Committee** (Chair: Oscar Duckworth) reviewed statistics on our sharply increasing number of ASA/ACI Nozzleman Certification sessions. They also

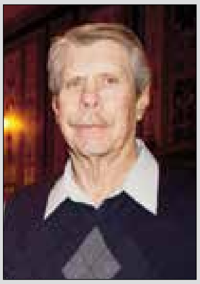
discussed progress on the Shotcrete Inspector Education program and the development of a Safety Education program in conjunction with our Safety Committee.

- The **Safety Committee** (Chair: Andrea Scott) spent most of their time on reviewing the format and potential content for a new Safety Education program. The format is initially expected to be a 1.5- to 3-hour on-site seminar. This may be offered as a supplement to our nozzleman education sessions, especially where those sessions include nozzlemen-in-training who may not have the hours of shooting experience certified nozzlemen must have.
- The **Contractor Qualification Committee** (Chair: Marcus von der Hofen and Honorary Chair: Chris Zynda) reviewed the PowerPoint presentation for the 1-day shotcrete contractor program. There was lively feedback, and a task group assigned to help finalize the slide deck before our summer Board of Directors meeting. After the Board approves the presentation, the committee will develop a written exam and then work with our marketing committee for promotion of the new program.
- Our **Publications Committee** (Chair: Ted Sofis) did not meet, but many of our committees did work on article topic/authors for upcoming issues. Chair Sofis also agreed to co-lead the Fall 2017 issue of *Shotcrete* magazine, along with Marketing Chair Joe Hutter, designated as the 20th Anniversary edition in celebration of this milestone year.
- Our **Technical Committee** (Chair John Zhang) also did not meet but has been very active reviewing technical articles for our magazine, updating our online bibliography and resources, and developing several topics for research that would be beneficial for the shotcrete industry.

Overall, the strength of our Association is our members. Working together allows us to achieve much greater progress in raising the visibility, credibility, and acceptance of shotcrete in the concrete construction industry. Thanks again to all our ASA members, who have given their time and effort to our committees, Board, and officer positions. We've seen many new faces at the committee meetings, but there is certainly room for more. Our outreach and diverse new education programs can only be successful by active member participation. **Your** involvement is what will help ASA and the shotcrete industry move forward.

In Memoriam

Chris Zynda (1949 – 2017)



Chris Zynda was a "Shotcreter." For a great many people, being a "Shotcreter" may not have any meaning. I can only describe it as a Brotherhood—a Brotherhood of those who make a living in the industry to the point that it defines who we are. We wear this title with pride. We defend it with passion. Engineers, or architects, or marines, or policemen all carry a distinction or recognition within their groups. We carry the same in ours.

Chris helped many forge their path in the shotcrete industry and I, and many others in this industry, are thankful for the times we spoke in depth about the industry, and especially about high-horsepower wet-mix shotcrete, the mantra of the West Coast Shotcreter.

Within our industry, Chris was leading the charge to fill the void created between simply requiring certified shotcrete nozzlemen and the need for qualified shotcrete contractors with a proven ability to produce quality shotcreted structures. He recognized the false sense of security given to owners or specifiers who thought nozzleman certification alone could ensure a quality job. The challenge that Chris undertook was communicating the importance of the entire company being qualified as a prerequisite for a quality shotcrete project. A trained workforce, insurance, credibility, experience, scheduling, equipment, and workable concrete mixture design are all items that must be provided by the qualified shotcrete company, along with ACI Certified Nozzlemen for quality shotcrete placement. Chris laid the foundation for quantifying the parameters essential for a qualified shotcrete contractor. With his wisdom and guidance, ASA has the foundation to move ahead and complete our Contractor's Qualification Program to accomplish Chris' vision.

-Marcus von der Hofen, 2015 ASA President

East Side Access Project

By Frank E. Townsend III

In May 2014, Superior Gunite was issued a subcontract by the Michels Corporation to shoot approximately 2000 yd^3 (1500 m^3) of shotcrete for overbreak build back on the arches of the East Side Access Project—CM005 Manhattan South Structures. This initial subcontract for the build back of the over-excavation of rock was required to achieve a 1:10 smoothness ratio for the application of the polyvinyl chloride (PVC) waterproofing membrane. As the project continued into 2015, the Michels Corporation and New York Metropolitan Transportation Authority (MTA) management further recognized the advantage that Superior Gunite provided to the scope of the CM005 Project and added 5000 yd^3 (3800 m^3) of structural shotcrete in the arch sections. The use of shotcrete in additional structural concrete portions of the project not only aided the overall production schedule but also added flexibility to place concrete in areas where expensive individual custom forms would be required for each placement.

Build Back and Smoothening

As construction continued in the early stages, it was realized that several areas of the project not only required a smoothening course to bring the substrate to a 1:10 smoothness ratio but also were found to have overbreak of up to 18 in. (450 mm) beyond A-line in the arch sections and beyond 18 in. (450 mm) in areas with intersecting geometries. In some of these areas of heavy overbreak, reinforcement dowels in conjunction with steel-reinforced fiber shotcrete (SRFS) was needed to support the depth of material being applied on the substrate.

Fig. 1: Upper-level arch section of three-level structure TT#1. Overbreak reinforcement dowels and grade control wires

Fig. 3: Tunnel section arch reinforcing bar upper-level arch of TT#1 structure

Fig. 2: Waterproofing membrane installed after build back and smoothing has been completed in the upper-level arch of TT#1 structure

Fig. 4: Tunnel and cross-passage intersection arch reinforcing bar upper-level arch of TT#1 structure

Fig. 5: Reinforced beam section in upper-level arch of TT#1 structure

Fig. 6: Upper-level arch of TT#1 structure, tunnel, and cross-passage interface

REINFORCING BAR

Some areas of the project contained extremely heavy and congested reinforcing bar layouts, including the upper level of TT#1. This structure was the intersection of four tunnel segments and an intersecting cross passage with an arch that contained a double mat of No. 11 and No. 9 (No. 36M and No. 29M) bars at 6 in. (150 mm) spacing and four beam sections. The combination of lap lengths, stirrups, and bars transitioning from the inner to outer mats at the interfaces in this reinforcing bar design forced the shotcrete to be placed in one lift.

SHOOTING

Shooting this area in one lift required the constant movement of the nozzleman shooting from different angles through the reinforcing bar as well as an adjacent worker with an air lance to constantly remove rebound and material from the outer layer of reinforcing bar to achieve proper consolidation. This was especially important in the reinforced beam section where concrete depths from the face were up to 24 in. (600 mm). It was also necessary to untie select reinforcement from the outer reinforcing bar mat when shooting the inner mat to provide good access for shotcrete placement, especially during placement in the beam sections. The untying of selected reinforcing bars, especially in the areas adjacent to the beams, gave the nozzlemen better shooting angles and the ability to place the nozzle further past the outer reinforcement layer. After the shotcrete was properly consolidated and placed beyond the inner mat, the reinforcing bar was reinstalled and the placement in that area continued.

The use of universal ring lock scaffolding provided a continuous and extremely stable platform for the overhead shotcrete operations. A rubber float finish was provided on the approximately 1500 ft^2 (140 m^2) surface area of these placements.

ADDITIONAL MAJOR STRUCTURES

The tunnels and cavern arches were two additional major structures on the project that benefited from the use of shotcrete. The tunnels that used shotcrete placement were located on the upper level of the project between two major caverns. Their isolated location made shotcrete the perfect process for placing the structural liners because the forms could not easily reach this area. The tunnel sections had an arc length from invert to invert of 52 ft (16 m) with No. 6 and No. 7 (No. 19M and No. 22M) reinforcing bars spaced at 12 in. (300 mm).

Fig. 7: Upper-level arch of TT#1 structure, tunnel, and cross-passage interface (opposite view)

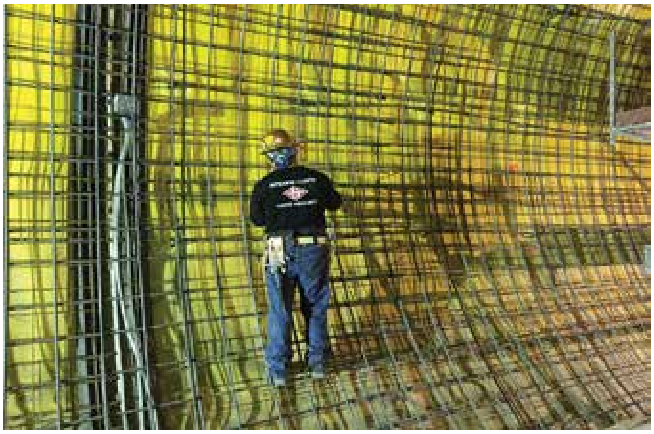


Fig. 8: Shotcrete wireman installing z-bars and pencil rod for grade control on running tunnel section

Fig. 9: Completed tunnel section

Fig. 10: Installation of GCT 1/2 arch with rod finish, working from boom lifts

The wide GCT 1/2 cavern arches were given a rod finish instead of a rubber float finish. This let the work be performed off of boom lifts rather than full-coverage scaffolding and increased the production rates. The arch was placed in three segments (left, right, and center) due to the overall size. The shotcrete process was advantageous, as the cavern arch reduced in size as the structure extended to the south.

LOGISTICS OF STREET POURS

The entirety of the project had concrete delivery from three locations, at street level in midtown Manhattan. The material was conveyed via 5 in. (125 mm) steel slick line, up to 1500 ft (450 m) in length. There was up to 8 yd^3 (6 m^3) in the delivery line prior to reaching the secondary concrete

Fig. 11: Finished access Tunnel 1 arch with rubber float finish

Fig. 12: Finished GCT 1/2 arch with rod finish. Walls were rubber float finished

pump located in the underground caverns for the final delivery and shotcrete placement. Due to the volume of material in the slick line and the slower nature of shotcrete placements, the concrete used a conventional retarding admixture to prevent the material from setting up in the slick line.

WORKER AND MATERIAL LOGISTICS

Unlike most typical tunneling projects that use multiple shafts along the tunnel length for the access of workers and materials, the East Side Access Project is unique, as the only material access is 7 miles (11 km) away in Long Island City. Here, the materials are loaded onto work trains and brought into the project on a designated schedule. This one point of access, in conjunction with the use of work trains, introduces an immediate 24-hour delay from when the materials arrive in the project yard to when they are available at the work location. Supply delays are further increased at peak project production times as availability of space on the working trains is quickly taken with the deliveries of steel, waterproofing, and equipment. As a result, materials need to be scheduled and delivered to the access point no less

Fig. 13: Pump location at intersection of 37th and Park in New York, NY, for the placements in upper-level arch of TT#1 structure

than 72 hours before they are required. Large equipment is needed at least a week in advance.

The general access for the workers on this project was also limited on the project. The general access was from street level near 48th and Madison in Manhattan. Some of the work locations underground were as far south as 37th Street and Park Avenue. The workers could not travel within the tunnels until the work day commenced, and thus required up to an additional 30 minutes of the work day spent in the morning for them to access the tunnel level via elevator (Alimak) and then walk to the day's work locations. This process was repeated at the end of the work day so that all workers would be out of the tunnel before the shift was over.

Over the course of the project, the use of shotcrete placement for structural concrete sections significantly increased. Superior Gunite shotcreted structural concrete in nearly every structure on the projects, including the running tunnels, cross passages, cavern walls, and arches. The use of shotcrete significantly benefited the Michels Corporation schedule and costs by reducing the formwork required and adding flexibility to the project. At the completion of the project in March 2016, Superior Gunite installed over 14,000 yd^3 (11,000 m^3) of shotcrete throughout.

***Frank E. Townsend III** is the East Coast Region Manager for Superior Gunite. He received his degree in civil engineering from Worcester Polytechnic Institute and his master's degree from the University of Missouri. Townsend comes from the U.S. Army Corps of Engineers and his diverse military background has led to him being deployed around the world. Townsend is an active member of ACI Committee 506, Shotcreting, and a Board member of ASA. He has been Awarded the U.S. Army Corps of Engineers deFluery Medal and the* Engineer News-Record *New York's "Top 20 under 40" award for design and construction leaders in 2016.*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Innovative Shotcrete Technologies for Advancement in Tunneling

By Nicolas Ginouse, William Clements, and Scott Rand

Sprayed concrete (shotcrete) is a well-established and proven component of ground support systems worldwide. Underground excavation projects currently involve more and more logistical and technical challenges to advance headings and keep the development cycles as short as possible.

In this context, the installation of ground support has become one of the longest components of the development cycle. In addition, larger headings and deeper excavations lead to larger volumes of material requiring transportation from the surface over longer distances. The use of shotcrete as a ground support technique has undergone several key technological advances that are explored in this paper, which include the reduction of rebound and dust, rapid strength gain shotcrete and ultra-high performance shotcrete materials for high stress conditions.

Wet-Mix Process

In non-accelerated wet-mix shotcrete, all the ingredients, including water, are mixed together before the delivery phase. The fresh mixture is then pumped through hoses or pipes to be sprayed onto a receiving surface using compressed air, which is introduced at the nozzle. In this case, the amount of mixing water added to the mixture is predetermined before the pumping and the shotcreting phases, which therefore makes the implementation of in-situ quality control quite simple. However, because of the material delivery phase, the wet-mix process requires management and control of all parameters influencing workability/pumpability of the mixture to ensure the material is delivered properly. Even if a mixture is found to be adequate for pumping, that does not necessarily mean that the same mixture is shootable and will adhere to the receiving surface after impact. In the case of accelerated wet-mix shotcrete, the set-accelerating admixture is introduced at the nozzle to provide rapid hardening while overcoming any potential issues with workability. Normal dosages of accelerator used within the industry are typically between 2 and 6% by weight of the cementitious content of the shotcrete mixture. In addition to the obvious impact on the final material cost, the dosage of set-accelerating admixtures must be carefully selected and monitored on site as higher dosages reduce the later age compressive strength and durability of portland cement-based concrete/shotcrete (Jolin, Melo, Bissonnette, Power, and Demmard, 2015).

In underground excavation projects, wet-mix shotcrete has become more and more popular. The popularity is mainly due to high application rates and the use of hydration-controlling admixtures. Hydration-controlling admixtures stabilize the shotcrete mix for long periods before spraying and provide additional flexibility/robustness in material delivery. However, the increased use of more sophisticated wet-mix shotcrete mixtures containing admixtures requires careful control. Increasing the dosage of hydration-controlling admixtures has an impact on cost, and requires a higher demand of set-accelerating admixtures to reactivate the hydration process and ensure rapid hardening during material placement.

Once again, as reported in the literature, the overdosing of set accelerator on site must be prevented/limited because of its detrimental effect on material porosity that could significantly affect the durability of the shotcrete lining (Jolin, Melo, Bissonnette, Power, and Demmard, 2015).

Dry-Mix Process

Fundamentally different to the wet-mix shotcrete process, the dry-mix shotcrete process consists of pneumatically conveying the dry mixture through hoses and adding the mixing water generally 10 ft (3 m) before the nozzle outlet (Fig. 1). In this case, all the mixture ingredients, including the admixtures such as set accelerator, are conveyed in dry form using compressed air. Mixing water is then added to the dry mixture in a fraction of a second before impacting the receiving surface. Therefore, the dry-mix process allows for very efficient delivery over long distances, and robust placement of mixtures onto vertical and overhead surfaces with limited use of admixtures.

The dry-mix process has become very popular for shotcrete operations involving very challenging logistics and rapid mobilization, such as tunnel projects with difficult access and/or requiring long conveying distances with frequent/unscheduled starting and stopping. Dry-mix shotcrete has also been proven effective for overhead and vertical applications, where the use of set accelerator is restricted due to durability concerns.

FIBER-REINFORCED SHOTCRETE

The use of fiber-reinforced shotcrete (FRS) has been used for many years in underground excavation projects to replace mesh in gravity failure conditions, manage rock bursts and manage ground deformations in moderate stress conditions. FRS is also used as temporary ground support in conjunction with tunnel boring machines, or as first pass support in dynamic (high-stress) conditions to manage seismicity ensuring safer re-entry before permanent ground support installation.

From a technical standpoint, the use of fibers is mainly to improve flexural strength and toughness where ground conditions require energy absorption.

In most countries, the design of a FRS lining for tunneling applications is based on the modified Barton chart, which is illustrated in Fig. 2. The modified Barton chart provides general guidelines for designing the FRS lining considering the rock mass quality (Q), the opening configuration and the associated reinforcement provided by the bolting pattern and FRS lining. The rock mass quality (Q) is evaluated via the empirical rock stability classification (Q-System) developed by Barton et al. (1974) and updated in 1994. The reinforcement provided by the FRS is related to the flexural toughness/energy absorption in Joules, measured in accordance with ASTM C1550 (ASTM C1550, 2008).

This design approach appears to be less valid for high-stress/challenging ground conditions, such as deep tunnels where seismic events can produce high-intensity rockbursts, and deformations exceeding 3.94 in. (100 mm). In these conditions, the relative stiffness of the FRS lining, and its limited load bearing capacity at such large deformations, limits the contribution of the FRS lining to the dynamic ground support system. The brittle behavior of FRS under dynamic loading (high strain rate), and the relative low tensile strength, limits the use of FRS linings in such high-stress conditions due to the risk of surface spalling (refer to Fig. 3).

In dynamic loading conditions, FRS or plain shotcrete is usually combined with other systems such as yielding bolts, mesh, cable lacing or mesh straps that increase energy absorption and provide better control of large ground displacements.

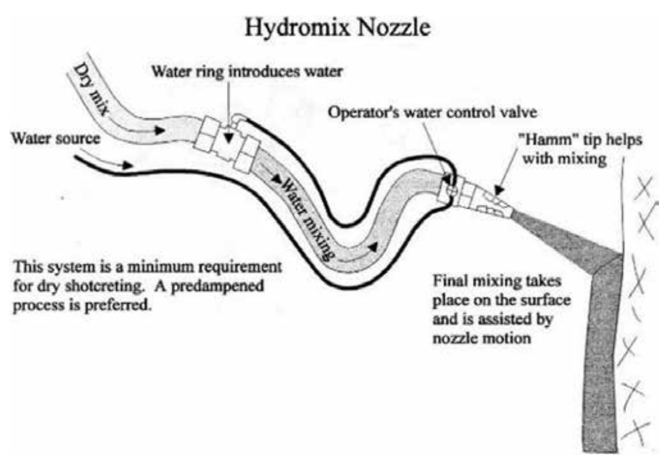

Fig. 1: Hydro-mix nozzle assembly (from ACI 506R-16)

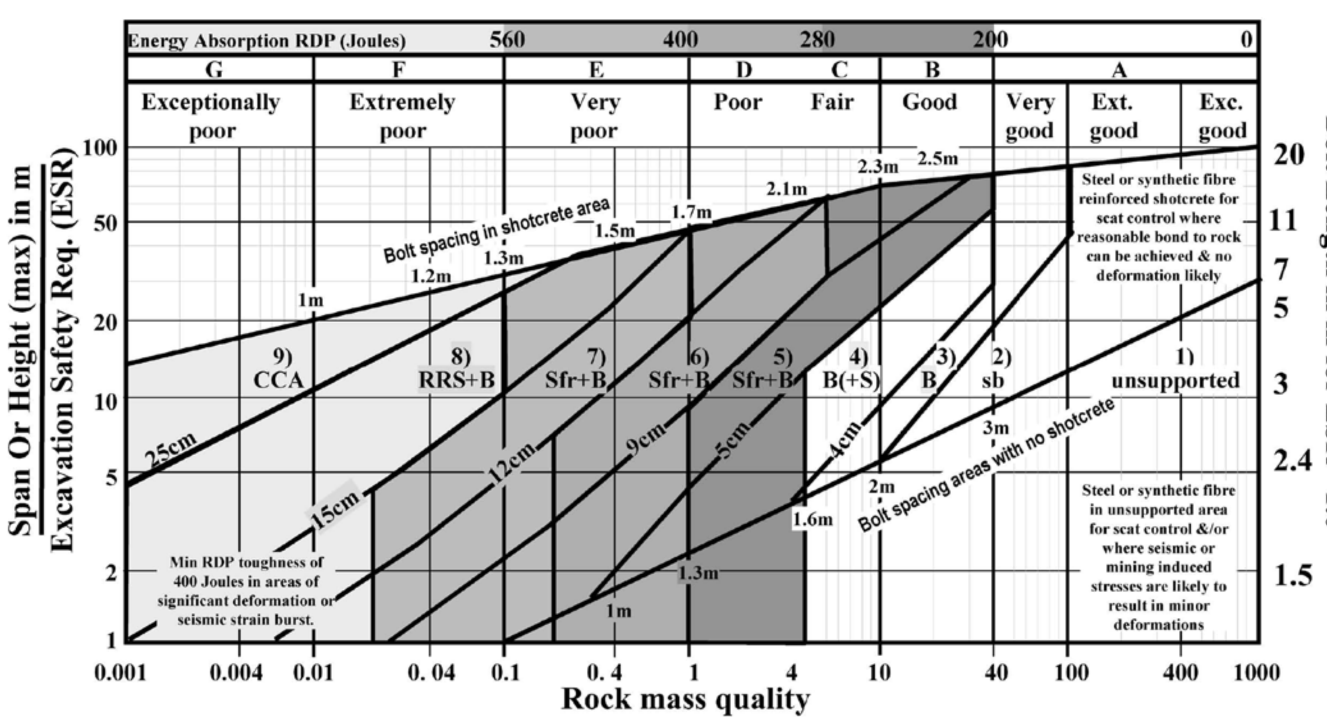

Fig. 2: Modified Barton Chart (from Papworth, 2002)

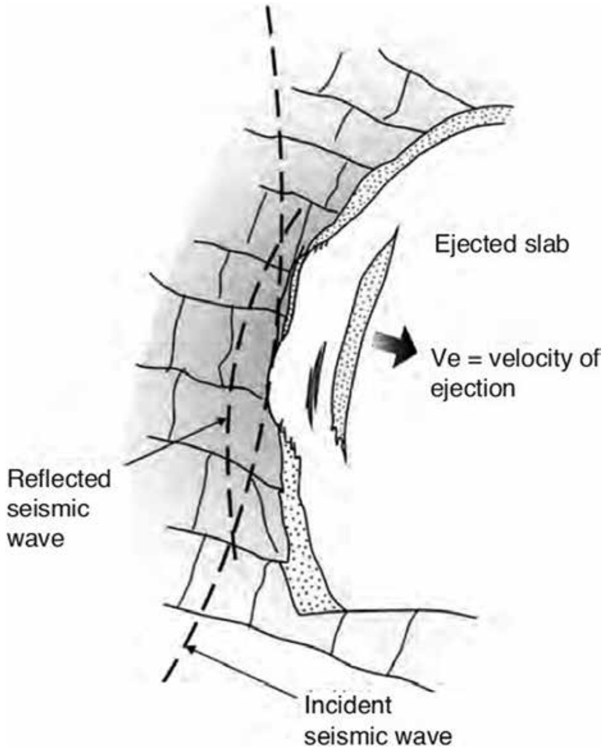

Fig. 3: Seismic spalling of brittle shotcrete lining (from Stacey, 2001)

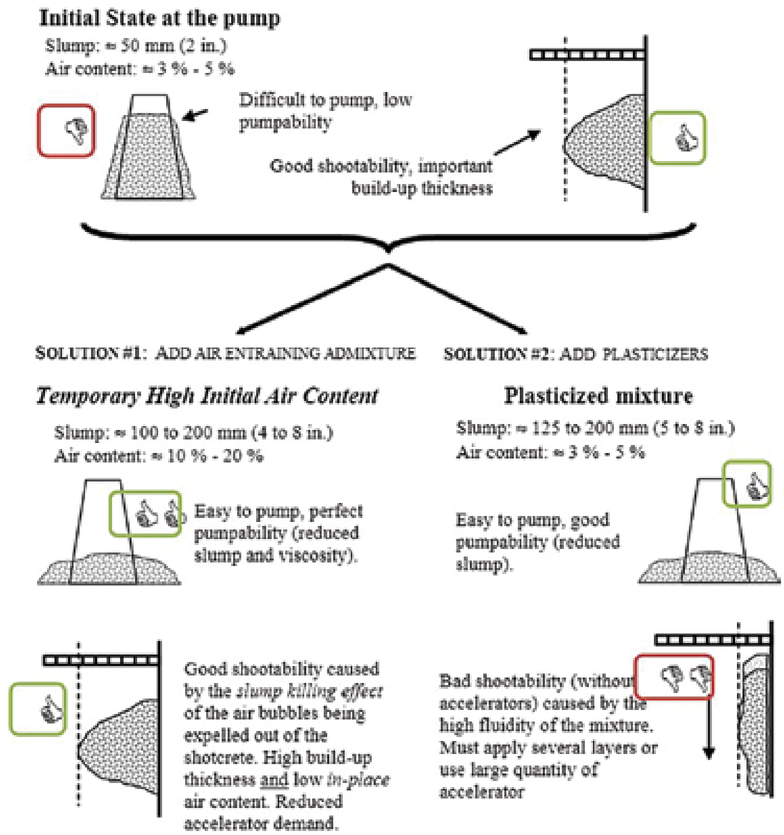

Fig. 4: Schematic illustration of temporary high initial air content concept (from Jolin and Ginouse, 2012)

SCOPE

The intent of the following sections is to provide a quick overview of emerging shotcrete technologies/practices offering solutions for these tunneling applications:

- Producing a highly durable shotcrete lining;
- Efficiently producing high quality shotcrete on-demand;
- Reducing rebound and controlling dust/chemical emission;
- Speed-up the development cycle and reduce the curing period of shotcrete before re-entry; and
- Improving the spalling/impact resistance of the shotcrete lining in challenging ground conditions.

INNOVATION IN SHOTCRETE TECHNOLOGIES

Highly Durable Shotcrete Lining

Several studies have proven that sprayed concrete materials can provide similar or better transport properties and durability than conventional cast-in-place concrete (Zhang, Morgan, and Mindess, 2016). This section briefly describes the key rules to follow produce a highly durable shotcrete lining.

MINIMIZING THE WATER-TO-CEMENT RATIO

Porosity in cementitious materials such as concrete/shotcrete is the first order parameter governing most of the material's performance, especially its durability.

Because porosity of concrete is directly related to the water-to-cement ratio (Neville, 2011), limiting the water content of sprayed concrete is the first preventive action to minimize porosity of the in-place material and therefore guarantee its performance in terms of mechanical properties and durability.

In the dry-mix process, even if the amount of water added to the dry mixture is controlled in real-time by the nozzleman, the placement mechanisms limit the water-to-cement ratio between 0.35 to 0.45 with 0.40 as typical value, which guarantees performance and durability (Zhang, Morgan, and Mindess, 2016). Even for overhead surfaces, the dry-mix process allows for instantly adjusting the plastic consistency to ensure proper build-up simply by reducing the amount of water added to the dry mixture. This straightforward and instant adjustment of the plastic consistency makes the dry mix process a very robust and reliable way to place durable shotcrete materials with low water-to-cement ratios. This is achieved with a limited amount of additives such as plasticizer and set accelerator.

In parallel, it is very common with the new generation of superplasticizers to produce good quality wet-mix shotcrete using typical water-to-cement ratios lower or equal to 0.40. However, as previously mentioned, highly pumpable concrete with a low water to cement ratio does not guarantee its shootability. In other words, the material can be very easy to pump but it can sag and not stick to walls especially overhead surfaces. If special care is not given to the mixture design of wet-mix shotcrete, one could incorrectly believe that adding plasticizing admixtures could be the solution to ensuring adequate pumping and shootability. As illustrated in Fig. 4, a highly plasticized mixture would generally exhibit poor shootability and would require higher dosages of set accelerating admixtures to ensure proper built-up onto the receiving surface particularly for overhead zones.

Minimizing the Set Accelerator Dosage and Avoiding Overdosing

The detrimental effect of overdosing set accelerators on shotcrete durability has been clearly demonstrated in literature (Jolin, Melo, Bissonnette, Power, and Demmard, 2015). In practice, the risk of overdosing is generally higher in the wet-mix process since the volume of accelerator is field controlled. In the dry-mix process, the set accelerator (when used) is pre-dosed/blended in dry form into the dry mixture before being used on site. In the dry-mix process, the plastic consistency needed for the desired material build-up is adjusted in real-time simply by adjusting the water content at the nozzle immediately before discharge. In contrast, in a highly plasticized wet-mix shotcrete, the material build-up during shotcreting is generally produced by the addition of set accelerator at the nozzle to achieve the desired stiffening/hardening effect. In wet-mix application, the risk of overdosing set accelerator is increased particularly when shooting overhead zones that require a higher degree of stiffening/hardening for build-up while reducing the risk of fall-out. The use of supplementary cementitious materials such as silica fume and/or fly ash and rheology modifier additives help to improve the material build-up process, and therefore reduce the set accelerator demand.

Fundamentally, the most efficient way to reduce set accelerator demand in wet-mix shotcrete, while ensuring both excellent pumpability and shootability, is the concept of temporary high initial air content, as illustrated in Fig. 4 (Jolin and Ginouse, 2012) developed over 20 years ago (Beaupré, 1994). As explained in Fig. 4, the high initial air content (10 to 20%) produces excellent pumpable material while ensuring good sag resistance and build-up once the material hits the surface. The air content typically drops to 4 to 6% during impact, which produces a "slump-killing effect" ensuring material consolidation without sagging or fall-out (Jolin and Beaupré, 2003). This concept significantly reduces the set accelerator demand to build thicker shotcrete layers per pass, particularly for overhead surfaces.

In practice, accurate control and monitoring on-site of the set accelerator dosage being added to the nozzle is critical for wet-mix shotcrete to limit the risk of overdosing, and the detrimental effect it can have on later-age performance and durability.

In comparison, the monitoring of set accelerator dosage is well controlled in the dry-mix process since the additives are pre-dosed/blended into the dry mixture before use on site.

Mobile Shotcrete Production Unit

For specific wet-mix projects, it is not always possible to order and receive wet-mix shotcrete from a ready-mix plant. Following is a partial list of potential situations when this is not possible:

Fig. 5: Mobile self-loading mixer with bulk bag lifter

- Projects in remote areas;
- Small volumes;
- Challenging schedules (difficult ground conditions, night shift, lane closures…);
- Local ready-mix producers do not have the knowledge and/or experience to produce high-quality specialty shotcrete mixtures;
- Limited availability of raw materials;
- Shotcrete mixture needs to be mixed on-site due to a short pot life; and
- Excessive dosage of hydration retarder and thus excessive accelerator dosage at the nozzle.

For these types of projects, it is currently possible to produce shotcrete on-demand, on-site using new types of equipment and dry pre-blended materials. Dry preblended material is usually produced in manufacturing facilities ensuring consistent raw materials, proven batching records and strict quality control.

Dry preblended wet-mix shotcrete material can be stored on-site in bulk tote bags, which are then available to be mixed on-demand using equipment such as the new mobile bag-lifting mixer (Fig. 5). A production ticket is printed and provided for each batch, allowing for the control and tracking of every batch produced.

This innovative system helps to reduce material waste and facilitate logistics in remote areas with difficult access for standard ready-mix trucks.

This type of system allows for the on-demand, on-site production of shotcrete minimizing the use of retardant and other admixtures traditionally used to offer logistical/delivery flexibility but also higher dosages of accelerator for overhead shotcreting and rapid strength gain.

It is also possible to use a mobile bulk dry-mix shotcrete sprayer. Using a bulk dry sprayer allows the user to take advantage of the robustness, flexibility and durability provided by the dry-mix process shotcrete while guaranteeing high application (output) rates and controlled dust emissions during spraying operations (Fig. 6).

This type of system can be loaded via bulk bins erected on-site (loading area) or by using bulk tote bags (McDonald and Cruz, 2015). These systems allow for on-demand production with optimized accelerator dosages in the dry preblended shotcrete mixture accurately dosed at the manufacturing facility. Thus, the accelerator dosage is not affected by any other admixtures or on-site conditions, and since the mixing water for dry-mix shotcrete is added at the nozzle, there is no need for the use of a retarder or hydration stabilizer. Additionally, the long-term durability of the in-place dry-mix shotcrete is not affected by the high porosity that can be the result of excessive accelerator dosage use in the wet-mix process (Jolin, Melo, Bissonnette, Power, and Demmard, 2015).

Fig. 6: Bulk dry shotcrete hauler/sprayer

Fig. 7: Adequate lighting and access to the shooting face in a tunneling application (from Croutch, 2014)

Practices for Reducing Rebound and Dust/Chemicals Emission

Proper shotcrete nozzling technique, including the encasement of embeds, openings and reinforcing steel is an important aspect of reducing shotcrete rebound. Adequate lighting and clear access to the shooting face are also important factors for allowing the reduction of shotcrete rebound (Fig. 7). Shotcrete used for ground support in mining and tunneling applications should be applied in accordance with ACI 506R-16, "Guide to Shotcrete." The ACI Shotcrete Nozzleman Certification Program developed and administered by ACI Committee C660 is an excellent program for qualifying and certifying shotcrete nozzlemen for most projects but does not directly cover all the requirements for a nozzleman working in mining and tunneling environments. For some large tunneling projects such as the Metropolitan Transportation Authority (MTA) CC/Long Island Railroad/East Side Access project in New York City, NY, it has become common practice for authorities to develop training and certification programs specific to the project (Drakeley and Rand, 2014). Specifying minimum requirements for shotcrete crew experience including nozzlemen, foremen and gun/pump operators also helps to ensure that the shotcrete will be applied properly.

The shotcrete mixture design used for tunneling applications can also be optimized for rebound reduction for both dry- and wet-mix shotcrete. The aggregate gradation should meet the requirements of Gradation No. 1 or Gradation No. 2 in accordance with ACI 506R-16, "Guide to Shotcrete." A properly designed shotcrete aggregate gradation will reduce rebound due to the optimal particle packing of the in-place shotcrete (Reny and Jolin, 2011). Supplementary cementitious materials used to replace Portland cement in the binder portion of the shotcrete mixture design can also help to reduce rebound. Silica fume has been shown to greatly reduce rebound in dry-mix shotcrete when used to replace a portion of the binder content (Wolsiefer and Morgan, 1993).

For dry-mix shotcrete, certain equipment choices and practices can also help dramatically reduce dust emissions in the underground environment. Using bulk pre-packaged tote bags in conjunction with a hopper hood manufactured to fit the receiving hopper of the shotcrete machine helps to seal the hopper and prevent the release of excess dust (Fig. 8). Proper maintenance and adjustment of the shotcrete equipment including the water ring in the nozzle, and the exhaust port, wear pads and wear plates on the dry-mix gun will also help to reduce dust emissions.

Pre-dampening equipment can also be used for dry-mix shotcrete to reduce the amount of airborne dust, as the

Fig. 8: Bulk pre-packaged tote bag with hopper hood

Fig. 9: Shotcrete pre-dampening gunning rig with dry-mix shotcrete machine

material is mixed with a small amount of mixing water prior to being introduced into the shotcrete machine (Fig. 9).

The use of a hydro-mix shotcrete nozzle improves particle wetting prior to exiting the nozzle, by moving the water ring roughly 10 ft (3 m) back from the nozzle exit and allowing for increased mixing potential between the mixing water and dry-mix shotcrete (Fig. 10).

Adequate ventilation and dust control devices such as a water atomizer that generates ambient fog is an efficient standard practice used in the mining industry to help control dust during shotcrete operations (Fig. 11).

When using wet-mix shotcrete in tunnel applications, it is typical to use many different liquid chemical admixtures including retarder to increase the pot-life for long underground travel times. Set accelerator would then typically be added at the nozzle to improve early age strength development. Chemical additives can become airborne in the underground environment once atomized in the air stream during the spraying process. Therefore, it is important to minimize the amount of additives as much as possible and as previously mentioned; these chemical additives can be significantly reduced and potentially even removed in the dry-mix process. In the wet-mix process, additives are critical to producing good quality material and use of admixtures can be minimized when using an optimized aggregate gradation, supplementary cementitious materials to facilitate pumping and reduce rebound, and by increasing the initial air content of the shotcrete to improve pumpability.

Fig. 10: Hydro-mix nozzle for dry-mix shotcrete (from Hutter, 2014)

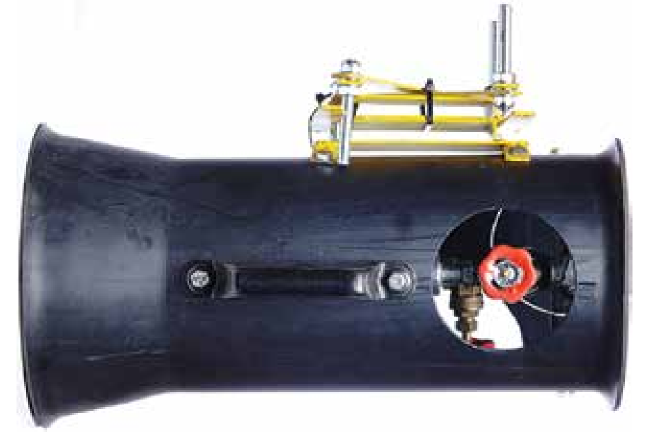

Fig. 11: Water atomizer used to reduce airborne dust

Ultra-Rapid Performance Gain Shotcrete

Among the existing techniques to speed up the development cycle of underground excavation operations, the use of ultra-rapid strength gain shotcrete is beginning to receive more traction in the industry. By manipulating the cement chemistry and mixture design, this innovative technology allows much earlier re-entry to headings after the completion of shotcrete operations.

Using current portland cement technology, high early strength cement (Type III or Type HE) and a high accelerator dosage, it is possible to provide a shotcrete mixture design capable of reaching early age compressive strengths of up to 1000 psi (7 MPa) at 4 hours. This is possible in both the wet- and dry-mix processes. However, to exceed this early strength level, the cement technology needs to be reviewed. From a cementitious matrix standpoint, the use of an ettringite-based cement such as calcium sulfo-aluminate (CSA) cement can provide very rapid strength gain compared to high early strength portland cement (Type III or Type HE) with a high accelerator dosage (Reny and Ginouse, 2014). At early ages, this rapid strength gain is mainly due to a rapid formation of ettringite, which occurs when the CSA based cement comes into contact with the mixing water.

Unfortunately, the rapid formation of ettringite is also accompanied by a quick decrease in the workability of the mixture, leading to placement issues (Lemay, Jolin, and Gagné, 2014). Even though it is possible to increase the workability period by using retarding admixtures, their use also generally increases set time and therefore delays strength gain. To overcome this workability issue while ensuring a rapid hardening behavior, the use of dry-mix process has been shown to be the ideal choice since the mixing water is added to the mixture in a fraction of a second before impacting the receiving surface. By using ettringite based dry-mix shotcrete, it is typically possible to obtain approximately 2900 psi (20 MPa) after only 2 hours (Reny and Ginouse, 2014) in contrast to 1000 psi (7 MPa) after 4 hours with accelerated portland cement-based shotcretes.

This makes the combination of CSA cement technology with the dry-mix shotcrete process an ideal solution for reducing the mining and tunneling cycle times. This technology is commonly referred to in the industry as RS Shotcrete technology.

RS shotcrete technology has been successfully introduced and used in Canadian mines to accelerate the development cycle of daily underground operations and to increase the speed of construction for critical permanent infrastructure. Reaching 2900 psi (20 MPa) after 2 hours allows for a much quicker re-entry time under the sprayed openings/zones and leads to reduced lead-time to the next development step.

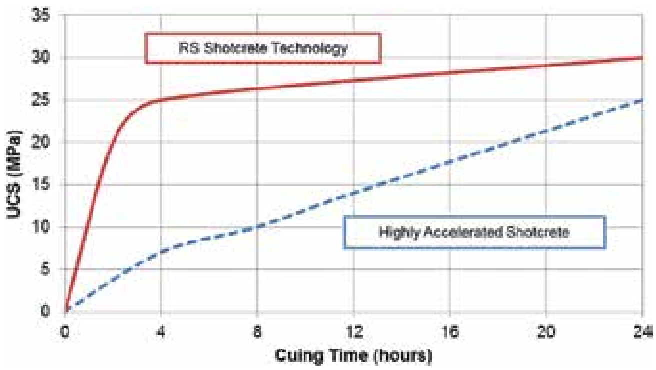

Fig. 12: Typical early age strength gain provided by RS shotcrete technology and highly accelerated portland cement shotcrete

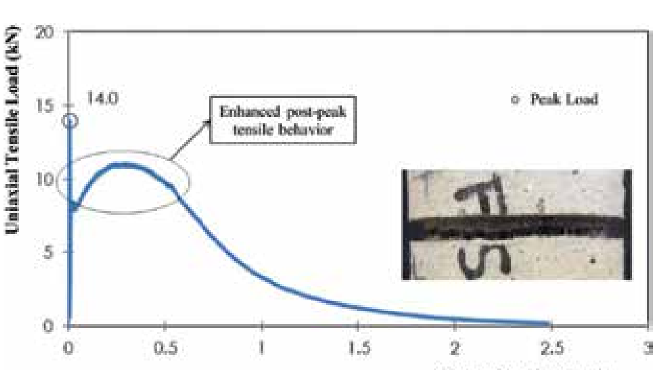

Fig. 13: Improved post-peak tensile strength of engineered high-performance shotcrete (from Ginouse, Reny, and Jolin, 2015)

Combined with structural fibers, the RS Shotcrete technology allows for developing ultra-rapid flexural toughness in challenging ground conditions requiring structural support and energy absorption as early as possible (Ginouse and Reny, 2015).

This technology has also been tested (Ginouse and Clements, 2015) and used successfully for rapid repairs of critical civil infrastructure requiring fast re-opening to traffic and services (Jolin, 2016).

Engineered High Performance Shotcrete

Using design principles similar to ultra-high performance concrete (De Larrard, 1999), recent advancements have been made to adapt this technology for ground support lining in underground projects (Ginouse, Reny, and Jolin, 2015).

This technology provides much higher tensile/flexural performance (see Fig. 13) than regular FRS resulting in higher spalling/impact resistance and energy absorption. On one hand, the overall ground support performance against seismicity and high-stress conditions are greatly improved. On the other hand, the technology is paving the way for thinner support innings, resulting in significant savings in material consumption, labor, time of application and overall logistics.

This novel shotcrete technology has been recently been introduced and successfully tested in Canadian mines facing very challenging ground conditions requiring high performance ground support with minimal amounts of material required to be transported underground from the surface.

Similar technology has been successfully used in tunnel repairs and surface protection in both Japan and the United States to extend durability of tunnel linings (Li, 2003).

Conclusions

Dry- and wet-mix shotcrete are practical, proven and well-adopted methods for ground support in underground excavation projects.

Among the different innovative technologies presented in this article and introduced during the past decades, here are the main technical, logistical and operational solutions/advancements available for underground projects:

- Enhanced shotcrete lining durability obtained using low water-to-cement ratio, supplementary cementitious materials, optimized aggregate gradation, high initial air content concept and minimal dosage of set accelerating admixture accurately monitored on-site in wet-mix shotcrete.
- Flexible and robust shotcrete operations using the dry-mix process or hydration control additives in wet-mix shotcrete to extend pumping life.
- High production of shotcrete material on-demand using either a bulk dry-mix loading/hauling/spraying system or a mobile self-loading mixer producing high quality wet-mix shotcrete on-demand using dry pre-blended materials.
- Low-rebound shotcrete by following good industry practices, properly trained crews, well-maintained equipment and an optimized mixture design.

- Low dust and chemical emissions by following best industry practices, closed bulk dry-mix system, pre-dampening equipment and an efficient water atomizer.
- Rapid development cycle and accelerated tunnel repairs using ultra rapid strength gain dry-mix shotcrete allowing for much faster re-entry and re-opening to traffic/services.
- High-spalling/cracking-resistant shotcrete for challenging ground conditions and protective lining layer using engineered high-performance shotcrete providing enhanced tensile/flexural performance and high-energy absorption.

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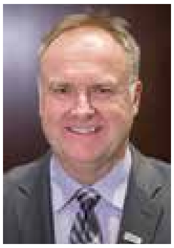

Scott Rand *is Vice President, Sales, for King Packaged Materials Company, where he is responsible for the Construction Products Group. Rand has over 30 years of experience in the concrete industry and has spent the past 20 years with King. He has had a major contribution in the growth of the King Shotcrete Solutions brand and its leading position in the North American shotcrete industry. Rand has been involved in high-profile projects in numerous cities from New York to Chicago. He is the 2017 President of ASA and a member of ICRI, UCA of SME, CIM, and ACI.*

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Modeling of Load-Bearing Behavior of Fiber-Reinforced Concrete Tunnel Linings

By Axel G. Nitschke

The use of fiber-reinforced concrete (FRC)—with steel or macro-synthetic fibers—has technical and economic advantages that primarily stem from the fact that fibers transform the post-cracking behavior from a brittle failure mode typical of unreinforced concrete into an elasto-plastic behavior. Numerous codes and guidelines provide qualitative or quantitative design approaches.[1-6] Modeling of the load-bearing behavior based on a stress-strain relationship (SSR) for tunneling applications is commonly used. This article discusses the modeling process and some typical results of a parameter study. It also identifies the weakness of the current concept and suggests a path to more fully use the structural and economic potential of FRC. The concept discussed herein is theoretical in nature and applicable for both steel and synthetic FRC. To limit the scope of this article, the discussion is focused on the load-bearing capacity under cracked conditions, which is typical for shotcrete initial linings. Therefore, design concepts that do not use the toughness potential of FRC (that is, by limiting it to uncracked conditions) are not discussed herein.

Different international codes and guidelines for FRC provide testing procedures based on simply supported beam tests that are used to define an SSR by basically amending the known trapezoidal or parabolic SSR for concrete on the compression side with assumptions for an SSR on the tension side. The latter is the primary subject of this article. For this discussion, it is irrelevant which type of macrofibers—steel or synthetic—is used because the SSR models a homogeneous, composite material behavior and not discrete fibers. In general, the SSR design approach follows the concept to adapt existing concrete design concepts and procedures and simply extend the SSR on the tension side to account for the effect of the properties of the composite material.

This article is focused solely on combined moment thrust or moment normal force (*M/N*) loading of tunnel linings in which bearing capacity relies on a tunnel arch. This is typical for soft ground tunnel linings and rock tunnels with soft-ground-like behavior. Nonetheless, the ideas and concepts can also be adapted in typical rock tunneling applications. However, they are not useful in tunnels with no arching effect, which is typical for tunnels with relatively thin linings or with an irregular shape. For these types of tunnels (that is, typical initial linings in classical rock tunneling), qualitative and empirical design concepts (for example, Barton chart[7,8]) are available but are not discussed in this paper.

The use of an SSR is typically evaluated on the basis of beam test data. Under elastic (uncracked) conditions, the beam theory and the classical mechanics for materials apply. However, after the initial cracking of the FRC, the material is no longer homogeneous and the theoretical conditions for beam theory no longer apply. The bearing behavior of FRC in beam tests in a cracked state are better described using a stress-crack width relationship rather than a stress-strain relationship. It is important to understand that for the aforementioned reason, an SSR cannot be measured directly in standard FRC beam tests. The codes and guidelines are therefore describing testing procedures that measure external forces and deformations, which are then transformed into stresses and "equivalent" strains via an equivalence model, which implies several assumptions. Research by Nitschke[9] has discussed flaws in some of these models by back-calculation of tests using the SSRs. It was shown that these flaws can be significant under loading conditions of combined moment and thrust, typical for tunneling. The same work also provided modified models to provide more useable and accurate procedures.[9]

STRUCTURAL BASICS OF FRC DESIGN

The biggest difference between the sectional strength of unreinforced or steel bar reinforced concrete and FRC is that the concrete in unreinforced or bar-reinforced concrete has (theoretically) no bearing capacity in tension. In the modeling of conventionally reinforced concrete sections, all tension is supported by the reinforcing bar. Because the location of the reinforcing bar is known, the location of the resulting tensile force is also known, and this simplifies the calculation of the equilibrium compared to FRC sections. The computation of axial equilibrium in FRC sections is much more challenging because the location of the resulting tensile force is an unknown during the computation and moves if the external load and the distribution of the strain over the cross section changes.

The design assumptions for the calculation of the sectional strength for FRC based on an SSR can be summarized as follows[10] (ACI 318-14, Section 22.2,[11] ACI Design Handbook, Section 7.4[12]):

1. Equilibrium shall be satisfied at each section;
2. Strain in the cross section of the member shall be assumed directly proportional to the distance from the neutral axis (Bernoulli's theorem). The cross section also remains plane during loading;
3. The stress-strain relationship for the FRC in compression is defined; thus, the stress for a given strain is known within defined limits; and
4. The stress-strain relationship of the FRC under tension is defined; thus, the stress for a given strain is known within defined limits.

A comparison of the essential design assumptions for moment and axial strength at sections for reinforcing bar reinforced concrete design in ACI 318 shows that the first and second assumptions—equilibrium (ACI 318-14, Section 22.2.1.1[11]) and Bernoulli (ACI 318-14, Section 22.2.1.2[11])—are adapted for FRC. However, by citing two additional design assumptions from ACI 318, two major differences between FRC and classical bar reinforced designs assumptions can also be highlighted. According to ACI 318-14, Section 22.2.2.2[11]:

"Tensile strength of concrete shall be neglected in flexural and axial strength calculations."

For sectional strength calculation of FRC, the tensile strength under uncracked as well as cracked conditions is used. This is one of the major differences between the modeling of FRC in comparison with unreinforced or bar-reinforced concrete.

According to ACI 318-14, 22.2.1.2[11]:

"Strain in concrete and non-prestressed reinforcement shall be assumed proportional to the distance from the neutral axis."

This design assumption is based on the hypothesis of perfect bonding between steel and concrete. While bar-reinforced concrete is modeled as a composite of concrete and steel, where each component has its own material properties (refer to ACI 318-14, Section 22.2.2, for concrete and Section 22.2.3 for non-prestressed reinforcement[11]), FRC is assumed to be a macroscopically homogeneous and isotropic material.[13] The material properties of a single fiber in the model becomes irrelevant. Therefore, the fibers and the concrete are modeled using a single SSR relationship and not two (that is, as for steel reinforcing bar and concrete).

After the cracking of the FRC material under tension, the material properties in the model are based on strains rather than a discrete crack. In the model, the cracked material is also viewed as homogeneous and isotropic. Because this is in the area around the crack, it is obviously not the case. This circumstance is very important to realize and understand when evaluating the sectional strength of FRC using an SSR. During the evaluation of material testing data based on beam tests (and subsequently the design of the structure), it is assumed that the crack is "smeared" over a certain length into an "equivalent strain," which is also referred to as the "integral approach."[10]

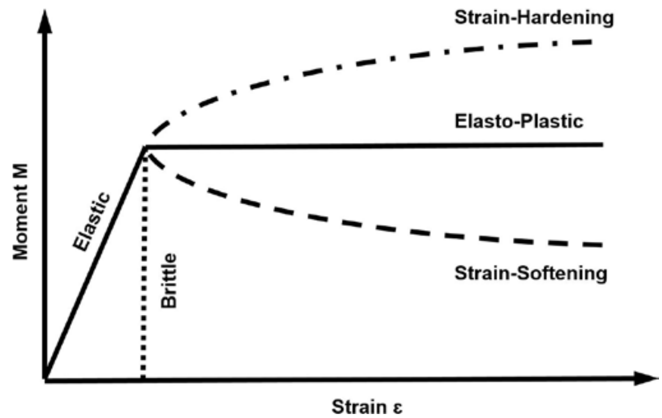

Fig. 1: Schematic post-peak response of fiber-reinforced concrete

Fibers influence the bearing behavior in multiple ways. However, three properties are most relevant for application in tunnels.[13] They slightly increase the flexural tensile strength (1), which is mostly needed if improved properties under uncracked conditions are desired (that is, to design for serviceability.) However, for the case of ultimate bearing capacity of tunnel linings, the residual flexural tensile strength under cracked conditions (2) and the increase of the toughness (3) are the major benefits. The focus of this paper is on the performance improvements attributable to (2) and (3).

The provision of a reliable and usable post-cracking tensile strength transforms the brittle failure mechanism of plain concrete into a ductile failure mode (refer to Fig. 1). This is a material property that provides major engineering and economic advantages, especially if used to facilitate system failure of a tunnel lining rather than a cross section failure at one presumably most-critical location. A concept for the design of a system failure will be presented later in this article.

According to Dietrich,[10] the load-bearing response of FRC under bending can be subdivided into three phases. The first "uncracked" phase is based on the behavior of the concrete matrix alone. The concrete matrix and fibers are assumed to be in "perfect bond" and the ratio of load supported by the concrete compared to the fibers is dependent on the moduli of elasticity of the materials. Due to the relatively small volume of fibers compared to concrete, the load-bearing share of the fibers is relatively small.

Microcracks develop in the matrix during the second phase of load response. The development of cracks is hampered by the fibers and leads, according to Dietrich,[10] to a more stable "strain softening" with a restricted expansion of cracks and less brittle material behavior. Phase two ends with crack widths of approximately 0.004 in. (0.1 mm).[10]

In the third phase, the concrete matrix no longer provides significant bearing capacity at the crack. The opening cracks are bridged by the fibers and the load transfer is effectively provided by the fibers alone.

SECTION DESIGN OF FRC USING STRESS-STRAIN RELATIONSHIP

The three phases of crack development are also reflected in SSRs found in different codes and guidelines. Studies by Nitschke[9,15] have shown that by using all three phases in computer simulations, test results obtained using beam tests can be simulated very accurately. Typically, all SSRs in codes and guidelines incorporate Phase I (elastic) and Phase III (macrocrack) behavior. However, because the distinction between uncracked and microcracking in Phase II is not clearly defined, Phase I and Phase II are oftentimes lumped together or Phase II is completely neglected.[9] It is important to note that for the modeling of ultimate load-bearing capacity in the macrocracked phase, a detailed evaluation of the microcracking Phase II is irrelevant. However, it might be significant for serviceability design.

A generic SSR and nomenclature of the variables used throughout this paper is shown in Fig. 2. The tension side is represented by the three sections discussed previously. The compression side uses a classical parabolic constant shape.

Nitschke[9] has conducted numerous simulations of beam test results under pure bending as well as combined *M/N* loading. The three load-bearing phases observed during the experimental studies could also be reflected with the simulation of the load-bearing behavior, using the SSR as follows. In general, it is possible to identify "typical" SSRs based on typical load-deflection curves from either tests or the simulation of results. By adhering to certain boundary conditions, it is almost possible to look at each of the three phases separately.[9]

The pure elastic (uncracked) behavior is related to the first part of the stress-strain relationship and conforms to the principles of elastic bending. The flexural strength f_{t1} results from the maximum elastic moment divided by the section modulus. The range of the related strain ε_{t1} is very limited and can either be measured during the test or—based on the used SSR—be calculated using the original modulus of elasticity. Alternatively, and if the major focus of the interest is the bearing capacity under cracked conditions, a generic value between 0.1‰ $\leq \varepsilon_{t1} \leq$ 0.15‰ (100 to 150 microstrain) will yield sufficiently accurate results because the overall influence of the elastic section on the bearing capacity under cracked conditions is diminished.[9]

The interim section of microcracking is reflected by the second section of the SSR on the tension side. In general, two different types of curves are used between ε_{t1} and ε_{t2}: 1) a plateau; or 2) a linearly decreasing curve (trapezoid). By using a plateau, the stress in the second section is constant ($f_{t2a} = f_{t1}$) (refer to Fig. 2). In general, the plateau creates load-deformation curves with a distinct maximum and a "hard" decline of the moment-bearing capacity in pure bending conditions. On the other hand, a declining curve in the second section ($f_{t2a} \geq f_{t2b}$) (refer to Fig. 2) "softens" this area of the moment-deflection curve.[9]

More complex curves can be used in the second section; however, the two selected types may encompass many other cases. As parameter studies have shown,[9] the overall influence of the second section of the SSR controls the shape of a specific area of the simulation of the bearing capacity but has only a small influence on the overall bearing capacity. It was also shown that more important than the value of the stress f_{t2b} is the specific strain ε_{t2}, which controls the shape of a moment-deflection curve in this area.[9]

However, by far the biggest influence on the load-bearing behavior under cracked conditions is the third section of the SSR. The tensile stress under cracked conditions is typically referred to as the "residual strength." Under consideration of the conducted beam tests with a maximum deflection of 0.14 in. (3.5 mm), SSRs up to a strain of ε_{t3} = 25‰ were investigated.

The load-bearing capacity of a cross section based on the SSR is calculated by finding the equilibrium between internal and external forces. Only a discussion of the basic principle is covered in this paper. A complete solution for the calculation of the inner forces resulting from a specific strain scenario is provided by Nitschke.[9] For the calculation of equilibrium between internal and external forces acting on

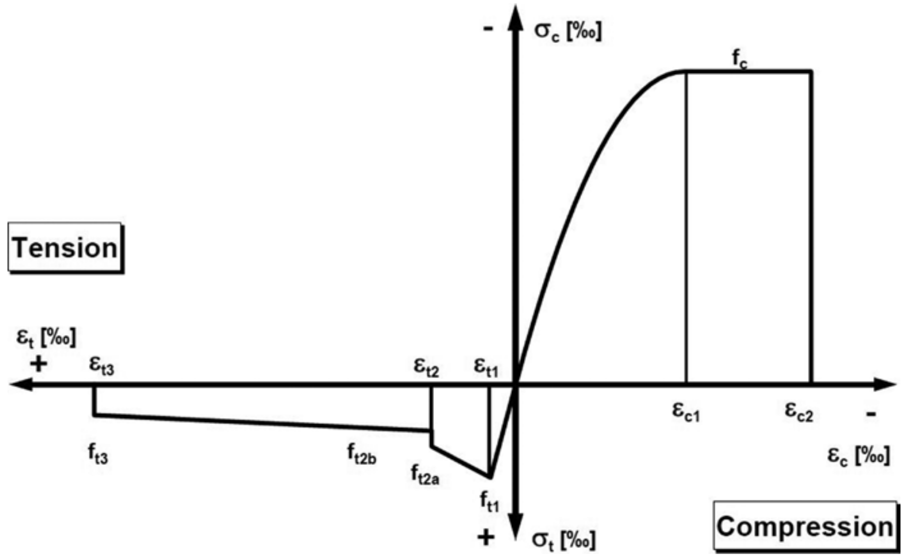

Fig. 2: Generic stress-strain relationship for fiber-reinforced concrete

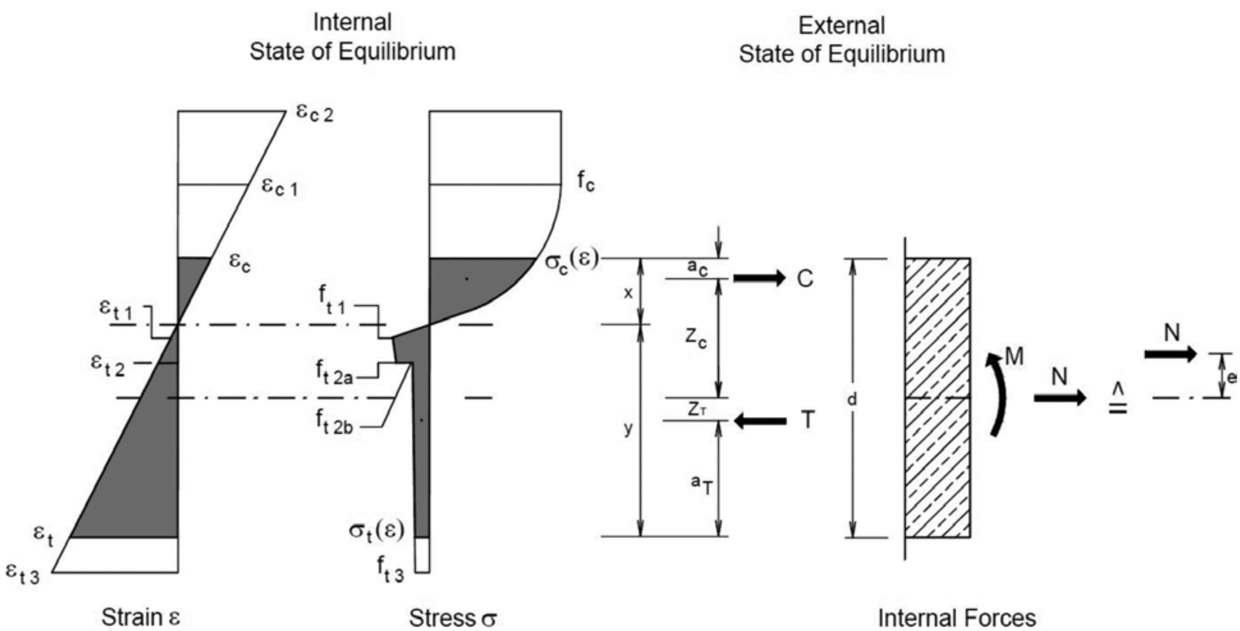

Fig. 3: Calculation of equilibrium between internal and external forces

a cross section under typical tunneling conditions, there are two equations (refer to Fig. 3)

$$\sum N = 0 \Leftrightarrow \quad C - T + N = 0$$
$$\sum M = 0 \Leftrightarrow \quad -C \cdot z_C - T \cdot z_T + M = 0$$

The internal lever arm *z*, as well as the height of the compression zone *x* and height of the tension zone *y* are calculated as follows

$$z_C = \frac{d}{2} - a_C \qquad z_T = \frac{d}{2} - a_T$$

$$x = \frac{|\varepsilon_c|}{|\varepsilon_c| + |\varepsilon_t|} d \qquad y = \frac{|\varepsilon_t|}{|\varepsilon_c| + |\varepsilon_t|} d$$
$$\text{for } \varepsilon_c \leq 0 \text{ and } \varepsilon_t \geq 0$$

Because only two equations for the equilibrium are available, all but two variables must be known to compute a unique solution. However, at first there are four unknowns: the resulting thrust (*C*), the resulting tensile force (*T*), and their respective levers (z_C, z_T). All four unknowns are directly related to the existing strain condition. By selecting a specific strain condition, the moment capacity, as well as the normal force capacity, can be calculated and the result is unique.

Theoretically, the reversed approach—selection of the external forces followed by the calculation of the corresponding strain condition—is possible. However, this solution is practically not achievable because, typically, an SSR of FRC is discontinuous and depends on numerous parameters. In addition, the solution often provides multiple equilibriums and is therefore not unique.[9] As a result, an iterative process is necessary to solve the equations, which requires a lot of computation effort.[14]

LOAD-BEARING BEHAVIOR AND DESIGN OF FRC UNDER COMBINED *M/N* LOADING

Moment-normal force interaction diagrams (MNID) are typically used during the design of tunnel linings (and columns under combined *M/N* loading in general) for steel bar reinforced linings as well as FRC. However, while generic MNID are available for bar-reinforced members, an SSR-specific MNID has to be developed for FRC. Generic MNIDs for FRC can be developed in a similar fashion to bar-reinforced members if the diagrams are dimensionless and all strength values are defined (that is, relative to the compressive strength f_c.) The dimensionless factor $n = N/(f_c \times b \times d)$ can hereby be interpreted as the use toward the maximum thrust under pure compression. The SSR used for the following parameter studies is defined in Table 1 and represents

Table 1: Stress-Strain Relationship used in the Parameter Study

	Tension				Compression	
Stress	f_{t3}	f_{t2b}	f_{t2a}	f_{t1}	f_{c1}	f_{c2}
N/mm²	0.5	1.0	4.0	4.0	–40.0	–40.0
% of fc	1.25	2.5	10	10	100	100
Strain	ε_{t3}	ε_{t2b}	ε_{t2a}	ε_{t1}	ε_{c1}	ε_{c2}
‰	10.0	0.16	0.16	0.12	–2.0	–3.5

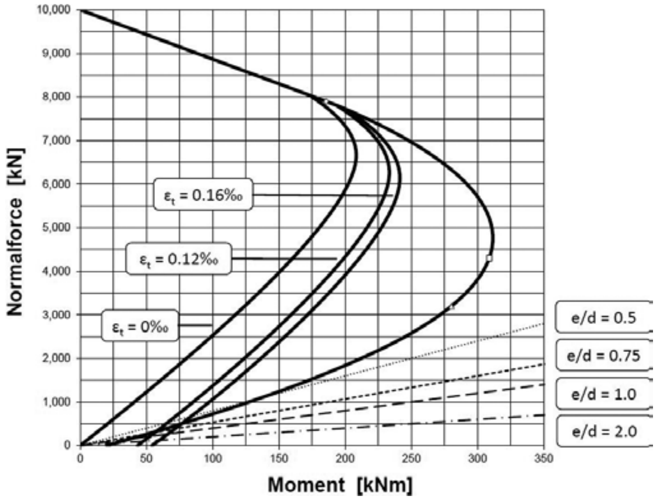

Fig. 4: Moment normal force interaction diagram (MNID)

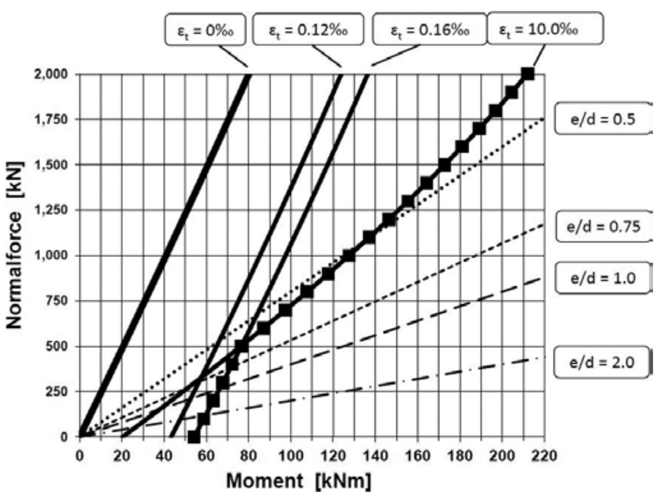

Fig. 5: MNID—enlarged section relevant for tunneling

typical values for FRC (that is, an initial tunnel lining.) For the nomenclature and shape, refer to the SSR in Fig. 2. The thickness of the lining was assumed to be 10 in. (0.25 m) and a 3.2 ft (1.0 m) wide tunnel lining section was assumed.

Figure 4 shows the complete MNID for the SSR presently used, while Fig. 5 shows an enlarged section of the same MNID. Focus on investigations are typically lines with a constant normal force, parallel to the x-axis, or lines with a constant "*e/d* ratio," which are inclined and intersecting the origin of the MNID. The dimensionless *e/d* ratio is defined as the eccentricity *e* over beam height *d*, with $e = M/N$. Figure 6 shows the results of a parameter study with varying *e/d* ratios; Fig. 7 shows a parameter study for varying normal forces.

It is important to highlight that all figures are basically different ways of displaying the bearing capacity of the same material, defined in Table 1. The results represented—for example, along the $e/d = 0.5$ line in Fig. 5—are the same as shown in Fig. 6 for the identical case. The results represented in Fig. 5 on a line with a constant normal force, parallel to the x-axis—that is, $N = 1000$ kN—is the same as shown in Fig. 7

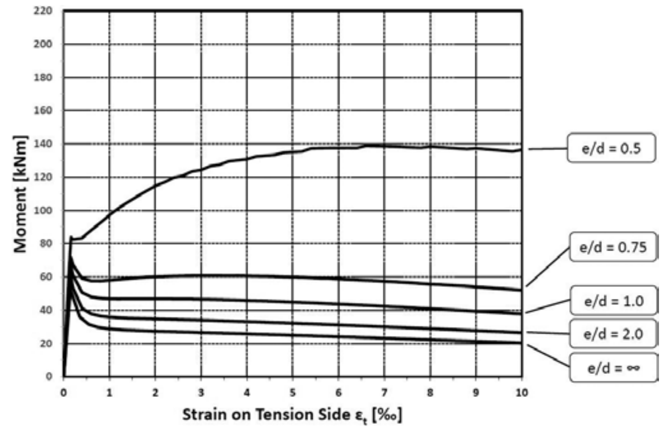

Fig. 6: Moment-strain diagram, parameter study e/d *ratio*

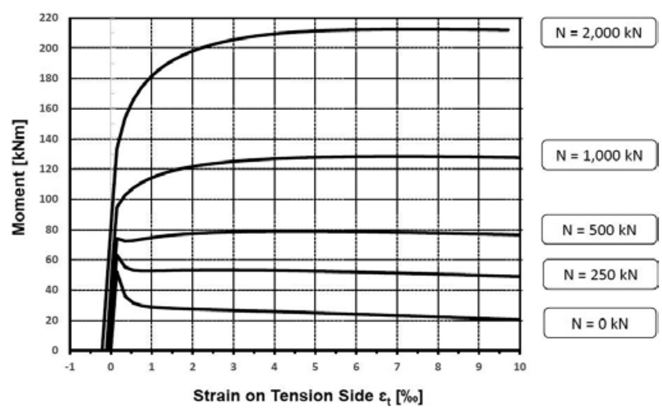

Fig. 7: Moment-strain diagram, parameter study normal force

for the same thrust. The bearing behavior under pure bending ($N = 0$; $e/d = \infty$) is represented on the x-axis in the MNID.

The example shown could also be transferred into a generic dimensionless MNID by using the following equations for the normal force and the moment

$$n = \frac{N}{f_c \times b \times d} \qquad m = \frac{M}{f_c \times b \times d^2}$$

The residual strength f_{t1} on the tension side can be expressed as a percentage of the compressive strength (refer to Table 1). The dimensionless MNID would be valid for all cases where the ratios between the tensile strength and the compressive strength are kept the same. The different lines in the MNID show cross section equilibriums for specific constant tension strains.

A good rule of thumb is that tunnel linings are typically using between 5 and 30% of the compression capacity of a member.[9] So, for example, in the MNID in Fig. 4, a typical use in a soft ground tunnel would be between 0.5 and 3 MN and only the lower one-third of the diagram would be relevant for the design; Fig. 5 shows this area of the MNID enlarged. Tunnel linings in this part of an MNID generally fail under tension by reaching the maximum allowable tensile strain ε_{t3}.

The different lines in the MNIDs represent lines of specific strains (Fig. 4 and 5). Left of the line marked with $\varepsilon_t = 0‰$ –

tensile strain zero – all members are under full compression. The ε_t = 0.12‰ respectively ε_t = 0.16‰-lines represent the end of the elastic behavior (Phase I/II) respectively the beginning of macro-cracking (Phase II/III). The ε_t = 10.0‰ line represents equilibriums reaching the maximum tensile strain defined for this example. Following this line into the area between N = 0 kN and N = 500 kN (Fig. 5) shows the area of pure bending in which axial thrust has a very small influence. In this area, the bearing capacity in the elastic state (ε_t = 0.12‰) and the microcracked state (ε_t = 0.16‰) is larger than the load in the cracked phase (0.16‰ < ε_t ≤ 10.0‰). That means the ultimate load is less than the peak load reached around the elastic/uncracked state (also refer to Fig. 6, $e/d = \infty$, 2.0, 1, 0, and 0.75 and Fig. 7, N = 0, 250, 500 kN). This shows the typical strain-softening behavior of FRC in bending tests (refer to Fig. 1). The intersection of the ε_t = 0.16‰ – line and the ε_t = 10‰ – line in the MNID marks the point of quasi ideal elasto-plastic behavior, meaning the maximum load level reached under uncracked or microcracked conditions can be maintained, which is reached in this example at roughly N = 500 kN (Fig. 1, 5, and 7).

The simulated examples, which are representative of behavior observed in tests, also show that the moment-bearing capacity in the elastic, the microcracking, and the cracked phase are all increased under the influence of an increasing normal compressive force. While typical FRC simply supported bending tests show a strain-softening behavior, it can be observed that an increased normal force leads to a quasi elasto-plastic and a quasi strain-hardening effect. The term "quasi" is used because the bending behavior is a characteristic of the structural system; material properties do not actually change. For the same material, the bearing behavior changes with an increased normal force influence (Fig. 1, 5, 6, and 7).

Figure 1 shows the difference between elastic-brittle, elasto-plastic, and strain-hardening behavior, and strain softening in a simplified manner. Strain-softening behavior is typical for pure bending; the moment-bearing capacity decreases after the peak load. An increased normal force influence leads to nearly elasto-plastic system performance (in our example for N ≈ 500 kN [refer to Fig. 7] and 0.5 < e/d < 0.75 [refer to Fig. 6), respectively) and under a further increased normal force influence, the behavior progresses to a quasi strain-hardening effect. In addition to a change in failure mode, represented by the shape of the curve, there is also an increase in the peak moment capacity. While in the example the maximum bearable moment at 10‰ tensile strain is around 20 kNm, every 100 kN additional normal force increases the moment-bearing capacity by roughly 10 kNm in this example.

FRC SPECIFICATION BASED ON RANGE OF NORMAL FORCE

What do these results mean for a tunnel lining design and FRC specification? The general desire from a structural perspective for a tunnel lining design under cracked conditions requires that the bearing capacity under cracked conditions shall be equal to or higher than the bearing capacity in the elastic state. Referring to Fig. 1, the behavior shall be at least "elasto-plastic" or display "strain hardening." In the previous section, it was shown that these conditions are highly dependent on the amount of normal force in the system. However, current tunnel designs do not take the range of expected normal force into consideration when specifying the material properties of FRC. Therefore, a lot of structural potential of FRC remains underused.

If elasto-plastic behavior or strain-hardening behavior is desired, material specifications should take the expected range of normal force, represented by the mean compressive stress in the lining, into consideration. The range of expected normal force, respectively the compressive strength in a lining, can be easily evaluated based on preliminary lining designs. As shown in the parameter study herein, a project-specific SSR could be specified that meets or exceeds the requirements. Subsequently, pure bending or tests under combined moment-normal force could be used to prove that the SSR requirements could be met. Rather than the absolute values for the residual strength, it is suggested to specify an SSR with strength values relative to the compressive strength of the material.

INELASTIC STRUCTURAL ANALYSIS USING PLASTIC HINGES

ACI 318 and other international codes provide several options for a structural analysis of reinforced concrete structures. In a typical tunnel design the forces of the lining are determined in a linear-elastic model. Representative pairs of moments and normal forces from this analysis are then transferred into a MNID to ensure that the load combinations can be born by the FRC lining.

As discussed previously, the inclusion of fibers increases the moment-bearing capacity compared to unreinforced concrete when a section is subject to a large compressive normal force. However, typically even light steel bar reinforcement can do the same or even exceed the bearing capacity of FRC. Where, then, is the benefit of FRC in the structural design? The benefit of FRC lies in the added toughness of the material, which allows—under elasto-plastic or strain-hardening conditions—to "hold" a moment in a lining even under severe deformation of the lining. However, these benefits are not used in a standard linear-elastic structural analysis. The structural and economic potential can be activated in an in-elastic structural analysis using, for example, a concept typically used for a simplified method for an in-elastic design of steel frames.

Structurally a cracked FRC lining acts like a "plastic hinge," which still transfers a moment while rotating. In a classical elastic analysis, the capacity of the plastic hinges could be used as follows for a quasi inelastic procedure: While increasing the load on a tunnel lining, the peak elastic moment will be reached at a specific point. The elasto-plastic or strain-hardening behavior would allow for the introduction of a hinge at this location and altering the overall static (elastic) system of the lining. In a next step, the external load would be increased further until the peak elastic moment would be reached at another location and another hinge would be introduced at this location, and so forth.

At the end of this process, the moments of each step would be superimposed and added. While increasing the external loads during this process, the values of the moments at the hinges could not be increased beyond the plastic moment, but the rotation could increase, making the overall system "softer." Following this approach, the lining would be locally weakened to induce a load redistribution and eventually show a system failure rather than failure at a specific cross section. The ultimate stage would be reached either as a result of system failure or by reaching rotation thresholds at the hinges or some other predefined limits. Given the properties of a tunnel lining as an embedded beam, a system failure would basically mean formation of hinge next to hinge in close proximity. For this reason, other meaningful structural thresholds or definition of a maximum number of hinges seem to be a viable option. The procedure described previously would allow full use of the properties and benefits of FRC in a structural analysis, while still using elastic structural analysis tools.

Conclusions

The article has presented and discussed the basics of FRC tunnel lining design using a selected SSR. The impact of normal force within the tunnel lining and the impact of a change of post-cracking behavior from strain softening to strain hardening was discussed in detail by means of a parametric study.

Current tunnel lining design does not fully use the potential of FRC because it disregards the positive benefits of the compressive force, which are not related to the material properties itself. Future material specifications for tunnels should consider the expected range of compressive stress in the lining and its beneficial influence on the ductility of FRC. The most advantageous property of FRC is its toughness when the tunnel lining has cracked. The potential of the toughness is currently not typically used when evaluating moment resistance in the cracked state under a simultaneous axial force. A procedure to introduce plastic hinges has been suggested that would allow use of the benefits of FRC using classical structural analysis tools and thereby realize the full structural and economic potential of FRC.

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New Hemp-Based Fiber Enhances Wet-Mix Shotcrete Performance

By Dudley R. (Rusty) Morgan, Lihe (John) Zhang, and Mike Pildysh

An innovative processed natural hemp-based fiber has been developed for use in concrete and shotcrete (wet- and dry-mix shotcrete processes) in lieu of conventional synthetic fibers, which are derived from hydro-carbon (oil and/or gas) feedstock. A driving force behind this development has been the desire to produce a truly sustainable green fiber with dramatic reductions in CO_2 emissions into the atmosphere during fiber production, compared to the synthetic (mainly polypropylene) fibers currently being used in the concrete and shotcrete industries. Synthetic microfibers have mainly been used in concrete and shotcrete to help mitigate early-age plastic shrinkage cracking. In the absence of adequate protection and initial curing, plastic shrinkage cracking has been an issue in the shotcrete industry. Figure 1 shows an example of shotcrete used for slope stabilization at a project in California that developed severe plastic shrinkage cracking in unfavorable environmental conditions (high ambient temperatures and winds and a low relative humidity).

Initial laboratory and field trials in Calgary, AB, Canada, indicated that natural hemp-based fiber was very effective in mitigating plastic shrinkage cracking. Consequently, the fiber manufacturer decided to commission a comprehensive study to evaluate the performance of the natural hemp-based fiber in cast-in-place concrete and wet- and dry-mix shotcretes, compared to plain concrete control mixtures without any fibers and mixtures with a synthetic (polypropylene) microfiber. These studies, conducted in Vancouver, BC, Canada, demonstrated that when used at equivalent fiber-volume addition rates, not only was the natural hemp-based fiber more effective in mitigating plastic shrinkage cracking than synthetic microfiber but it also provided many additional benefits in the plastic and hardened concretes. This was particularly true for the wet-mix shotcrete process, where some marked benefits to the shotcrete application and finishing processes were found.

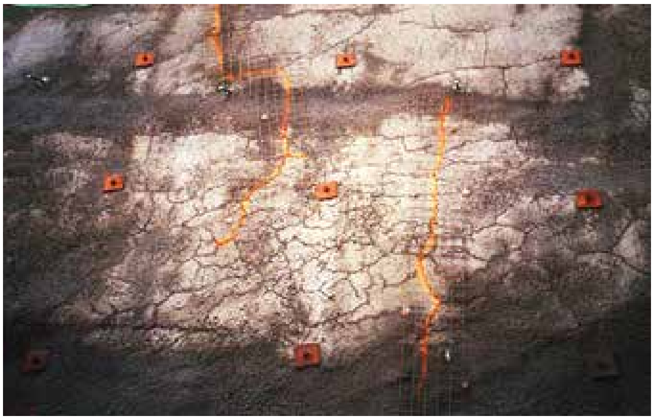

Fig. 1: Plastic shrinkage cracking in shotcrete slope stabilization

This article provides a summary of the findings from the wet-mix shotcrete laboratory study. It also provides observations from a subsequent full-scale field application of wet-mix shotcrete with the natural hemp-based fiber, with ready mixed concrete batching, mixing, and supply and conventional pumping, shooting, and finishing of structural shotcrete walls at a project in California.

Introduction

Natural fibers have been used in building products such as brick, mortar, and plaster since ancient times for the known benefits they provide to such products. One of the strongest and most durable of natural fibers has been hemp-based fiber, the same product widely used in marine ropes. Up until now, such fiber has, however, not found any significant use in portland cement-based products. This has been in part because of concerns about the durability of such fiber in a highly alkaline portland cement environment.

The manufacturers of the natural hemp-based fiber used in this report have, however, developed a process for production and surface treatment of the fiber, which makes it suitable for use in an alkaline portland cement environment. The hemp-based fiber has a higher modulus of elasticity (E-value) and tensile strength than high-quality polypropylene synthetic fibers. Also, unlike synthetic fibers, which are hydrophobic (repel water), the treated hemp-based fiber is hydrophyllic (absorbs water). This is a highly beneficial attribute for portland cement-based products such as concrete, as it promotes development of both mechanical and chemical bond of the paste to the fiber. It also reduces bleeding in concrete, thus reducing the formation of continuous bleed channels, which increase permeability and reduce durability. In addition, the fibers act as an internal curing aid, releasing water into the cement paste matrix as the concrete dries. It is believed that this, in conjunction with the higher modulus of elasticity and higher tensile strength of the hemp-based fiber, is what helps mitigate plastic shrinkage cracking in concrete and shotcrete.

In addition to the previously mentioned beneficial attributes, the incorporation of the natural hemp-based fiber in wet-mix shotcrete was found to impart several other benefits to the application and performance of shotcrete, as detailed in the Laboratory and Field studies described in the article, which follows.

LABORATORY STUDY

Shotcrete Mixture Designs

In the wet-mix shotcrete laboratory study, a comparative evaluation was conducted on the performance of shotcrete made with the natural hemp-based fiber (mixture designation WNF) compared to a plain control shotcrete without any fiber (mixture designation WP) and a shotcrete with a microsynthetic (polypropylene) fiber (mixture designation WSF). The fiber addition rates for the different mixtures are shown in Table 1. While the natural and synthetic fibers have the same fiber volume addition rate, the quantities added in kg/m^3 (lb/yd^3) differ because the natural fiber has a relative bulk density (specific gravity) of 1.48, while the synthetic fiber has a relative bulk density (specific gravity) of 0.92.

Table 2 shows the concrete mixture proportions for each of the three shotcreted mixtures. The cement, fly ash, coarse and fine aggregate contents, and water added in all three mixtures was the same. The only differences in the mixtures were the type of fiber added and small variations in the amount of water-reducing admixture and air-entraining admixture added to provide the required slump and air content. The shotcretes were designed to meet CSA A23.1/23.2-2014 Class C1 exposure requirements—that is, structurally reinforced concrete exposed to chlorides with or without freezing-and-thawing conditions. Such concrete (or in this case, shotcrete) is required to have a maximum water-cementitious materials ratio (*w/cm*) of 0.40, a minimum compressive strength of 5100 psi (35 MPa) at 28 days, and be suitably air entrained. The base shotcrete mixture design in Table 2 has a fly ash content of 20% by mass of cementitious material and is typical of structural wet-mix shotcrete used in Western Canada and other parts of North America. The slightly higher water-reducing admixture dosage rate in the WNF mixture is attributed to water uptake by the natural fiber and hence the need to increase the admixture dosage to provide the required slump.

Shotcrete Batching, Mixing, and Application

The shotcrete mixtures for this laboratory study were pre-batched with aggregates in an oven-dry condition and supplied in 0.5 yd^3 (0.38 m^3) bulk bin bags. The dry bagged materials were discharged into a pan mixer with counter-rotating paddles, where the mix water and liquid air-entraining and water-reducing admixtures were added. Figure 2 shows dry-bagged material being discharged into

Table 1: Wet-mix shotcrete mixtures

Mixture type	Shotcrete designation	Fiber content		
		kg/m^3	lb/yd^3	% volume
Plain	WP	0	0	0
Natural fiber	WNF	2	3.4	0.15
Microsynthetic fiber	WSF	1.35	2.3	0.15

Table 2: Wet-mix shotcrete mixture proportions

Material	Mixture WP: Plain shotcrete		Mixture WSF: Microsynthetic fiber shotcrete		Mixture WNF: Natural fiber shotcrete	
	kg/m^3	lb/yd^3	kg/m^3	lb/yd^3	kg/m^3	lb/yd^3
Cement type GU (ASTM Type I)	360	607	360	607	360	607
Fly ash	90	152	90	152	90	152
Coarse aggregate (10-5 mm, SSD)	430	725	430	725	430	725
Fine aggregate (SSD)	1290	2174	1290	2174	1290	2174
Water, L	180	303	180	303	180	303
Water-reducing admixture, L*	1.15	2	1.05	2	1.3	2
NForce fiber	—	—	—	—	2	3.4
Microsynthetic fiber	—	—	1.35	2.3	—	—
Total	2351.15	3963	2352.4	3965	2353.3	3967

*Water-reducing admixture added during mixing at dosage required to achieve the maximum allowable *w/cm* and required slump

Fig. 2: Prepackaged dry shotcrete materials discharging into pan mixer

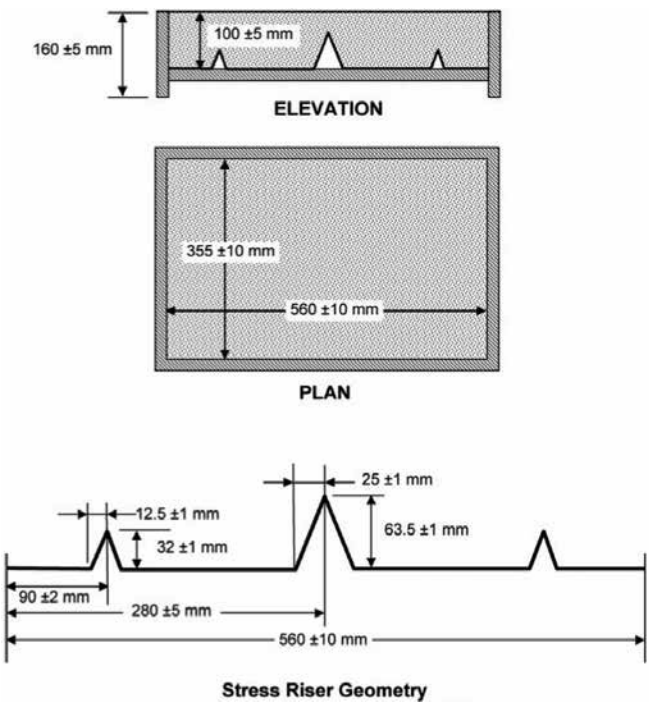

Fig. 3: Configuration of plastic shrinkage cracking test mold (Note: 1 mm = 0.0394 in.)

Fig. 4: Shooting into mold for plastic shrinkage cracking testing

the 1.0 yd^3 (0.76 m^3) pan mixer. Such mixers are commonly used in the precast concrete industry but are also very useful for laboratory studies. Weighed-out quantities of the loose natural and synthetic fibers were added to mixtures WNF and WSF and mixed for a minimum of 5 minutes. The quantities of water-reducing and air-entraining admixtures added were adjusted as necessary to produce the required slump and air content.

The mixed shotcrete was discharged into a Putzmeister shotcrete pump, which conveyed the shotcrete in a 2 in. (50 mm) internal diameter rubber hose to the nozzle, where air was introduced from a 185 ft^3/min (5.24 m^3/min) air compressor to pneumatically project the shotcrete at high impacting velocity onto the receiving surface. The fibers appeared well dispersed in both fiber mixtures and the mixtures shot well with no problems of fiber balling or pump blockages being encountered. Shotcrete application was done by an ACI Certified Shotcrete Nozzleman.

The nozzleman shot standard vertical test panels with sloped sides, from which cores were extracted for testing for:

a. Compressive strength at 7 and 28 days to ASTM C39;
b. Boiled absorption (BA) and volume of permeable voids (VPV) at 28 days to ASTM C642; and
c. Rapid chloride penetrability (RCP) at 91 days to ASTM C1202.

In addition, two molds were shot horizontally for each of the fiber mixtures for production of test specimens for ASTM C1579, "Standard Test Method for Evaluating Plastic Shrinkage Cracking of Restrained Fiber Reinforced Concrete (Using a Steel Form Insert)." Figure 3 shows the configuration of the test mold. Figure 4 shows shooting into the mold.

Plastic Shotcrete Properties

The temperature, slump, and air content of the plastic shotcrete was tested at the point of discharge into the shotcrete pump. In addition, the as-shot air content was determined by shooting the shotcrete into a standard ASTM C231 air pressure meter bowl. Test results for all three mixtures are provided in Table 3. The slump for all three mixtures was in the design range of 2 to 3 in. (50 to 75 mm). The slightly higher-than-design air content in the as-batched WNF mixture is attributed to the effect of the higher water-reducing admixture dosage in this mixture.

In addition to the standard tests, the plastic shotcretes were assessed for characteristics such as shootability (adhesion and cohesion and resistance to sagging and sloughing) when applied to a vertical surface. Figure 5 shows shooting a beehive (extended thickness mounded in center of shotcreted area) of the plain concrete mixture (WP) on a vertical plywood panel.

While all three mixtures shot well and could be built up to a 6 in. (150 mm) thickness on a vertical plywood form in a single pass, some marked differences were found in the shooting characteristics of the mixtures. The plain WP mixture displayed the lowest adhesion and cohesion performance. Shortly after being built up to the full 6 in. (150 mm) thickness, it started to sag, and then sloughed

Table 3: Plastic shotcrete properties

Mixture	Fiber content			Slump		Air content, %		Temperature	
	kg/m³	lb/yd³	% volume	mm	in.	As-batched	As-shot	°C	°F
WP	0	0	0	50	2.0	5.5	4	13	55
WNF	2	3.4	0.15	70	3.0	9	4.3	18	64
WSF	1.35	2.3	0.15	60	2.5	8	4.8	20	68

Note: Specified slump is 3 ± 1 in. (70 ± 20 mm); specified as-shot air content is 3.0 to 6.0%.

Fig. 5: Shooting a beehive of plain concrete mixture (WP) 6 in. (150 mm) thick on a vertical plywood panel

Fig. 6: Synthetic fiber mixture (WSF) sloughed off plywood panel after being disturbed by cutting

off the plywood panel under its own weight. The synthetic fiber mixture (WSF) displayed better performance in that it did not sag or slough off the plywood form immediately after shooting. However, when it was disturbed and when an attempt was made to cut it with a trowel, it sloughed off the plywood form, as shown in Fig. 6.

Fig. 7: Measuring thickness of natural fiber mixture (WNF) beehive

Fig. 8: Cutting and trimming natural fiber mixture (WNF) with no sagging or sloughing

By contrast, the natural fiber mixture (WNF) displayed great adhesion and cohesion and did not sag or slough when built up to the full 6 in. (150 mm) thickness, as shown in Fig. 7. The WNF mixture could be cut, trimmed, and finished without any sagging or sloughing, as shown in Fig. 8. In fact, considerable effort had to be expended by a finisher to dislodge the beehive from the plywood form using a flat spade. It is believed this markedly enhanced adhesion and cohesion is attributable not only to the reinforcing effect of the natural fiber but also due to the hydrophyllic fiber absorbing some of the excess water of workability from the shotcrete and reducing bleeding tendencies in the applied mixture.

Plastic Shrinkage Cracking Test

As previously mentioned, evaluation of the plastic shrinkage cracking characteristics of the plain concrete mixture (WP), compared to the synthetic fiber mixture (WSF) and natural fiber mixture (WNF), was conducted using the ASTM C1579 test procedure. In this test, two molds were shot, finished, and tested for each mixture. After finishing in a prescribed manner, the test specimens were placed in individual environmental chambers (essentially heated wind tunnels), which provided an environment of: temperature 97 ± 5°F (36 ± 3°C); wind velocity of 15.4 ft/s (4.7 m/s); and relative humidity 30 ± 10%, as required by the test method. In addition, a water sample in a beaker was placed in each environmental chamber to monitor the evaporation rate. ASTM C1579 specifies a minimum evaporation rate of 0.2 lb/ft^2-h (1.0 kg/m^2-h) and this requirement was met in all environmental chambers. A setting time test was conducted to ASTM C403, "Standard Test Method for Time of Setting by Penetration Resistance." Once the shotcrete samples reached final set, the samples, still in their molds, were removed from the environmental chambers and placed in still air in a temperature- and humidity-controlled room in the laboratory for curing at 73 ± 4°F (23 ± 2°C) and 50% relative humidity for 24 hours, as prescribed by the test method. Average crack widths in the specimens were then measured with a crack comparator.

The test method requires the plain concrete control sample (WP) to develop a minimum crack width of 0.02 in. (0.5 mm). The average crack widths in the fiber-reinforced samples (WSF and WNF) were compared against the WP mixture specimen crack widths. A factor called the crack reduction ratio (CRR), expressed as a percentage (%), is then calculated.

CRR = [1 – average crack width of fiber-reinforced shotcrete mixture/average crack width of plain control shotcrete mixture] × 100%.

In this study, the plain concrete control mixture (WP) developed an average crack width of 0.025 in. (0.63 mm), which satisfies the ASTM C1579 requirement. The synthetic fiber mixture (WSF) developed an average crack width of 0.004 in. (0.10 mm) and the natural fiber mixture (WNF) developed an average crack width of 0.002 in. (0.05 mm). The calculated CRR was 84% for the synthetic fiber mixture WSF and 92% for the mixture WNF. In other words, the synthetic fibers and natural fibers were effective in reducing plastic shrinkage crack widths by 84% and 92%, respectively. In short, both fiber types were effective in mitigating plastic shrinkage cracking, but when used at equal fiber volume addition rates (0.15%), the natural fiber was more effective than the synthetic fiber.

Finishability

While in some shotcrete applications, such as ground support in tunnels and mines and rock-slope stabilization, the final surface is left in the rough, natural, as-shot surface condition (such as can be seen in Fig. 7), there are many applications where the applied shotcrete is cut and trimmed to line and grade and then finished to a specified surface tolerance and finish texture. This is common in structural

Fig. 9: Finishing tools used, from left to right: steel trowel, magnesium trowel, wood float, hard rubber float, textured rubber float, and sponge float

shotcrete walls and other elements, canal linings, bobsleigh and luge tracks, resurfacing of concrete dams and spillways, swimming pools and other liquid-retaining structures, and architectural applications. Finishing is labor-intensive and can require three to five or even more finishers to keep up with one nozzleman, depending on the nature of the project. (For example, finishing of a bobsleigh/luge track may require as many as eight finishers for one nozzleman). Thus, anything that can be done to enhance the finishability of shotcrete can have significant impact on productivity and hence costs of a shotcrete operation.

In this study, the wet-mix shotcrete mixtures were shot into 14 x 22 x 4 in. (355 x 550 x 100 mm) plywood boxes and finished using different hand-held finishing tools to evaluate the finishability of the different mixtures. The finishing tools used (in sequence from smoothest to most textured surface finish) are shown in Fig. 9 and were: steel trowel, magnesium trowel, wood float, hard rubber float, textured rubber float, and sponge float.

The plain shotcrete mixture (WP) was relatively easy to finish with all the selected finishing tools, showing the expected sequence of smoothest to more textured surface finishes for the different tools, as described earlier. The mixture with synthetic fibers (WSF) proved to be the most difficult to finish, particularly with the tools producing more textured surface finishes, as they tended to pull fibers to the surface, leaving a rougher surface with many protruding fibers. Even the steel- and magnesium-troweled surfaces displayed some protruding synthetic fibers. This is attributed to the hydrophobic characteristics of the synthetic fiber. Some architects and engineers find this to be an annoyance and ask the contractor to burn off protruding synthetic fibers using a torch. Figure 10 shows an example of the WSF mixture finished with a magnesium trowel. Protruding synthetic fibers were present in the finished surface.

By contrast, the mixture with natural fiber displayed superior finishing characteristics to both the plain shotcrete mixture and the synthetic fiber mixture. The treated natural fiber provided the applied shotcrete with greater cohesion

Fig. 10: Synthetic fiber mixture WSF finished with a magnesium trowel

Fig. 11: Natural fiber mixture (WNF) finished with a magnesium trowel

and appeared to act as a finishing aid. This resulted in relatively smoother-textured surface finishes for all the finishing tools used, particularly when compared against the mixture with synthetic fiber. Virtually no fibers were present in the finished surface of the WNF mixture finished with steel and magnesium trowels. Figure 11 shows an example of the WNF mixture finished with a magnesium trowel. Very few fibers were drawn to the surface, or were evident in the panels finished with wood, rubber, or sponge floats. The greater ease of finishing for mixtures incorporating the natural fiber has very positive implications for shotcrete productivity.

Hardened Shotcrete Tests

Tests were conducted on cores extracted from hardened shotcrete test panels for determination of:

a. Compressive strength to ASTM C39;
b. Boiled absorption (BA) and volume of permeable voids (VPV) to ASTM C642; and
c. Rapid chloride penetration to ASTM C1202.

Test results for the hardened shotcrete properties are provided in Table 4.

With respect to compressive strength, all three mixtures readily meet the CSA A23.1 minimum design strength of 5100 psi (35 MPa) at 28 days for concrete with a Class C1 exposure. Clearly, natural fiber addition does not have any detrimental effect on compressive strength. The mixture with natural fibers displayed the highest compressive strength at both 7 and 28 days of all three mixtures tested.

With respect to tests for BA and VPV, all three mixtures had values well below the typical maximum of 8% for BA and 17% for VPV for quality shotcrete with nonporous aggregate with normal cement factors as recommended in ACI 506R-16, "Guide to Shotcrete." Natural fiber addition does not have any detrimental effect on permeability. The mixture with natural fiber displayed the lowest BA and VPV values of all three mixtures tested.

With respect to the tests for rapid chloride penetration (RCP), CSA A23.1 requires a maximum allowable value of 1500 Coulombs at 91 days for a concrete with Class C1 exposure. With test results for all three mixtures in the 898 to 1037 range, ASTM C1202 and CSA A23.1 would rate such shotcretes as having "Low" chloride penetrability. The addition of natural fiber to the mixture is not detrimental to the chloride penetrability of the shotcrete.

FIELD EVALUATION

Mixture Designs and Shotcrete Batching, Mixing, and Supply

The second phase in the evaluation of the use of the natural hemp-based fiber in wet-mix shotcrete was to assess its

Table 4: Hardened shotcrete properties

	Fiber content			Compressive strength				Boiled absorption	Volume of permeable voids	RCP results at 91 days
Mixtures	kg/m³	lb/yd³	% volume	7 days, MPa	7 days, psi	28 days, MPa	28 days, psi	%	%	Coulombs
WP	0	0	0	35	5075	47.9	6950	5.3	11.9	966
WNF	2	3.4	0.15	43.7	6340	57.6	8355	5.1	11.5	1037
WSF	1.35	2.3	0.15	36.6	5310	51.7	7500	5.4	12	898
Design/specified value:				**30**	**4350**	**40**	**5800**	**max. 8.0%**	**max. 17%**	**1500**

performance in a full-scale field trial, with ready mixed concrete batching, mixing, and supply, in a structural shotcrete application. The evaluation was carried out at the Jos. J. Albanese yard in Santa Clara, CA. Two different wet-mix shotcrete mixture designs commonly used by them in the Bay Area were modified by the addition of

Fig. 12: Natural fiber-reinforced shotcrete (Mixture B) being discharged from concrete truck chute into pump hopper; note highly cohesive nature of mixture

Fig. 13: Reed C50 pump used to pump wet-mix process shotcrete

Fig. 14: Formwork and reinforcing bar for L-shaped wall

the natural hemp-based fiber, and used to construct two structural shotcrete walls for aggregate storage bins. The actual shotcrete mixture designs used are proprietary and so are not reproduced in this paper. Both mixtures had the same portland cement content and contained 15% fly ash by mass of cement. The main difference between the two mixtures was Mixture A had a 3/8 in. (10 mm) pea gravel coarse aggregate and the second mixture, Mixture B, had a 0.5 in. (13 mm) crushed granite coarse aggregate.

The natural hemp-based fiber was supplied in 1 lb (0.45 kg) shreddable bags and added to the concrete truck during batching and mixing. The fibers were incorporated into the mixtures at addition rates of 1.5 lb/yd^3 (0.89 kg/m^3) for Mixture A and 3.0 lb/yd^3 (1.8 kg/m^3) for Mixture B. Figure 12 shows Mixture B being discharged from the concrete truck chute into the pump hopper. An 8.0 yd^3 (6.1 m^3) load of Mixture A was supplied at a slump of 3.5 in. (90 mm). A 7.0 yd^3 (5.4 m^3) load of Mixture B was supplied at a slump of 3.0 in. (75 mm). The shotcrete temperature for both mixtures was 76°F (24°C) and the ambient temperature was around 72°F (22°C) at the time of shooting.

Both Mixtures A and B were highly cohesive and pumped and shot well, without any signs of fiber clumps or remnants of the water-shreddable bags being evident during shotcrete discharge, pumping, and shooting or in the as-shot structural walls. The shotcretes were pumped to the nozzle where compressed air was added to pneumatically project the shotcrete at high impacting velocity onto the receiving surface, using the Reed C50 pump shown in Fig. 13.

Structural Shotcrete Walls Construction

Two structural shotcrete walls, one L-shaped and the other straight, were formed and shot. The L-shaped wall was approximately 16 ft (4.9 m) long and 6 ft (1.8 m) high. The straight wall was approximately 20 ft (6.1 m) long and 4 to 5 ft (1.2 to 1.5 m) high. Both walls were 18 in. (450 mm) thick and were reinforced with a double mat of No. 6 (No. 20M) reinforcing bar. Figure 14 shows the L-shaped wall. The walls were constructed as extensions to aggregate storage bins in the Jos. J. Albanese yard and provided a good opportunity to evaluate how the natural fiber-reinforced shotcrete behaved during shotcrete application, finishing, and subsequent field performance.

Both shotcrete mixtures were observed to be very cohesive and the ACI Certified Nozzleman doing the shooting could bench shoot (stack) the structural shotcrete to the full height in both walls without any sagging, sloughing, or fallout. The shotcrete was applied to just cover the outer layer of reinforcing bar. A blow-pipe operator worked alongside the nozzleman, blowing out any accumulations of rebound and overspray from the areas about to receive shotcrete. A finish coat of the shotcrete was then applied from the top down, to build the walls out to their full thickness. Figure 15 shows bench-gun shooting the L-shaped structural wall.

Shooting wires had been installed to control line and grade and the nozzleman shot the final layer to just cover the

Fig. 15: Bench-gun shooting L-shaped wall

Fig. 17: View of finished straight wall

Fig. 16: Trimming shotcrete to shooting wires with cutting screed (rod)

Fig. 18: Stripped face of L-shaped wall is defect-free

shooting wires. Because of the very cohesive characteristics of the natural fiber-reinforced shotcrete, the finisher using the cutting screed (rod) could follow immediately behind the nozzleman (only a few feet away), cutting and trimming the shotcrete to the shooting wires to control line and grade. Figure 16 shows the finisher trimming the shotcrete to the shooting wires in the straight wall.

A finisher with a darby (long wood float) followed right behind the cutting screed operator, closing and smoothing the shotcrete surface. Final finishing with wood hand floats was carried out to provide a stucco-like surface finish appearance. No fibers were found protruding in the finished shotcrete surface. Figure 17 provides a view of the finished face of the straight wall. The nozzleman and finishers were impressed with the enhanced productivity provided by being able to bench shoot the walls to their full height in one pass and, after shooting of the layer, follow immediately behind the nozzleman with finishing operations, without any problems of shotcrete sagging, sloughing, or fallout. The finishers also commented on how easy it was to finish the walls; the natural fiber appeared to act as a finishing aid for the shotcrete.

Shotcrete Examination and Testing

A few days after shooting, the plywood forms were stripped from the back side of the aggregate bin walls and the stripped faces of the aggregate bin walls were examined. The walls were observed to be essentially defect-free, with no significant voids from incomplete consolidation, sags, tears, or shadows behind the reinforcing bar. Figure 18 shows the stripped face of the L-shaped wall. Also, examination of the structural shotcrete walls after several weeks of service showed no evidence of plastic or restrained drying shrinkage cracking.

In addition to shooting the structural walls, the nozzleman shot a 2 ft x 2 ft x 4 in. (610 x 610 x 100 mm) test panel with Mixture A. The test panel was cured on site until shipment to a testing laboratory in Vancouver for testing. Cores were extracted for testing for compressive strength to ASTM C39, and values of BA and VPV to ASTM C642 at an age of 28 days. The average 28-day compressive strength was 4440 psi (30.7 MPa), which satisfied the specified minimum compressive strength of 4000 psi (27.6 MPa) at 28 days for this project. The average values for BA and VPV were 7.6 and 16.9%, respectively, which satisfied the maximum allowable values of 8% BA and 17% VPV.

These values are higher than measured in the laboratory study (refer to Table 4), but this is because the Field Evaluation mixture had a higher *w/cm* of 0.45, compared to a *w/cm* of 0.40 in the laboratory study mixtures shown in Table 2.

SUMMARY

The comparative laboratory study and field evaluation detailed in this paper has demonstrated that treated natural hemp-based fiber has several beneficial attributes that enhance the performance of wet-mix shotcrete with no detrimental effects. These beneficial attributes include the following:

1. The treated natural hemp-based fiber is hydrophyllic (absorbs water) and as such is compatible with portland cement-based systems. In particular:
   a. The fiber is readily dispersible in wet-mix shotcrete, providing uniform distribution of the fiber during mixing, pumping, and shooting, without fiber balling or segregation.
   b. Water absorbed by the fiber during batching and mixing acts as an internal curing aid because water is available to the cement paste during hydration. This is beneficial in helping to mitigate early-age plastic and drying shrinkage-induced cracking.
2. The natural fiber shotcrete displayed a superior CRR in the ASTM C1579 plastic shrinkage cracking test, compared to the microsynthetic fiber-reinforced shotcrete.
3. The natural fiber addition produced a very cohesive wet-mix shotcrete, suitable for pumping and shooting without segregation or pump blockages.
4. The natural fiber shotcrete displayed remarkable adhesion characteristics when applied to a vertical plywood form, compared to the plain control shotcrete and shotcrete with microsynthetic fiber. Unlike those two shotcretes, considerable effort was required to dislodge a beehive of natural fiber shotcrete from the plywood form. This has very positive implications for shotcrete applications to vertical and overhead surfaces, where adherence of fresh shotcrete to the substrate surface is an important consideration (for example, in shotcrete repair and restoration works and in tunneling, mining, and rock slope stabilization projects).
5. Because of the very adhesive and cohesive rheology of the natural fiber mixture, it was possible to bench shoot (stack) 18 in. (450 mm) thick structural shotcrete walls to heights up to 6 ft (1.8 m) in a single pass without sagging, sloughing, or fallout. This provides opportunities for accelerating the shotcrete construction schedule.
6. The natural fiber shotcrete displayed superior finishing characteristics to the microsynthetic fiber-reinforced shotcretes because fibers were not drawn to or exposed on the surface by finishing operations. The finishers commented that the natural fiber appeared to act almost like a finishing aid.
7. Because of the stable nature of the just-shot natural fiber shotcrete (resistance to sagging, sloughing, and fallout), finishers could follow closely behind the shotcrete nozzleman. This provides opportunities for accelerating the shotcrete construction process.
8. Tests conducted on cores extracted from the hardened shotcrete demonstrated that the natural fiber had no detrimental effects on properties of the hardened shotcrete, such as compressive strength, BA, and VPV (an indicator of permeability), or rapid chloride penetrability (an indicator of resistance to chloride ion intrusion). In fact, the natural fiber shotcrete displayed slightly higher values of compressive strength and lower values of BA and VPV compared to the plain control shotcrete or shotcrete with microsynthetic fibers.
9. Finally, because the natural fiber is produced from custom-farmed hemp plants, it is a sustainable green product, with much reduced CO_2 emissions compared to microsynthetic fibers that are derived from hydrocarbon (oil and gas) feedstock.

Based on the studies detailed in this paper, it is recommended that the treated natural hemp-based fiber be added to wet-mix shotcrete at fiber addition rates as follows:

a. In favorable ambient environmental conditions with low evaporation rates (cooler temperatures, high relative humidity, and low wind speeds) and thus a low potential for early-age plastic and drying-shrinkage-induced cracking, use a fiber addition rate of approximately 1.5 lb/yd^3 (0.89 kg/m^3).

b. In less-favorable ambient environmental conditions with higher evaporation rates (warm temperatures, lower relative humidity, and higher wind speeds), with a higher potential for early-age plastic and drying shrinkage cracking, use a fiber addition rate of approximately 3.0 lb/yd^3 (1.78 kg/m^3).

c. In severe ambient environmental conditions (high temperatures and wind speeds and very low humidity) with a consequent high potential for early-age plastic shrinkage and drying-shrinkage-induced cracking, use a fiber addition rate of approximately 3.4 lb/yd^3 (2.0 kg/m^3), or even higher if necessary.

For each of environmental conditions (a), (b), and (c), good shotcrete protection and curing practices, as detailed in ACI 506R-16, "Guide to Shotcrete," should still be implemented.

Acknowledgments

The laboratory study and field evaluation of wet-mix shotcrete presented in this paper were sponsored by Canadian Greenfield Technologies Corporation of Calgary, AB, Canada. The processed natural hemp-based fiber used is manufactured by them and sold under the trade name NForce-Fiber. The shotcrete used in the laboratory study was batched and dry-bagged by Basalite Concrete Products Vancouver ULC and the wet-mix shotcrete production and testing was carried out at their Surrey, BC, Canada, plant. Shotcrete equipment and application was provided by Structural Shotcrete Ltd., Surrey, BC, Canada. The ACI Certified Shotcrete Nozzleman used to apply the shotcrete in the laboratory study was S. Ellis of Structural Shotcrete Ltd. The field and laboratory testing was conducted by LZhang Consulting & Testing Ltd., Vancouver, BC, Canada.

The field evaluation of the NForce-Fiber in wet-mix shotcrete was carried out in the Jos. J. Albanese plant in Santa Clara, CA. Wet-mix shotcrete mixture designs and supply were by Central Concrete Supply Company, a division of U.S. Concrete Company. Shotcrete equipment and structural shotcrete walls construction were provided by Jos. J. Albanese. Laboratory testing was carried out by LZhang Consulting & Testing, Vancouver, BC, Canada. Overall project initiation and management was provided by D. R. Morgan of Victoria, BC, Canada.

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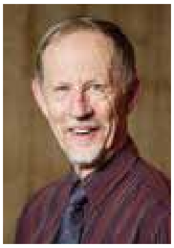
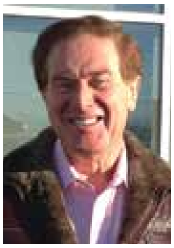


***Dudley R. (Rusty) Morgan**, PhD, PEng, FACI, is a Civil Engineer with over 50 years of experience in the concrete and shotcrete industries. He was a member and Secretary of ACI Committee 506, Shotcreting, for over 25 years. He is a past member of ACI Committees 365, Service Life Prediction, and 544, Fiber-Reinforced Concrete. Morgan is a founding member and Past President of ASA. He is an ACI C660-approved Shotcrete Nozzleman Examiner and presenter for the ASA Shotcrete Nozzleman Education course. Morgan is a past member of the Canadian Standards Association Concrete Steering Committee and was Canadian Representative on the International Tunneling Association Committee: Shotcrete Use. He has worked on over a thousand concrete and shotcrete projects around the world during his consulting career and has edited five books and published over 150 papers on various aspects of concrete and shotcrete technology. In 2001, Morgan was elected as a Fellow of the Canadian Academy of Engineering.*

***Lihe (John) Zhang**, PhD, PEng, is an Engineer and Owner of LZhang Consulting & Testing Ltd. He received his PhD in civil engineering from the University of British Columbia, where he conducted research on fiber-reinforced concrete. He has over 15 years of experience in concrete and shotcrete technology and the evaluation and rehabilitation of infrastructure. Zhang is a member of the American Concrete Institute. He is Chair of ACI Subcommittee 506-F, Shotcreting-Underground, and a member of ACI Committees 130, Sustainability of Concrete; 506, Shotcreting; and 544, Fiber-Reinforced Concrete. He is an ACI C660-approved Shotcrete Nozzleman Examiner and presenter for the ASA Shotcrete Nozzleman Education course. Zhang is a member of ASTM Committee C09, Concrete and Concrete Aggregates, is an ASA Officer and Board Member, and chairs the ASA Technical Committee.*



***Mike Pildysh**, MEng, PEng, is President of Canadian Greenfield Technologies Corporation. He is a civil engineer with over 35 years of experience in the building materials industry. He was, for a time, Head Civil Engineer for Monenco Engineering, which was then the second largest engineering company in Canada. He subsequently founded and operated a group of companies, including the very successful Cementec Industries Inc., which supplies specialty construction materials to the civil engineering and oil industries. Pildysh is a licensed professional engineer in Alberta, British Columbia, and Ontario. He has authored 12 patents and has over 20 publications. He is a former member of the United States Research Technology Board. Pildysh is a member of ASA, the American Concrete Institute, the American Chemical Society, and the Chemical Institute of Canada.*

SHOTCRETE CALENDAR

JUNE 4-8, 2017	**The International Bridge Conference** Gaylord National Resort and Convention Center | National Harbor, MD **www.miningamerica.org**
JUNE 11-14, 2017	**ASTM International Committee C09, Concrete and Concrete Aggregates** Sheraton Toronto | Toronto, ON, Canada **www.astm.org**
SEPTEMBER 17-20, 2017	**Railway Interchange 2017** Indiana Convention Center | Indianapolis, IN **www.railwayinterchange.org**
OCTOBER 11-13, 2017	**First International Conference on Underground Mining Technology** Radisson Hotel Sudbury | Sudbury, ON, Canada **www.umt2017.com**
OCTOBER 14, 2017	**ASA Fall 2017 Committee Meetings** Disneyland Hotel | Anaheim, CA **www.shotcrete.org**
OCTOBER 15-19, 2017	**The ACI Concrete Convention and Exposition** Theme: "Making Connections" Disneyland Hotel | Anaheim, CA **www.concrete.org**
NOVEMBER 1-3, 2017	**International Pool | Spa | Patio Expo** Orange County Convention Center (North Halls A&B) | Orlando, FL **www.poolspapatio.com**
DECEMBER 3-6, 2017	**ASTM International Committee C09, Concrete and Concrete Aggregates** Sheraton New Orleans | New Orleans, LA **www.astm.org**
JANUARY 22, 2018	**ASA Meetings at World of Concrete** Las Vegas Convention Center | Las Vegas, NV **www.shotcrete.org**
JANUARY 23-26, 2018	**World of Concrete 2018** Las Vegas Convention Center | Las Vegas, NV **www.worldofconcrete.com**
JANUARY 23-25, 2018	**The Pool & Spa Show 2018** Atlantic City Convention Center | Atlantic City, NJ **www.nespapool.org**
MARCH 25-29, 2018	**The ACI Concrete Convention and Exposition** Theme: "Concrete Elevated" Grand America & Little America | Salt Lake City, UT **www.concrete.org**
WANT MORE INFORMATION?	**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.**

Lining Raise-Bore Shafts

By Kristian Loevlie

When raise boring is used, a circular excavation is produced either between two existing levels in an underground mine or between the surface and an existing level in a mine. In raise boring, a pilot hole is drilled down to the lower level, the drill bit is removed and replaced by a reamer head having a diameter of the same dimension as the desired excavation, and this head is rotated and pulled back up toward the surface.

Oftentimes, the ground consists of various geological layers—some are very unstable and need to be controlled as soon as possible; otherwise, the hole may collapse. Because workers are not allowed in unsupported ground, the conventional way to line a raise is to use steel cans or forms from top and down, in stages, and backfilled with concrete. This is a slow and lengthy process. Initial support is always an issue, which then can decide the stability or collapse of a shaft.

Introduction of robots using dry-mix shotcrete were a huge improvement and saved many shafts from collapse. It still took weeks or months to finish, leaving the ground open and exposed to the elements. Wet-mix shotcrete was not considered due to logistical problems, plugging hoses after a certain vertical distance, the weight of the hoses full of concrete, the shotcrete going into a "free fall," and so on.

Facts

- **Pneumatically operated centrifugal lining works in 2 to 12 ft (0.6 to 3.6 m) diameter shafts and will place up to 8 yd^3 (6 m^3) per hour of shotcreting.**
- **For shafts 10 to 20 ft (3 to 6 m) in diameter, STI uses a continuous 2 x 2 in. (50 x 50 mm) nozzle robot. The two nozzles keep the robot centered, minimizing the violent bouncing that using only one nozzle would create.**
- **The two-nozzle robot will spray up to 14 yd^3/h (11 m^3/h). The shotcrete mixture is pumped through all the hoses on the surface before being lowered down, connected to the cable every 50 ft (15 m) to disperse the weight of each concrete hose.**
- **The lining of 1000 ft (300 m) shafts is easily achieved and we are considering lining much deeper shafts using the double nozzle system.**

When it comes to sprayed concrete lining, there is conventional dry-mix shotcrete (water added at the nozzle) or wet-mix shotcrete (air added at the nozzle). Both technologies have long been used for lining horizontal pipes, tunnels, culverts, and vertical shafts.

In a whitepaper by Morgan et al. (2010), the authors explain that these systems have generally worked well and provide high-quality lining. They are not without their challenges, however, including maintenance of the robotic rig and the need to regularly clean the shotcrete nozzle. Shotcrete Technologies, Inc. (STI) developed another option—a centrifugal-sprayed concrete spinner head system that they have used in horizontal structures since about 2005. In 2009, they deployed the first use of this technology in North America to line a 11 ft (3.5 m) diameter, 1000 ft (300 m) deep raise-bore shaft at the New Afton copper-gold mine near Kamloops, BC, Canada (owned by mining company New Gold).

At the New Gold Project, STI demonstrated that centrifugally placed wet shotcrete can be used to structurally line 1000 ft (300 m) in substantially less time than with robotically placed dry-mix shotcrete. The timeframe was 6 days versus 6 weeks in this particular case.

For the wet-mix centrifugal sprayed concrete, instead of adding water at the nozzle as in dry-mix shotcrete, or air at the nozzle as in wet-mix shotcrete, the concrete mixture is pumped to a spinning head, which spins at 4000 to 5000 rpm. The concrete is then centrifugally sprayed onto the receiving surface at high velocity.

In 1998, Pan American Silver acquired the La Colorada underground silver mine in Zacatecas, Mexico, in the Sierra Madre mountain range. An expansion of the mine, launched in 2014, will increase the mine's capacity from 1250 tons (1130 tonnes) per day to 1800 tons (1630 tonnes) per day by 2018.

Work is expected to be complete by 2017, and involves the construction of a new 2000 ft (600 m) deep extraction shaft between two of the mine's main zones, with a capacity for hoisting ore and waste of 2300 tons (2100 tonnes) per day, as well as serving as the main access to working areas for mine personnel and additional underground development to extend the operations for deeper levels.

Pan American Silver was raise boring the 2000 ft (600 m) deep by 20 ft (6 m) interior diameter shaft in Zacatecas last fall. Construction of the new shaft advanced smoothly through good ground conditions that allowed construction crews to compete the 1030 ft (312 m) of the raise bore, according to Michael Steinmann, Pan American Silver's President.

Lining a Shaft in One Day

The upper 700 ft (210 m) was in questionable ground, so it was decided to raise a smaller 10 ft (3 m) diameter bore to shotcrete the shaft and then excavate from the top down.

The day after the bore machine was removed, crews lowered a camera down and marked where the shotcrete was needed—a total of 240 ft (70 m) in various areas.

"At 11 a.m. we started lining a flash coat, top to bottom," says Kristian Loevlie, President, Shotcrete Technologies, Inc. "We then lined 3 in. (75 mm) of shotcrete where needed and by 6 p.m. the same day, we had completed the shaft lining."

A total of 38 yd^3 (29 m^3) was in place. The company made its shaft lining concrete mixture on-site using local materials and the on-site batch plant. "We used 900 ft (270 m) of hose to keep everything flowing smoothly," Loevlie adds.

There was no noticeable rebound and this structural shotcrete reached 3000 psi (20 MPa) in 24 hours and 7000 psi (50 MPa) in 14 days.

References

Morgan, D.R.; Loevlie, K.; Kwong, N.; and Chan, A., 2010, "Centrifugal Sprayed Concrete for Lining Horizontal Pipes, Culverts, and Vertical Shafts," 3rd International Conference on Engineering Developments in Shotcrete, New Zealand, Mar. 15-17, 7 pp.

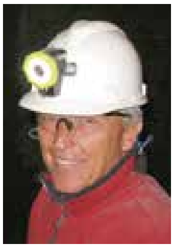
Pan American Silver

Fig. 1: Hoses before lining

Fig. 2: Lowering the egg into shaft

Fig. 3: Shaft lining with the spider

Fig. 4: Crane over the shaft



*Norwegian-born **Kristian Loevlie**, Cofounder and Owner of Shotcrete Technologies, Inc. (STI), is one of the world's leading experts in wet-mix shotcreting. His technical expertise, including specifications, mixture designs, logistics, equipment and system design, and training has provided STI a firm foundation in the shotcrete world with the cutting edge of new technology and techniques.*

Will Trump's Immigration Stance Foil U.S. Revitalization Plans?

By Chako Perez and Brett Holubeck

While on the campaign trail, President Trump stumped for revitalizing the country's infrastructure and creating thousands of new jobs in construction and manufacturing. However, his intended follow-through changes to immigration law and reduction of refugee programs could conflict with those national rebuilding plans.

President Trump's 10-point immigration plan includes a call for a wall along the U.S.-Mexico border, terminating current amnesty plans that provide work benefits, and eliminating job and benefit magnets. Post-election comments and recent Executive Orders involving travel prohibitions and limits on refugee and visa programs point to President Trump following through on these campaign promises. Industry groups, however, caution that these actions could actually limit the construction industry's ability to meet his similarly important goal to rebuild America. In 2015, the National Association of Home Builders analyzed labor use in residential construction over a 10-year period, and concluded that the flow of the immigrant community is highly correlated with the booms and busts of single-family sales and starts. Any policies that result in the net loss of current and future immigrant workers would leave companies with few substitutes for a similarly skilled, reliable, and flexible workforce to meet future fluctuations in demand. The particular impact of these policies on the construction sector is magnified by an already shrinking pool of skill craft laborers, such as concrete workers and carpenters.

Workplace Inspections

Further, President Trump's plans to curtail illegal immigration could place new obligations on construction employers and the likelihood of increased enforcement actions. In particular, President Trump called for nationalization of the E-Verify system, which would require employers to run new hire identities through Department of Homeland Security (DHS) and Social Security Administration databases. Although certain federal contractors have been obligated to do this for several years now, the residential and commercial construction industry has not faced this obligation. While some have voluntarily registered to use the automated system under the false hope that it guarantees Form I-9 compliance or that it keeps the company 100% free from undocumented workers, unfortunately, this has not proven to be the case in practice.

One additional area of major significance to construction industry employers is the likelihood of renewed worksite enforcement through Notices of Inspection (NOIs) and renewed workplace raids by DHS. While such actions had been de-emphasized under the Obama Administration, they are likely to increase in the effort to deny jobs to undocumented immigrants and punish companies who employ them. This will renew the trend last seen with the Bush II Administration where the construction industry was a particular investigation target. It was not uncommon for these companies to not only be cited for their faulty Form I-9 records, but to also lose a large number of workers who could not pass DHS scrutiny. Those who were grossly negligent or who knowingly skirted the law also found themselves paying huge fines and even defending themselves against criminal charges.

Preparing for the New Enforcement Priorities

With civil penalties now doubled to a minimum of $216 for each incorrect Form I-9 found during a DHS Notice of Inspection (NOI), a good place to start is with an audit of existing Form I-9s and hiring practices to ensure the Form I-9 is being filled out completely and correctly. (The current version of the Form I-9 may be accessed at **www.uscis.gov/I-9**.) Any incomplete Form I-9 should be corrected to avoid these failures being used as evidence that the company had little regard for complying with its obligations against knowingly hiring undocumented workers. Companies who depend on second- or third-tier subcontractor companies should also work with those partners and competent legal counsel to ensure their practices do not put the company at risk of a DHS raid or sudden loss of labor.

Employers should also be aware of their state's discrimination laws to avoid going too far into inquiries of individual's national origin or work authorization that could draw a government investigation. For example, effective January 1, 2017, California now prohibits employers from requesting more documentation than is required under federal law, refusing to honor documents that on their face appear genuine, and restricts the ability to reinvestigate/re-verify an incumbent employee's work authorization absent a legitimate, nondiscriminatory reason.

Front office and human resource staff should be aware of the protocol to follow in the event of any government visit—especially one involving DHS. Here are a few simple steps to follow in the event a company is served with an NOI:

If DHS personnel inquire regarding the employer's hiring practices, immigration policies, or business operations, staff should be trained to refer such questions to counsel.

While in some instances, DHS will secure a warrant for records and/or interviews, an NOI itself is not a warrant. As a result, the employer should not consent to any DHS interviews of supervisors without the presence of immigration counsel.

Nor should the employer consent to an immediate review of I-9 records during an NOI. Employers are allowed 3 days to provide their Form I-9 records and additional extensions are possible. This time will allow your counsel to audit the Form I-9s to understand any areas of concern and consult with the company on the next phases of the NOI process.

Although employers will welcome the more employer-friendly regulatory reforms already undertaken by the Trump Administration, all employers—including those in the construction industry—should expect increased scrutiny and immigration enforcement activity. Employers should take this opportunity to be proactive, analyze their current practices, and make any necessary changes.

Chako Perez *has extensive experience defending companies in court and before government agencies, including the Equal Employment Opportunity Commission (EEOC), Department of Labor (DOL), and Department of Homeland Security (DHS). Perez is a regular writer on labor and employment law and conducts seminars to client companies and trade associations across the country.*

Brett Holubeck *is an Attorney at Alaniz Schraeder Linker Farris Mayes. His practice is devoted to defending businesses from investigations by government agencies. Questions about this article can be addressed to Brett Holubeck at (281) 833-2200 or bholubeck@alaniz-schraeder.com.*

Form-and-Pour to Shotcrete

By Ross King

In today's increasingly competitive and challenging structural concrete marketplace, the need for innovative solutions to challenging forming issues is greater than ever. Old standbys aren't the answer for increasingly complex requirements. These challenging issues require new and better solutions.

Not too long ago, form-and-pour methodology completely dominated the forming marketplace, but that's changing. Today, the marketplace is seeing structural shotcrete gain far greater acceptance as a more logical and efficient option for structural concrete applications. And with today's increased emphasis on sustainability and environmental responsibility, structural shotcrete is well-positioned to make further inroads and experience increased demand and growth.

Shotcrete for structural needs was first adopted on the west coast of North America beginning in California and then eventually moving north to Washington state. Until relatively recently, however, shotcrete was rarely used in thick, heavily reinforced structural concrete applications east of the Rockies in the United States or in any parts of Canada. Over the last 5 years, however, recognition and acceptance of structural shotcrete in thick, heavily reinforced sections has now extended to the east coast and across Canada as well. This growth has been driven by the efficiency of one-sided shotcrete formwork panels for buildings and civic structures and the ability to produce high-quality concrete in place using wet-mix shotcrete placement.

Fig. 1: Tall segmented radius, one-sided "shoot panels" for curved wall forming

The greatest barrier to acceptance in the early stages of adoption was a resistance by structural engineers, architects, and project owners to consider shotcrete as a viable alternative. The hard work and persistence of structural shotcrete pioneers on a prove-it-as-you-go basis, however, has steadily helped dispel concerns that existed in the past. Today, the acceptance of structural shotcrete as an option to concrete poured into two-sided forms built to contain high fluid pressures is commonplace. Structural shotcrete placement is now routinely included in project specifications for a wide variety of high-quality concrete structures.

Structural shotcrete offers several compelling advantages that are now coming to light and driving its growth in the construction marketplace:

- Substantially less formwork is required;
- The formwork that is required is substantially lighter in weight;

Fig. 2: Architectural reveals and recessed panels on single reskinned shoot panels for curved wall prior to reinforcing bar placement

- Greater square footage (m^2) per day can be delivered consistently;
- Project schedules are accelerated because of productivity and efficiency gains;
- Faster project completion translates into substantial cost savings;
- The inherent flexibility of shotcreting versus pouring reduces the complexity of many structural forming challenges; and
- More surface finishing options are available.

Fig. 3: Complex forming for architectural "Y" columns, using one-sided shoot panels

Fig. 4: Retaining wall with an architectural pattern of radiating reveals, with alternating broom-and-polished finish

LESS FORMWORK

All vertical, two-sided formwork is designed to withstand a minimum of 600 lb/ft^2 (2900 kg/m^2) of concrete head pressure. The resulting forms are substantial and heavy to carry this high internal pressure. With shotcrete applications, however, a one-sided form is all that is required and this form only needs to withstand 50 lb/ft^2 (240 kg/m^2) of pressure. This reduced pressure requirement is a direct result of

Fig. 5: Complex shoot panel formwork for a church; notice the lack of internal bracing required in the window blockout

Fig. 6: Finished shotcrete structure using only one-sided shoot panels, eliminating the risk of voids in the slender pillars that can occur when using form-and-pour

the high-velocity, pneumatic application of the concrete impacting over a small area, as opposed to pouring in a form that has fluid pressure along the entire form length.

There's far less pressure at the bottom of a one-sided shotcrete form and the pressure resistance requirement is only to keep the form from moving or vibrating during the shotcrete placement. With the dramatic decrease in form pressure, forms can be much lighter and thinner than traditional form-and-pour panels. And with the need for only a one-sided form rather than a two-sided form factored in, overall formwork materials can be reduced by up to 75%. In addition, the reduction in form pressure means that details for corners, intersections, fillers, and bulkheads are easier to produce, resulting in significant material and labor savings.

Fig. 7: Tall, light one-sided shoot panels with pinwheeled corners and uneven base; not possible with form and pour

The decreased volume of formwork materials required on the jobsite further reduces storage needs and crane requirements. The number of forms that must be stored offsite and transported to and from the jobsite is lessened; that also reduces costs while accelerating scheduling. By reducing the amount of formwork required and thus eliminating a substantial portion of transport requirements, a shotcrete application reduces the environmental impact of a project and contributes to more sustainable construction.

LABOR AND SCHEDULE SAVINGS

When the quantity, size, weight, and complexity of onsite formwork are reduced, labor requirements are also minimized. The level of required labor skill is usually also lowered and this often allows skilled labor to be used in other high-demand project areas that are commonly strained during busy times.

When labor requirements decrease, schedules accelerate. Schedule acceleration reduces site overhead, which results in less consumption and greater sustainability.

The reduction of formwork requirements is especially advantageous in tight urban project sites. Fewer deliveries and materials onsite reduces crane time and frees up lifts for other critical operations, further contributing to schedule

Fig. 8: Tall shoot panels braced from the shot side due to property line constrictions

acceleration. As an additional bonus, fewer deliveries means less traffic congestion and in some cities, that equates to significant savings on lane closure fees associated with extended loading and unloading requirements.

On remote sites, the reduction in transport time and lessened crane requirements also reduces project completion timing and transport costs.

SHOTCRETE ADVANTAGES IN SPECIALTY APPLICATIONS

With the combined savings achievable in materials, labor, and site logistics, structural shotcrete offers new forming opportunities not available or associated with two-sided form-and-pour methodology:

- Shooting or finishing a wall from both sides with stay-form or insulation in the middle;
- Laminating over an existing structure that is tight to the floor and ceiling with no access from above to pour concrete into traditional two-sided forms;
- Creating curved walls without the cost of building complicated two-sided curved formwork;
- Easily creating tapered concrete sections that provide the exact concrete thickness where needed;
- Creating shotcrete wall finishes similar to architectural floor finishes with color, stamping, carving, and offset facing not possible with traditional form liners; and
- Hoisting or formwork moving challenges encountered in constricted spaces such as subways and tunnels are mitigated or eliminated when the form panel size and weight is reduced, or rendered unnecessary.

ENVIRONMENTAL IMPACT—SUSTAINABILITY

All areas of the construction industry are being impacted by increased pressure to contribute to more sustainable and environmentally friendly work processes—and rightly so. And while it's a challenge for many segments of the industry, this increased awareness and subsequent demand represents another significant opportunity for structural shotcrete to position itself as a better application alternative and continue to grow and flourish.

Wet-mix shotcrete placement creates a fresh concrete surface that can be a troweled, smoothly finished surface free of bug holes, lift lines, and form tie holes. The surface is denser and can be treated like an industrial floor. The result is a longer life cycle with added protection against freezing and thawing, chloride penetration, abrasion, and wear from environmental conditions. These characteristics enhance the overall sustainability of the shotcrete application methodology. Structures that last longer have less overall impact on the environment.

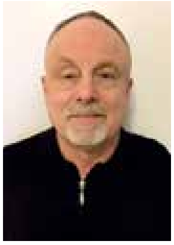
Rebound and waste concrete can be turned into a usable retaining wall and barrier blocks. This recycling of waste into marketable by-products further contributes to the sustainability of structural shotcrete in a significant and tangible way.

Fig. 9: Finish troweled curved wall, with post saw-cut architectural reveals

Fig. 10: Rebound and waste shotcrete cast onsite into useable retaining wall and barrier blocks, further contributing to the sustainability of shotcrete

From the offsite prefabrication and delivery stage right through to cleanup at the end of the project, structural shotcrete can increase sustainability and result in a more durable, longer life structure that requires less maintenance in the future.

When you add the sustainability benefits of structural shotcrete to the significant cost savings and schedule advantages it creates, it's not hard to see that structural shotcrete applications will continue to gain ground and truly represent a bright future for the construction industry.



Ross King *is Vice President of Business Development for Torrent Shotcrete Group in Toronto, ON, and Vancouver, BC, Canada. He has more than 40 years of experience as a Principal in the heavy concrete construction business.*

Marina Heights Project

By Kevin Somerville

The Marina Heights project in Tempe, AZ, is the regional headquarters of State Farm Insurance, who also serves as its anchor tenant. This is a mixed-use project with the lion's share of office space being leased by one tenant, State Farm. The primary development stakeholders were Sunbelt Holdings, Ryan Companies, and Arizona State University (ASU). Ryan Companies is a national construction company founded in Minnesota and was also acting as the general contractor, in addition to their development interests.

The project is located on the south bank of the Tempe Town Lake in the heart of Tempe, and directly adjacent to the football stadium for ASU. The project is situated between a busy city road, Rio Salado Boulevard, on one side; a new apartment development also nearing the construction phase on another; and an empty parcel on the third. The fourth side, not the least of which, was the longest tangential stretch along the Marina Heights project and intersected the slope of the earthen levee for the Salt River and Tempe Town Lake. The levee is a multi-jurisdictional flood control structure and so governed by intergovernmental agreements between the City of Tempe and the Flood Control District of Maricopa County. Because the development intersected the slope of the levee, all construction was subject to review and permitting by both government agencies. The project site was surrounded by appreciable volumes of university vehicular and pedestrian traffic. Groundwater, with a perched water table, was pres-

A relevant article regarding the State Farm Development can be found at **www.bizjournals.com (July 31, 2013), by Erin Roman.**

Fig. 1: Aerial view of Buesing Corp.'s mass excavation, shoring, and shotcrete finish wall work in progress

ent just a few feet (meters) below the bottom of the proposed garage excavations. The site also had historical wildcat dumping decades ago; thus, sorting and then legal disposal of debris was required from the beginning of the site work.

The proposed project plan by the development team included a parking garage with a 19 acre (77,000 m^2) footprint, two levels below street grade approximately 24 ft (7 m) deep, podium layout construction, with five individual glass office towers within the garage footprint. The total office space of the five buildings was 2 million ft^2 (190,000 m^2), and 60,000 ft^2 (5500 m^2) of retail space. The development was proposed to maximize the land parcels and therefore the below-grade garage footprint was pushed out to near the property lines, requiring shoring systems to be installed at the wall line—or, in other words, at the back of the proposed perimeter finish wall. In 2013, the project was initially programmed to be constructed at a project cost of $600 million to deliver shell buildings and completed sitework. Subsequent scopes and contracts were to include build-to-suit space and furnishings for the buildings. These final scopes are being finalized and completed, and will be ready for occupancy this spring of 2017. Occupancy of some building spaces began sometime last year. The size of this project in terms of dollars and area is the largest ever in the metropolitan Phoenix, AZ, area, just edging out CityScape, where Buesing also performed the three similar scopes in 2008.

Once the Marina Heights land closed escrow, the pressure was on to begin construction. Ryan Companies solicited budget pricing based on preliminary schematic drawings to more than three bidders for the sitework, shoring, and concrete/shotcrete walls. Buesing was successful in being awarded all three of these scopes on this project and swiftly began collaborating with the project team on all aspects, including removals, mass excavation, shoring/earth retention, and shotcrete finish walls. In this process, we refined the guaranteed maximum price (GMP) type budgets for contract, and collaborated on detailed schedules and work plans. Buesing began sitework within 2 weeks of being awarded the contract because of the fast-track nature of this project.

Although mass excavation, sorting and hauling debris, hauling excess soil, and shoring all began in late July 2013, the concrete trade subcontractor (Suntec Concrete) was immediately behind Buesing starting the concrete mat foundations, interior columns and shear walls, and perimeter wall reinforcing bar installations. By November 2013, we began installing shotcrete finish walls in some limited areas while we were still excavating and shoring in other areas. It is also interesting to note that our temporary shoring system included a 4 in. (100 mm) thick shotcrete facing, which required daily crews to keep the shoring operation on schedule. Therefore, oftentimes we were installing shotcrete facing for shoring with one crew and installing the permanent, perimeter shotcrete finish walls on the perimeter with a second crew.

SHOTCRETE WALLS

The structural or finish perimeter walls for the below-grade garage were initially designed to be conventional form-and-

By the Numbers

- 19 acres (77,000 m^2) of garage footprint
- 470,000 yd^3 (360,000 m^3) of mass excavation and haul off
- 105,000 ft^2 (9750 m^2) of shoring/earth retention (three systems)
- 97,000 ft^2 (9000 m^2) of permanent shotcrete finish walls

Fig. 2: Buesing Corp. setting ground (piano) wires from scaffolding (reinforcing bar curtain by concrete subcontractor)

Fig. 3: Nozzleman shooting shotcrete (wet-mix) for structural finish wall

Fig. 4: Multiple shotcrete activities on three levels of scaffolding

pour concrete construction, with a 6000 psi (40 MPa) concrete design mixture. Buesing submitted pricing for shotcrete installation of these perimeter walls as a value engineering alternative to the form-and-pour construction, showing both a time and cost savings to the project. For synergy of cost control, scheduling, and overall coordination of scope, our contract for these shotcrete finish walls was directly with Suntec instead of Ryan Companies. Through this collaboration process, our wall installation was performed in six phases over the span of 12 months (November 2014). To accelerate the schedule and help accommodate the aggressive schedule by Suntec, Buesing increased its crew size by 20% from what is typical, and worked 9- to 10-hour-long days, and frequently worked Saturdays.

An extensive mockup panel was constructed to evaluate and test the various integral components, an appreciably more robust mockup panel than typical. The mockup structure included the soil nail heads for shoring, the complete waterproofing system, reinforcing bar installed per plans, an inside corner, and an outside corner. As planned, the actual shotcrete finish wall was installed atop the completed waterproofing system, which was installed over our

Fig. 5: Rod, float, and trowel work to tolerance wall thickness to ground wires

Fig. 6: Applying a light broom finish

Fig. 7: Completed shotcrete finish walls in the background (CIP columns by concrete subcontractor in foreground)

Fig. 8: Aerial view of near-complete Marina Heights (State Farm) development (January 2017)

temporary shotcrete shoring facing system. The shoring served as the back form for the perimeter finish wall in most cases, and there was also back forming required to be installed by Suntec above our shoring to achieve design elevations around the perimeter. The perimeter finish wall design included horizontal corbels and notches for the intermediate floor. All columns were designed away from the perimeter so there were no pilasters (in-wall columns). The shotcrete installed, met, or exceeded the 6000 psi (40 MPa) design requirement. Both construction joints and scored control joints were implemented in our shotcrete installation. A wood float finish followed by a light broom drag was selected as the final shotcrete wall finish.

Buesing met or exceeded the requirements and expectations of the 6000 psi (40 MPa) design mixture, the quality control testing, finish, and schedule. The shotcrete scope(s) that we performed on this project was intense, working alongside a robust concrete operation by Suntec that included multiple tower cranes and a steady stream of concrete ready-mix deliveries. All in all, the project was successful because of early and effective planning, and hard work by our employees on the project, certainly inclusive of the shotcrete crew.

About the Company

Buesing Corporation is a Phoenix-based construction contractor that performs a variety of civil and site work services for multiple markets. It has served the construction industry since 1965, beginning in Minnesota, and moving to Arizona in 1986. It owns a wide variety of equipment that is well maintained at the company's shop or by two shifts of mobile mechanics. Buesing works on many high-profile projects and for some of the largest developers and general contractors. Although shotcrete is a fraction of their business, they have become a leader in the market, providing shotcrete services for the construction and shoring projects they are awarded, as well as an ancillary service. For years, one of the company's successful formulas has been to self-perform mass excavation, shoring (earth retention), and shotcrete finish or structural walls on numerous basements or below-grade garages in Phoenix and Tucson.

Kevin Somerville *graduated from Arizona State University in the construction management program in 1990 and immediately began a career at Dames & Moore that later merged with URS, both of which are international engineering/geotechnical/consulting/environmental firms. Somerville was a lead estimator, construction manager, spec writer, scheduler, design task leader, and project manager and rotated those responsibilities through the years from project to project. He has his engineering-in-training certificate as he has worked with civil and structural engineers daily during his 13-year career there. Somerville joined Buesing Corp. in May 2002 as the Chief Estimator. He was instrumental in bringing the shoring design-build services to Buesing Corp. in 2003 with his engineering background. Somerville became Vice President of Estimating & Business Development/Marketing in 2005. Last year, Bill Kelton joined the company as VP of the estimating department, and Somerville is currently VP of Business Development/Marketing, while still an integral part of estimating.*

What's the Hurry?

Effective tools to determine the correct stack rate

By Oscar Duckworth

Apparently, seeing the concrete truck arrive does not bring out the best in people.

I know seasoned concrete professionals who suffer painful anxiety on pour day in the agonizing moments before they must place tall form-and-pour walls. Experienced concrete workers know first-hand what may happen as enormous fluid pressures are contained within tall concrete formwork. Most days, the pour is uneventful and workers quickly return to their boisterous selves.

With the shotcrete process, placement of tall walls tends to be a little less stressful. That is because only momentary impact pressure over a small area must be carried by the form, whereas, in the form-and-pour approach, the full fluid head pressure must be carried along the entire length of the cast section.

Although placement of tall walls tends to be less risky with shotcrete placement, nozzlemen must be aware that shotcreted materials can be stacked in vertical lifts too quickly. When this occurs, internal stacking pressures can quickly escalate to levels potentially damaging concrete that has not yet reached sufficient strength to support the weight of the concrete above. Similar to the traditional form-and-pour operations, placing materials in very tall lifts can increase the risk of a failure, potentially collapsing large sections of freshly placed material. All nozzlemen know that stacking a wall in excessively tall lifts is a gamble, but collapse is only one of the potentially destructive effects that can occur.

UNDERSTANDING THE STACK RATE

Ask a nozzleman to identify the correct stack rate. Most will reply: as high as possible. But experienced nozzlemen can describe, usually from their personal experience, a collapse caused by stacking a wall too quickly. Shotcrete should never be stacked excessively before the in-place material below reaches a sufficient set to support its own weight without deforming. Nozzlemen know this as the

Nozzleman Checklist

- Aggressive stack rates do not save time. The risk of injury, fallouts, waste, and damage to in-place work is completely avoidable.
- Movement can cause hidden cracks and delaminations of the in-place material. Learn to avoid potential trouble by recognizing the subtle cues of an excessive stack rate.
- Completely cut out and reshoot materials that exhibits signs of cracking, sags, or delaminations.
- Prior to placement, check reinforcement rigidity by giving it a firm tug. Visually validate that there is sufficient anchorage between front and rear curtains and to the substrate surface.
- Use the best tools available to you—your hands, eyes, and experience—to determine a safe stack rate.
- Plan to give in-place materials sufficient time to reach initial set before proceeding.

Fig: 1: Moments after a potentially dangerous collapse of plastic material caused by stacking a wall too quickly material's stack rate. Numerous job-specific placement conditions will influence how tall a given wall may be safely stacked per hour.

To enhance productivity and minimize hose movements, nozzlemen tend to attempt the tallest stack rate possible. Unfortunately, nozzlemen and other in-field workers may not be aware of the potential damage that can occur to the in-place work from overly aggressive stack rates.

SUBTLE CLUES OF TROUBLE

The obvious risk shotcrete crews encounter when building up too quickly is the risk of creating fallouts or a dangerous collapse (Fig. 1)—at minimum, fallouts, sags, and cracks caused by aggressive stacking waste material and time. Many times, vertical wall fallouts can create a risk of injury to workers. Even small fallouts may weigh several hundred pounds (kg). Because a fallout can occur unexpectedly, workers may not realize that they are at risk. Head, neck, and shoulder injuries—even potentially deadly scaffold failures—have occurred due to fallouts.

Far less obvious is the risk to in-place material quality from aggressive stack rates. Shotcrete nozzlemen who stack a wall too quickly negatively affect in-place quality well before the work is at risk of a fallout. Reinforcements specified for shotcrete placement must be firmly secured to remain in place and resist movement while the material is in its plastic state (Fig. 2).

Aggressive stack rates subject reinforcement and formwork to strong downward pressures from immense weight. Freshly placed materials are vulnerable to cracking, sags, or delamination damage from internal movement due to the weight of higher levels being carried through the fresh concrete that has not yet reached enough set (and strength) to carry the loads (Fig. 3).

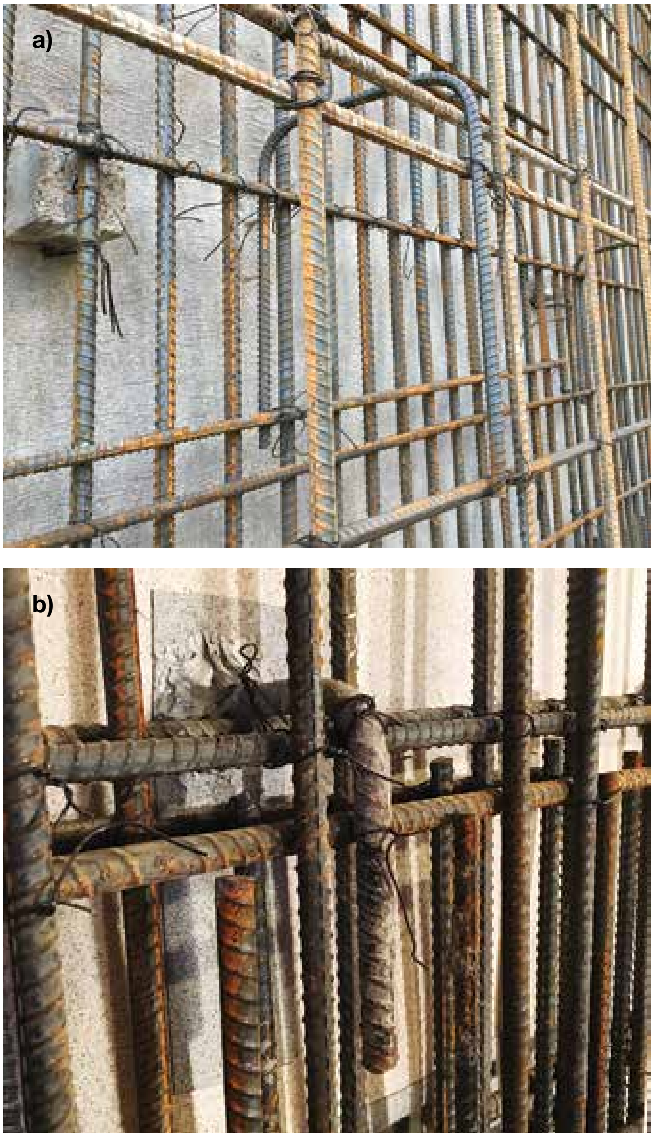


Fig. 2: Reinforcements must be sufficiently rigid to resist movements as loads are transferred to them from the stacking of plastic materials. Note: (a) inverted U-shaped transfer bars between curtains; and (b) rigid anchorage to the substrate

Fig. 3: (a) Visual evidence that excessive downward pressure has caused cracks within the plastic material; and (b) sagging materials have lost their bond with reinforcements and the substrate surface. These cracks, sags, or delaminations must be cut out and reshot

Downward force imparts pressures that act powerfully against the in-place materials, the receiving surface, and the reinforcement. As pressure increases, these pressures tend to distort the supporting previously placed concrete and embedded reinforcement. This can often push curtains of reinforcing apart and force them away from the receiving surface. The effects of the deformation and subsequent movement, whether within the material, forms, or reinforcement, tend to produce cracks and delaminations along the reinforcement within the work that will not reconsolidate (Fig. 4).

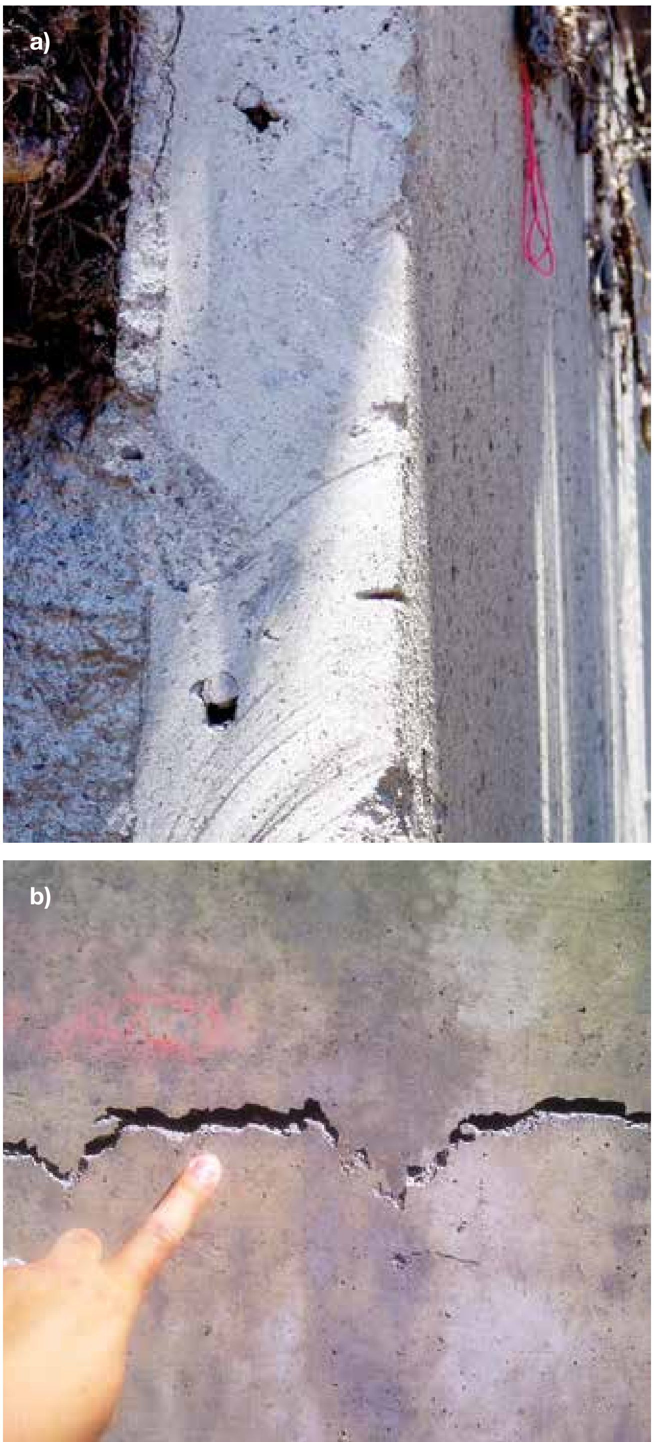


Fig. 4: (a) Saw cut reveals delaminations beneath reinforcements caused by downward movement; and (b) substantial crack visible from formed surface caused by excessive weight

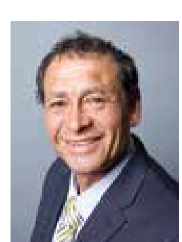
Freshly placed materials that exhibit sags, cracks, or other delaminations lack structural properties and must be identified, completely cut out, and reshot before final set.

Choosing the proper stack rate should not be guesswork. The best stack rate gauges are the nozzleman's hands, eyes, and experience.

Damage and risk due to aggressive stack rates are caused by the actions of the nozzleman. Rather than shoot a very tall lift, then hope for the best, nozzlemen should choose the appropriate stack rate by using all the tools available to them. Placement condition variables invalidate simple 3 to 6 ft/h (1 to 2 m/h) stack rate guidelines. Cold weather, concrete mixture, substrate surface, reinforcement, low nozzle velocity, or excessively thick elements are just a few of the varying conditions that require nozzlemen to limit the stack rate.

Nozzlemen must determine the project's safe stack rate by using keen sensory skills, their hands, eyes, and experience rather than simply reaching "as high as possible." Prior to placement, nozzlemen should use their hands to tug the reinforcements and validate they are properly retained. During placement, they should feel in-place material, constantly validating sufficient set has occurred prior to placing additional shotcrete above previously placed material. Nozzlemen should keep a watchful eye for signs of movement within the reinforcement and the area below where fresh material is being stacked, and immediately stop if movement is noted. Nozzlemen should diminish risk by planning to allow more time for in-place materials to reach proper set before building additional height. Give in-place materials time by slowing the placement volume rate, increasing the horizontal length of a bench, or stop and move to another location.

It is important to remember that choosing the proper stack rate is the nozzleman's responsibility. Any efficiencies gained by shooting very tall lifts will be quickly erased by sagging, fallouts, or by hidden damage to in-place work.



ACI Certified Nozzleman ***Oscar Duckworth*** *is an ASA and American Concrete Institute (ACI) member with over 15,000 hours of nozzle time. He has worked as a nozzleman on over 2000 projects. Duckworth is currently an ACI Examiner for the wet- and dry-mix processes. He serves on the ASA Board of Direction and as Chair of ASA's Education Committee. He continues to work as a shotcrete consultant and certified nozzleman.*

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Challenges on the Lagoon at Treasure Island Resort

By Zach Brazier

Global Specialty Contractors, Inc., was contracted by Knutson Construction, Minneapolis, MN, to build four substantial water features in their new "Lagoon" expansion at the Treasure Island Resort and Casino in Welch, MN. The $19 million dollar, 40,000 ft^2 (3700 m^2), project began in May 2015.

Global Specialty was brought on site in late summer of 2015 and given a completion time of 5 months. The centerpiece of the new Lagoon project is the 325 ft (100 m) lazy river. The river is complete with rapids and waterfalls. Global placed 150 yd^3 (110 m^3) of floor and wall. Once the work area was ready, they broke up the concrete placement in three sections. The Global Specialty carpenters paid extra attention to build proper joints to ensure watertightness.

The adjacent 2000 ft^2 (185 m^2) leisure pool's walls were placed with another 55 yd^3 (42 m^3) of wet-mix shotcrete. At this point in the project, the building that included the Lagoon expansion had not been enclosed from the elements.

Fig. 1: First section of lazy river placed

Fig. 2: Lazy river

Fig. 3: Leisure pool ready for shotcrete application

Fig. 4: Lounge pool

Synthetic BurLene® blankets were used for curing of the entire workspace.

Not the largest vessel, but still complicated, was the aesthetically pleasing Lounge Spa. The monolithic shotcrete structure of 35 yd^3 (28 m^3) was placed and carved by skilled workers. The formwork prior to shotcreting looked like a web of reinforcing bars, tubes, and water stops. It is often a challenge to fit enough workers to place, finish, and remove rebound in these smaller water features. After about a 14-hour day, a swim-up bar was easily recognizable.

Just before Christmas, they began work to form and shoot the two-tiered cascading spa. This last water feature proved difficult as the other trades were also trying to wrap up their work. A lot of planning and coordination took place to allow Global to pump shotcrete without damaging the surroundings from hose breaks or rebound.

By Christmas, all four of the water features were in. Global Specialty's tile and plaster crews were working behind the concrete crews throughout the various new structures' placement. It was certainly a challenge to maintain proper curing time and method, with Knutson pushing to get finishes applied to the shotcreted structures. Through good communication and coordination, we were able to cure and keep the final finishing on schedule.

Behind the scenes, the casino was moving forward, adding an additional outside spa to the project. Knutson produced a change order and directed Global Specialty to begin work immediately on the outside spa. Knutson Construction was very understanding and helpful with the need to maintain a proper working environment for building the shotcrete structure.

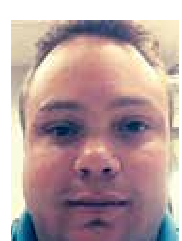
As the shotcrete crew was getting ready to go ice fishing for the winter, they were called back. The mission was the same: build a quality vessel in very little time. Knutson was as accommodating as possible for the work area; in return, we assured that all shotcrete placement would follow standard industry practice. In the freezing temperatures, we had a pre-application meeting with the ready mix supplier. We successfully shot a monolithic spa of 15 yd^3 (11 m^3) and Knutson was kind enough to allow the little enclosure to be heated for an appropriate cure time.

With all the usual difficulty of a large project, I found the biggest challenge was to stay in close contact for coordinating with the various oversight groups. The Owner had a high demand for quality and timeliness. The engineering and management firms onboard had an equally high demand for proper placement, curing, and protection practices. I personally learned in my early years in the shotcrete business that it is more economical to use proper methods, and avoid cutting any corners. There was a lot of stress to keep the various inspectors satisfied, but our team slept well at night knowing we were delivering a high-quality product.

Fig. 5: Finished Lagoon

As the expansion came to a completion, the casino heavily advertised the new Lagoon on radio, TV, and online. To date, the Lagoon has had over 100,000 swimmers. The indoor waterpark is the second largest for the Minnesota Casinos. This facility has truly made Treasure Island Resort and Casino a family destination.

After less than a year of operation, Global Specialty was honored to be selected to construct two more pools in yet another expansion at the casino. The new pool expansion is adjacent to the Lagoon, and so far, we've placed another 45 yd^3 (34 m^3).



Zach Brazier *is Vice President at Global Specialty Contractors, Inc. With father Charles "Ron" Brazier being an Owner at Global, Zach considers himself born into the business of shotcrete. Outside the shotcrete crews, Zach manages various projects in Minnesota and assists the Hawaii Division. He also serves as the Company's Safety Director, which his continued shotcrete education betters the safety program at Global. Visit our website:* ***www.globalspecialty.net****.*

Shotcrete Technologies, Inc.

Shotcrete Technologies, Inc. (STI), is a Colorado company with a global reach that supplies mining, tunneling, and infrastructure projects with quality shotcrete products and services that includes:

- **STI Shotcrete Equipment**, including our industry-standard Shot-Tech Robotic Arm which can be mounted on many types of carriers.
- **STI Shaftlining**, a robotic system for lining/repairing shafts and tunnels. This new process is quick, non-disruptive, efficient, and at a lower cost than conventional techniques.
- **STI Shotcrete Accelerators** and admixtures, including our well-known Shotset 250 accelerator and ST Alkali Free.
- **Technical Support and Training**: The STI team of professionals understand, support, and add value to every aspect of your shotcrete application.
- **Auxiliary Equipment**: pumps, hoses, and everything you need for a complete system.

Our service starts long before the spraying begins. With over 35 years of global experience, expect our professionals to be involved from start to finish on your shotcrete project. Whether it's small-volume infrastructure repair or 10,000 yd^3 (8000 m^3) on a mega-project, STI prides itself on individual solutions for every job. In addition to our core team, we have a network of top professionals: engineers, specifiers, project managers, and nozzlemen that work with us to ensure the most efficient and cost-effective result for our customers.

SHOT-TECH ROBOTIC ARMS

The Shot-Tech Robotic Arm sets the standard for robotic shotcrete in most every application from 5 to 40 yd^3/h (4 to 31 m^3/h) in tunneling, mining, and other applications both under and above ground. It is also the choice for dry-mix applications, depending on the shotcrete pump/delivery system. Our versatile workhorse is designed for mounting on a variety of carriers, including flatbed rail cars, tractors, trucks, and loaders. It has become an industry standard for reliability and productivity and provides many thousands of yd^3 (m^3) of dependable shotcreteing for a reasonable investment.

Standard reach: 29 ft (8 m) vertically and 23 in. (5.5 m) horizontally. Boom and nozzle rotation both a full 360 degrees. Radio- or remote-controlled with proportional functions. Nozzle tilt: 100 degrees.

SHAFTLINING

The system constructs a new permanent in-place lining using a cementitious mixture that will develop a compressive strength of 6000 psi (41 MPa) or greater in 7 days. The

Fig. 1: Positioning and ready to begin the video. Note the bars of lights so we can get a very clear picture of what the shaft looks like

Fig. 2: Getting everything in position prior to the operations beginning of the shaft lining

Recent Project Highlights

- I-70 Twin Tunnels, Colorado
- San Francisco Hydro, Ecuador
- Hollywood Station, LA Metro
- Lake Mead Outlet, Nevada
- East Side Water Intake, New York
- Kinross Gold
- Barrick Gold
- Storm-Water Repairs, Mumbai
- Caracas Metro, Venezuela
- E330 Bellevue Tunnel, Washington

resulting lining is more acid- and abrasion-resistant and more impermeable than ordinary concrete.

The STI custom-designed system is operated via remote control with cameras, using a "spinner" or double nozzle that uniformly sprays the material onto the surface and will fit through an opening as small as 3 ft (1 m) in diameter so no excavation is needed. A crew of three can place up to 500 ft (152 m) per day of 1 to 2 in. (25 to 50 mm) thick under normal circumstances. After the lining is in place, it is ready within hours of placement with no adverse effect on the environment.

ShaftLining Success

- In December 2015, Pan American Silver was raise boring a 2011 x 20 ft (613 m deep x 6 m wide) I.D. shaft in Zacatecas, Mexico. The upper 689 ft (210 m) was in questionable ground, so it was decided to raise a smaller 10 ft (3 m) I.D. bore, shotcrete the shaft, and then excavate from the top and down.
- The day after the bore machine was removed, STI lowered a camera down and marked where 3 in. (75 mm) of shotcrete was needed—a total of 240 ft (73 m) in various areas.
- At 11:00 a.m., we started lining a flash coat top to bottom. We then lined 3 in. (75 mm) of shotcrete where needed and by 6:00 p.m. the same day, we had completed the shaft lining—a total of 39 yd^3 (30 m^3) was in place!
- The STI Shaft Lining Mix was made on site using local material and an on-site batch plant.
- There was no noticeable rebound and this structural shotcrete would reach 3191 psi (22 MPa) in 24 hours.

Our process-oriented approach includes helping you from mixture design and specification to material handling, logistics, equipment selection, and training. Total support from the ground up!

Shotcrete Technologies, Inc.

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ACI ANNOUNCES NEW OFFICERS FOR 2016

The American Concrete Institute (ACI) introduced its 2017-2018 President, Vice President, and four Board members during The Concrete Convention and Exposition in Detroit, MI, in March 2017.

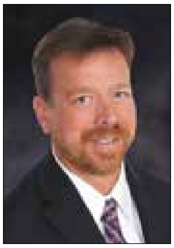
Khaled W. Awad, FACI, Chairman and Founder of ACTS, a material and geotechnical consulting firm based in Beirut, Lebanon, and operating in Qatar, Saudi Arabia, and several other countries of the Middle East, has been elected to serve as President of the Institute for 2017-2018. Randall W. Poston, FACI, Senior Principal with Pivot Engineers, Austin, TX, has been elected ACI Vice President for a 2-year term. David A. Lange, FACI, Professor of civil and environmental engineering, is now the Institute's senior Vice President, which is also a 2-year term. Awad succeeds Michael J. Schneider (FACI, Senior Vice President and Chief People Officer at Baker Concrete Construction, Inc.), ACI President 2016-2017, who will now assume a position on the ACI Board of Direction as a Past President member. His position replaces Anne M. Ellis, ACI President 2012-2013. Schneider joins William E. Rushing Jr., ACI President 2014 and Sharon L. Wood, ACI President 2015, to complete the requisite three Past Presidents of ACI serving on the Board as stipulated by the Institute's Bylaws.

Additionally, four members have been elected to serve on the ACI Board of Direction, each for 3-year terms: H.R. Trey Hamilton (FACI, Professor of civil engineering in the Engineering School of Sustainable Infrastructure and Environment at the University of Florida, Gainesville, FL), Joe Hug (FACI, Technical Services Manager for The Monarch Cement Company in Humboldt, KS), William M. Klorman (FACI, President, CEO, and Founder of W.M. Klorman Construction Corporation), and Tracy D. Marcotte (FACI, an expert and professional engineer in metallurgical and materials engineering with CVM, based in King of Prussia, PA).

Awad

Poston

Hamilton



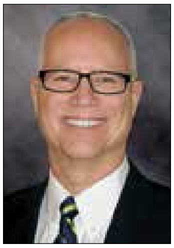
Hug

Klorman

Marcotte

JAMES D. HUSSIN RECEIVES ACSE GEO-INSTITUTE'S "WALLACE HAYWARD BAKER" AWARD

James D. Hussin, PE, MASCE, is the recipient of the Wallace Hayward Baker Award from the American Society of Civil Engineers' Geo-Institute. The award was presented by Garry H. Gregory, PhD, PE, DGE, President of the Geo-Institute, on March 13, 2017, at the Geo-Frontiers 2017 conference in Orlando, FL.



Hussin

In receiving the career award, Hussin was cited for his "extraordinary contributions to the ground improvement industry through development of soil mixing technologies and the creative application of Vibro ground improvement" in the North American construction industry.

Hussin has more than 35 years of experience in geotechnical engineering and construction. He joined Hayward Baker Inc. in 1984 as a Senior Project Engineer and in 1992 became Chief Engineer in the company's office in Tampa, FL. In 2002, Hussin was appointed a Director at Hayward Baker Inc., and in 2015 he was named a Director at Keller Foundations LLC, Hayward Baker's parent company.

Hussin has participated in some of the largest and most challenging ground improvement projects in the United States, often involving multiple techniques. Among them are ground improvement for the Steel Creek Dam at the Savannah River Plant in South Carolina, the Kings Bay Naval Submarine Base in Georgia, the LNG Import Terminal in Puerto Rico, U.S. Highway 1 at Jewfish Creek near Key Largo, FL, the Wando Terminal in South Carolina, several Cape Canaveral Airforce Station launch pads, and the Herbert Hoover Dike in Florida.

Hussin's work has made a significant contribution to the practical design and construction of many types of ground modification systems. He is the author of more than 20 published papers pertaining to ground improvement, grouting, and geotechnical engineering.

The Wallace Hayward Baker Award was established in 2000 by the Geo-Institute of the American Society of Civil Engineers (ASCE). The award is given in recognition of creative and innovative contributions in the field of ground modification. Emphasis is placed on the resourceful development of new technologies—or the creative application of existing technologies—to achieve performance not previously demonstrated in the ground modification field.

Commenting on the award announcement, John Rubright, President of Keller North America, stated, “We are delighted that the Geo-Institute has recognized Jim’s expertise and outstanding contributions to the ground improvement field. Through his efforts, ground improvement technologies have made great strides in the United States in terms of their practical application.”

Hussin is a member of numerous professional organizations, including ASCE, International Society for Soil Mechanics and Foundation Engineering (ISSMFE), the Deep Foundations Institute (DFI), and the National Society of Professional Engineers (NSPE), among others. He has been very active in ASCE, serving as a counselor for the ASCE Technical Coordination Council representing the National Soil Improvement Committee, Grouting Committee, and Deep Soil Mixing Task Force. Hussin is also a past chairman of the ASCE National Technical Committee on Soil Improvement. He can be reached at (813) 884-3441 or jdhussin@kellerfoundations.com.

About ASCE and the Geo-Institute

Established in 1852, the American Society of Civil Engineers is America’s oldest national engineering society. It represents more than 40,000 members of the civil engineering profession. The society’s mission is to “provide essential value to ASCE members and partners, advance civil engineering, and serve the public good.” ASCE members hold a bachelor’s or higher degree from an accredited civil engineering program, are licensed professional engineers, or have a minimum of 5 year’s responsible charge of engineering experience.

The Geo-Institute was established in 1996 and is one of ASCE’s eight institutes. Its members include scientists, engineers, technologists, and organizations interested in improving the environment, mitigating natural hazards, and economically constructing engineered facilities. Its award programs, including the Wallace Hayward Baker Award, offer members opportunities to be recognized for their contribution to the geotechnical profession.

About Hayward Baker Inc.

Hayward Baker (**www.haywardbaker.com**) is North America’s leader in geotechnical construction, annually ranked by *Engineering News-Record* (ENR) magazine No. 1 in foundation construction. With a more than 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.

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**.

AIRPLACO ANNOUNCES CE CERTIFICATION FOR GUNITE MACHINES

The Airplaco Equipment Company (**www.airplaco.com**) is excited to announce the industry-leading C-10SL Rotary Gunite Machine is now CE Certified and available for purchase in the European Union. The Airplaco C-10SL is a dry shotcrete machine with decades of proven performance across multiple applications: swimming pools, concrete repair, bridge repair, retaining walls, soil stabilization, refractory, mining, and more. All Airplaco machinery is built in the

United States and is ISO 9001:2008 certified. In addition to equipment, Airplaco keeps a well-stocked warehouse of parts, accessories, and finishing tools.

Airplaco has a long history of selling throughout the world and the CE designation plays a key part in expanding business in Europe. “We are very excited to officially be CE Certified because it shows the dedication to quality we take in our manufacturing process and allows us to formally respond to the high demand of inquiries we receive,” remarked Ken Segerberg, Vice President Sales of Airplaco.

Airplaco is currently finalizing distribution relationships throughout the European Union; in the meantime, all international inquiries regarding Airplaco Gunite Machines should be directed to Todd Ferguson, International Sales Manager, at (513) 824-8344.

About Airplaco

The Airplaco Equipment Company began business in 1947 and has been a leader in construction equipment manufacturing since the beginning. Airplaco specializes in the design and manufacturing of grout pumps, wet-mix shotcrete machines, and dry-mix gunite machines. Airplaco also carries and sells a full line of parts, accessories, and finishing tools for various construction industries. Airplaco is a division of Mesa Industries, Inc., a family-owned corporation with diverse operating divisions across multiple industries.

CONCRETE 2029 CONTINUES BUILDING TO THE FUTURE

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

The last workshop, held prior to SDC Technology Forum #41, took place on May 22, 2017, in Dallas, TX. The meetings summarized work accomplished since initiation of the program a year ago and focused on issues such as defining and improving in-place concrete quality, increasing workplace productivity, and improving industry promotion and perception.

Participants acknowledge that a clear vision and excellent strategy are vital for the concrete construction industry to thrive in the future. SDC and ASCC continue to build broad support for the Concrete 2029 initiative.

About ACI Foundation

The ACI Foundation was established in 1989 to promote progress, innovation, and collaboration and is a wholly owned and operated nonprofit subsidiary of the American Concrete Institute. 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.

ASA EXHIBITING AT RAILWAY INTERCHANGE 2017 IN INDIANAPOLIS THIS SEPTEMBER

At the ASA Spring Board meeting, with the recommendation of the Marketing Committee, ASA decided to exhibit at the Railway Interchange 2017, to be held September 17-20 in Indianapolis, IN. Railway Interchange is the largest combined railway exhibition and technical conference in North America. Attended by nearly 10,000 industry professionals from around the globe, this truly massive event showcases the latest technology, services, and research by members of the Railway Supply Institute (RSI); the Railway Engineering-Maintenance Suppliers Association (REMSA); and Railway Systems Suppliers, Inc. (RSSI). Railway Interchange also features technical presentations and discussions by the American Railway Engineering and Maintenance-of-Way Association (AREMA) and the Coordinated Mechanical Associations (CMA). ASA's booth is #4943. For more information and registration, visit **www.railwayinterchange.org**.

ASA EXHIBITING AT THE INTERNATIONAL POOL | SPA | PATIO EXPO IN ORLANDO THIS FALL

ASA will once again co-sponsor and exhibit at the International Pool | Spa | Patio (PSP) Expo to be held in Orlando, FL, on November 1-3. The PSP Expo is a very well-attended event for the pool, spa, and backyard professional to stay abreast of trends, market directions, and cutting-edge technology. ASA will be presenting a Nozzleman Education class on Wednesday, November 1, and ASA Past President Bill Drakeley will be presenting with Genesis' Construction 201: Basic Pool Construction on Tuesday, November 2. ASA will be exhibiting in Booth #1162 (**www.shotcrete.org/pages/news-events/calendar.htm**). For more information on the conference and expo, visit **www.poolspapatio.com**.

ASA HEADQUARTERS OFFICE HOSTS SPRING MEETINGS

Although ASA usually meets at the same facility in the spring and fall as The ACI Concrete Convention and Exposition, this March, with the ACI meetings nearby our office, the ASA Board decided to host our spring meetings at the ASA offices in Farmington Hills, MI, where we share office space with ACI. The meetings started on Friday, March 24, with a task group meeting of ASA members led by President Scott Rand, reviewing progress on our strategic plan and refreshing the goals and activities as we look forward. On Friday night, many of our committee and Board members enjoyed a group dinner at a nearby fine dining restaurant. Saturday morning saw our committees meet in the dual-track format, followed by a catered lunch and finishing up the afternoon with our Board meeting. We had very favorable feedback on the facilities (provided by ACI) and the event coordination. Many thanks to Alice McComas and ACI Event Services staff for doing all the work behind the scenes to make the meetings such a great success. For more information on the business covered and results of the meetings, please refer to Scott Rand's President's Message, Oscar Duckworth's (Education) Committee Chair Memo, and Charles Hanskat's Executive Director Update also in this issue.

NEW ASA MEMBERS

american shotcrete association | asa

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INTERESTED IN BECOMING A MEMBER OF ASA?

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

GCP APPLIED TECHNOLOGIES PRESENTS ITS TYTRO ADMIXTURE SYSTEM FOR SHOTCRETE APPLICATIONS

The TYTRO® system is designed to deliver lower costs, superior performance, and reduced cycle times

During Conexpo, GCP Applied Technologies Inc. (GCP) presented the TYTRO Shotcrete System, a complete state-of-the-art admixture solution that makes shotcrete for underground construction better, faster, and less expensive than conventional systems available today. The TYTRO System includes a nanotechnology-based rheology control agent, patented macro-synthetic fibers, and several other newly developed admixtures that enhance productivity of the spraying operation and material performance.

"Our TYTRO Shotcrete System provides improved agility and additional capabilities that applicators and global contractors have been demanding for decades," said Craig Merrill, Vice President of Global Marketing, GCP.

The TYTRO Shotcrete System provides underground construction professionals with the capability to reduce operating costs and minimize excavation downtime, without sacrificing performance or relaxing safety standards. The TYTRO Shotcrete System provides faster early strength and enhanced bonding-to-rock with an increased one-pass thickness buildup. The system also minimizes rebound during spraying.

Main advantages provided by the TYTRO Shotcrete System compared to conventional mixtures include*:

- Up to 10% lower installed cost, achieved through mixture optimization, waste minimization, and shorter cycle times;
- Rebound rates reduced to 5 to 8%;
- Faster re-entry times, due to more rapid early-age strength development at equal accelerator dosage rate;
- Superior bond-to-rock and adhesion between layers, providing greater thickness in one pass; and
- More robust and dosage-efficient system.

"Our technical specialists have analyzed the unique challenges of underground construction projects to create

*Referenced results are based on internal and external test data. Results may vary due to temperature conditions, mixture design, cementitious materials content, and aggregate gradations.

customized mix designs, delivering the most optimized and cost-efficient concrete mix for each project. We also support our customers with world-class site support and training," said Merrill.

The TYTRO Shotcrete System includes the following products:

- TYTRO WR: High-range water-reducing admixtures for shotcrete that provide superior flow, prolonged slump life, and excellent plasticity, maximizing strength performance by allowing a lower water-cementitious materials ratio (*w/cm*);
- TYTRO HC: Cement hydration control admixture, extending the working life of shotcrete up to 72 hours;
- TYTRO RC: Innovative pozzolan-based rheology control admixture that is designed to reduce installed material cost when used as a replacement for silica fume or other cementitious materials. It provides faster early strength, superior bond to rock, enhanced sprayability, lower rebound, and reduced cycle times;
- TYTRO SA: Latest generation of high-performance, alkali-free set accelerators, specifically formulated to provide high early-strength at low dosage rates and improve productivity by shortening the time of setting without compromising long-term strength and durability;
- STRUX BT: Macro-fibers featuring a patented design developed for underground shotcrete applications and offering superior flexural toughness and post-crack energy absorption;
- TYTRO AE: Air-entraining admixture for use in shotcrete mixtures to protect against damage from freezing-and-thawing cycles; and
- TYTRO RM: Rheology-modifying and mixture-enhancing admixtures formulated to improve the pumpability and sprayability of the shotcrete mixture.

GCP's complete portfolio of solutions for the mining and infrastructure tunneling industries includes admixtures for shotcrete and concrete, proprietary fiber reinforcement systems, injection technologies for ground support, and waterproofing systems for shotcrete. The company

combines its technical expertise in shotcrete mixture design optimization, on-site monitoring systems, and ground control technologies to fit to every project's unique needs. GCP's technical specialists work to provide solutions to overcome project geotechnical challenges around the world.

About GCP Applied Technologies

GCP Applied Technologies is a leading global provider of products and technology solutions for customers in the specialty construction chemicals, specialty building materials, and packaging sealants and coating industries. Their products help improve the performance of their customers' products, increase productivity in their application or manufacturing processes, and meet the increasing regulatory requirements impacting their industry. GCP has approximately 3000 employees on six continents, and serves customers in more than 110 countries. More information is available at **www.gcpat.com**.

gcp applied technologies
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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: *We are building an area of a park that is on an existing pier in Brooklyn, NY. We are researching using shotcrete to form contours on certain areas. Weighting of the pier is an issue. Our question is, can lightweight concrete, or cellular concrete, be used in shotcrete? If so, what are the weights?*

Answer: Shotcrete is a placement method for concrete. Lightweight concrete usually ranges from 90 to 115 lb/ft^3 (1400 to 1800 kg/m^3). In wet-mix shotcreting, lightweight concrete should use presoaked aggregate to make the mixture pumpable. When it's pumpable, as with conventional concrete mixtures, it is then accelerated to a high velocity by air at the nozzle and projected onto the surface. Lightweight aggregates can also be used directly in dry-mix, and there you don't need to worry about pumpability because the dry materials are conveyed through the delivery hose. Water is added at the nozzle.

Here's the specific reference on lightweight from ACI 506R-16, "Guide to Shotcrete":

> 2.1.3.2 Lightweight aggregates—Lightweight aggregates should conform to ASTM C330/C330M if used in shotcrete. The aggregate should meet one of the gradations shown in Table 1.1.1. Wet-mix shotcrete with lightweight aggregate is seldom used and is difficult to pump because the aggregate absorbs water, which reduces the consistency of the mixture. Presaturating the lightweight aggregate before batching improves pumpability. Lightweight aggregate mixtures have been shot for wall and floor construction. Shotcrete is frequently employed for fireproofing structural steel members using lightweight aggregates in the mixture.

We suspect that cellular concrete cannot be shot because it uses injection of a pre-formed foam into a cement slurry and is highly fluid. That would preclude any stacking of material to make a vertical surface, and would instead just be pumped in place like a high slump concrete.

Question: *Can we find an appropriate and easy way to evaluate the shrinkage performance of shotcrete?*

Answer: Shotcrete is a placement method for concrete. So, standard concrete tests for shrinkage are applicable. You will find an article from *Shotcrete* magazine, "Shotcrete Testing—Who, Why, When, and How," helpful. Here's a link to the archived PDF of the article (**www.shotcrete.org/media/Archive/2011Sum_Hanskat.pdf**). The specific section on drying shrinkage tests says:

"Drying shrinkage of the shotcrete can be tested using general provisions of ASTM C157. Because the shotcrete is shot into a large panel and not into the relatively small mold specified by ASTM for the shrinkage test beam, it is recommended that a beam approximately 11.25 in. (285 mm) in length be sawed from a test panel. As most shotcrete uses coarse aggregate less than 1 in. (25 mm), a 3 in. (75 mm) thick panel with a 3 in. (75 mm) wide cut should approximate the ASTM requirements. The A/E should specify in the contract documents drying shrinkage limits that are appropriate for the design of the structure."

Question: *Is there a way for me to find out what the standard or appropriate repair for exposed reinforcing bar in a shotcrete swimming pool shell?*

Answer: Because shotcrete is a placement method for concrete, standard concrete repair techniques are applicable. If the repair is being done by shotcreting new concrete on the existing concrete, the repair should include these steps:

1. Chip the poor or weak concrete back to sound concrete.
2. If reinforcing bars are exposed, they should be cleaned of any rust.
3. If more than half of the perimeter of a reinforcing bar is exposed, the concrete should be chipped back to provide at least a 0.75 in. (19 mm) space behind the bar to allow shotcrete to flow around the back of the bar.
4. Before shooting any additional shotcrete, the surface should be cleaned and then wetted to a saturated surface-dry condition (SSD).

5. SSD means the substrate is damp, but there is no flowing water. It should feel damp to the touch, but no water is picked up on your hand when placing it against the surface.
6. Do not use bonding agents, as they can interfere and reduce the bond of the new shotcrete to the old shotcrete surface.
7. When the new shotcrete is in place, the contractor should initiate water curing as soon as possible. In warm, dry, or windy weather, fogging of the fresh surface immediately after finishing would be helpful.
8. Water curing (where the concrete is kept continuously moist) should be supplied for at least 7 days.

Question: *The plaster color installed in my pool was the wrong color. The plaster has been chipped out. My concern is damage to the shotcrete shell in the process. There are deep holes and gauges and there was water seepage in a few areas behind the shotcrete. There is also evidence of honeycombed areas in the shotcrete, as well as some other shotcrete concerns since reading up on the shotcrete process. Please help, as I'm being told that they will just plaster over these concerns. However, the plastering information reads that plaster thickness should not exceed 7/8 in. (22 mm) thickness (but can be a little thicker around plumbing fixtures).*

Answer: Shotcrete is a placement method for concrete. When the pool shotcrete contractor uses quality materials, properly sized and maintained equipment, and experienced crew members, the shotcreted pool shell should be watertight. Proper shotcrete application would also not exhibit voids, honeycomb, or major seepage through the pool shell. Before replastering, the pool shell should be evaluated and all defects (voids, cracks, porous sections, deep holes, and so on) repaired using industry-standard methods and materials. You may consider retaining a professional engineer or experienced pool consultant to evaluate the pool shell and make specific recommendations on the appropriate repair for your specific issues. You can use our Buyers Guide (**www.shotcrete.org/pages/products-services/Buyers-Guide/index.asp**) to locate consultants in your area. You also may want to review our pool-specific Position Statements on our website at **www.shotcrete.org/pages/products-services/shotcrete-resources.htm**. The "Watertight Shotcrete for Swimming Pools" would be particularly informative for you to assist in discussions with your pool contractor.

Question: *I am a structural engineer and we have recently begun work with a shoring contractor. We have been designing soil nails, micropiles, soldier piles, and so on with temporary and permanent shotcrete facings. The contractor has requested that some of our future designs use chain-link mesh in lieu of welded wire mesh, particularly in temporary situations with walls under 10 ft (3 m). I understand that chain link is a cost-effective alternative and, according to the contractor, handles the shotcrete well. Do you have any experience with this type of design/installation process? Can you point me to any literature on the use of chain-link reinforcement in shotcrete walls?*

Answer: Some mines have used chain link mesh in shotcrete in severely deforming ground and claim that it is better in holding the ground than mesh after large deformations, in which the shotcrete sustains major cracking with deformations. Other than for such unusual applications, we do not recommend the use of chain-link reinforcement in shotcrete. It cannot be fixed "tight" and as such is susceptible to vibration and movement during shooting, resulting in shotcrete sloughing and formation of voids in the shotcrete. Also, the mesh interconnections are conducive to the formation of voids during shooting. Additionally, there don't appear to be any consistent material standards on the strength, flexibility, or brittleness of the steel (or other materials) used in the fencing material, so a designer has no way to establish the tensile or flexural strength of the concrete sections. In brief, don't use chain-link mesh if you want to produce quality, durable shotcrete.

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