

# Durability Investigation of Ultra-Rapid Strength-Gain Dry-Mix Shotcrete

By Nicolas Ginouse and William Clements

It has already been shown that rapid strength-gain dry-mix shotcrete using calcium sulfoaluminate (CSA) cement and providing about 2900 psi (20 MPa) after only 2 hours can be effectively produced and placed in mining applications (Reny and Clements 2013). As already discussed in several papers (Reny and Ginouse 2014; Lemay et al. 2014), the use of such rapid strength-gain dry-mix shotcrete can be a very efficient and robust solution to provide ultra-rapid support and reduce the mining/tunneling cycle by reaching the re-entry criteria much faster than with traditional portland cement-based dry-mix shotcrete using set accelerators.

In this context, the use of ultra-rapid strength-gain shotcrete appears to be a very attractive solution for emergency repairs in civil applications, where rapid strength-gain materials such as mortars or concretes are already employed to meet shortened construction schedules due to restricted lane closure times on bridges and roadways and restricted access time in tunnels. However, the use of rapid strength-gain repair materials is still a relatively new practice, and a practice that has not been fully investigated with respect to the durability of these repair materials even if several papers covering this topic have already been published (Barde et al. 2006; Garcia 2014). To develop a durable rapid strength-gain dry-mix shotcrete for emergency repairs, King Packaged Materials Company, Burlington, ON, Canada (King), conducted a testing program focused on certain durability properties of CSA cement-based dry-mix shotcrete. Therefore, the intent of this article is to present the preliminary results of this investigation.

## Materials and Methods

Even though the cement chemistry and the hydration process controlling the rapid strength development of CSA cement-based materials have been the topic of several scientific studies (Juenger et al. 2011; Pelletier et al. 2010; Bernardo et al. 2006), the durability of such alternative cementitious materials is still under investigation. To investigate the durability properties of rapid strength-gain dry-mix shotcrete using CSA cement-based binder further, the testing program was divided into two phases.

The first phase of the testing program consisted of selecting three candidate mixture designs using the equivalent mortar method. As mentioned in Lemay (2013), this method is very useful for conducting preliminary optimization of early-age strengths for dry-mix shotcrete formulas because it allows the user to work on mortar mixtures having the same total specific area as the dry-mix shotcrete mixtures. Because mortars do not contain coarse aggregate, the equivalent mortar method first involves calculating the amount of surface area provided by the coarse aggregate in the candidate shotcrete/concrete mixture design. Then the surface area provided by the coarse aggregate is replaced by the equivalent surface area in the form of fine aggregate in the equivalent mortar. Using the equivalent mortar method allows for close approximation of the early-age strength development between the candidate shotcrete/concrete mixture design and the equivalent mortar as each material maintains the same paste proportions at the aggregate-binder interface.

In this first step, the equivalent mortar method was used to select three candidate formulas presenting the most promising early-age strengths among many different mixture designs in a relatively quick and economical fashion when compared to shooting all of the candidate mixtures. The three candidate shotcrete mixtures selected include a variation of the earlier developed rapid strength-gain dry-mix shotcrete for mining applications (King RS-D2 Mining Shotcrete) but including an air-entraining admixture (CSA-AEA), and two shotcrete mixtures combining CSA cement-based binder with a redispersible polymer (CSA-Polymer A and CSA-Polymer B). During this first step, the three formulas were also adjusted to provide an initial set time of 20 minutes to guarantee a minimum finishing period.

For the second phase of the testing program, a full-scale shotcrete trial was conducted at King's facility (Sudbury, ON, Canada) using all three candidate shotcrete mixtures packaged in 66 lb (30 kg) bags (Fig. 1).

Shooting operations were conducted using an Aliva 246 dry-mix shotcrete machine (Fig. 2),



Fig. 1: Candidate shotcrete mixtures packaged in 66 lb (30 kg) bags



Fig. 3: Nozzleman shooting a test panel for later-age strengths and durability properties



Fig. 2: Aliva 246 dry-mix shotcrete machine



Fig. 4: Steel end-beam mold used for early-age strengths measurements

connected to a 2 in. (50 mm) hose with a hydro-mix nozzle introducing pressurized water to the material stream through a water ring located 10 ft (3 m) from the nozzle. Conventional shooting procedures described in ACI 506R-05, “Guide to Shotcrete,” were followed for each dry-mix shotcrete formula tested (Fig. 3). All dry-mix shotcrete mixtures were shot using the “wettest stable consistency” as recommended by ACI 506R-05 for steel reinforcing bar encapsulation in repair applications.

Early-age compressive strengths were determined using the end-beam test method (using rectangular steel molds presented in Fig. 4), adapted from ASTM C116 (1990), whereas the initial set time was obtained using a hand-held penetrometer in accordance with the test method (ASTM C1117 [1994]).

Later-age compressive strengths and certain durability properties were determined using square test panels illustrated in Fig. 3. More precisely, the compressive strength at 7 and 28 days was obtained in accordance with ASTM C1604 (2012). The durability properties tested for each shotcrete mixture include the determination of the

boiled water absorption and volume of permeable voids, rapid chloride permeability, air-void system analysis (CSA-AEA mixture only), and freezing-and-thawing resistance. The boiled absorption and volume of permeable voids was determined in accordance with ASTM C642 (2013). The rapid chloride permeability was determined in accordance with ASTM C1202 (2012). The freezing-and-thawing resistance was determined in accordance with ASTM C666/C666M (2008). The air-void system analysis was only determined on the CSA-AEA mixture in accordance with ASTM C457/C457M (2012). The two polymer-modified mixtures were air-cured only, whereas the CSA-AEA mixture was kept in wet curing conditions for 28 days prior to testing.

## Results and Discussion

The early-age strengths and the initial set time measured on the three dry-mix shotcrete mixtures conformed to the results targeted during the preliminary tests using the equivalent mortar mixtures. As expected, all shotcrete mixtures started to set after 15 to 20 minutes and then rapidly developed compressive strength, reaching more than 3600 psi (24.8 MPa) after only 2 hours and reaching more than 7300 psi (50.3 MPa) after 28 days. The CSA-Polymer A shotcrete mixture reached a 28-day compressive strength in excess of 9000 psi (62 MPa). Early-

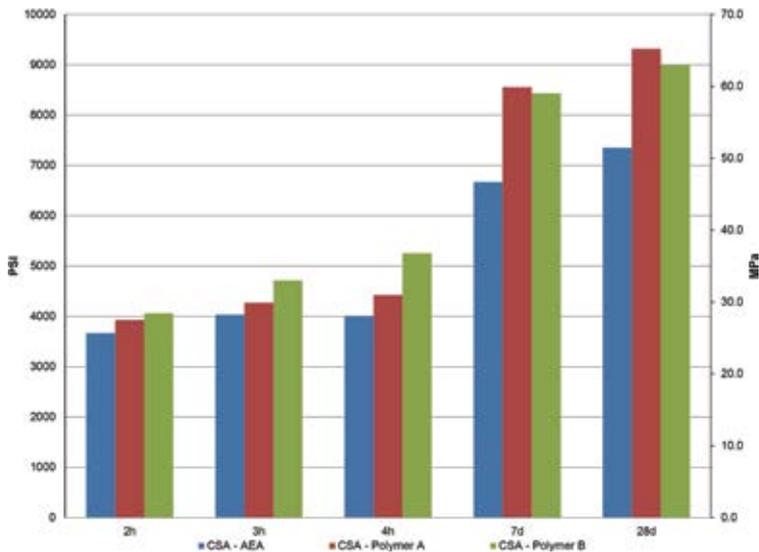


Fig. 5: Early- and later-age compressive strengths obtained with the candidate CSA cement-based dry-mix shotcrete mixtures

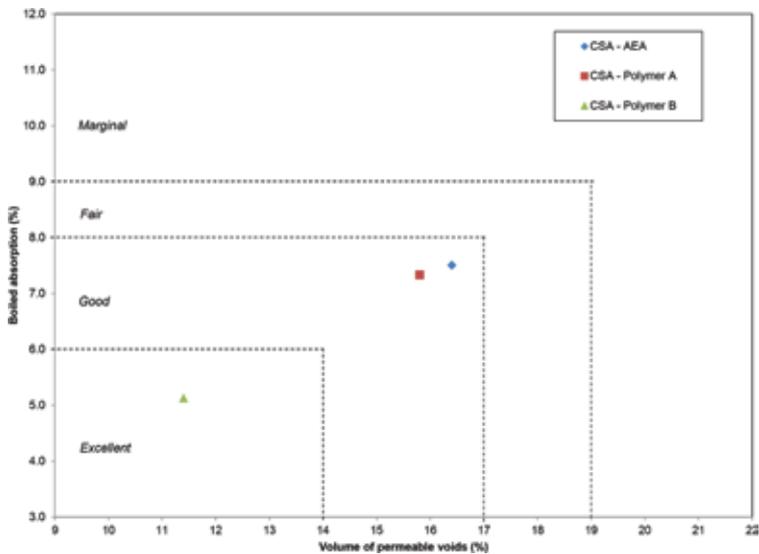


Fig. 6: ASTM C642 results obtained on the three CSA cement-based dry-mix shotcrete mixtures

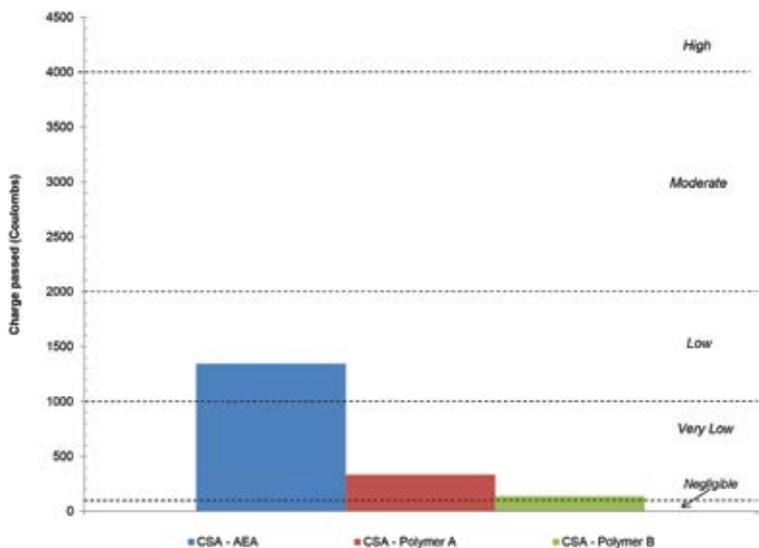


Fig. 7: RCPT (ASTM C1202) results and the associated chloride ion penetrability index obtained with the CSA cement-based dry-mix shotcrete mixtures

and later-age compressive strengths obtained for the three candidate mixtures are illustrated in Fig. 5.

Once the ultra-rapid strength development was confirmed for the three mixtures (refer to Fig. 5), the next step consisted of analyzing certain durability features and indicators.

The boiled water absorption and the volume of permeable voids were the first durability properties analyzed, as these tests are typically performed in the shotcrete industry to provide an indication of the quality of the in-place shotcrete. The absorption results obtained for the three CSA cement-based dry-mix shotcrete mixtures and the associated shotcrete quality indicators proposed in the literature and generally accepted in the industry (Austin and Robins [1995]) are presented in Fig. 6.

As shown in Fig. 6, in addition to very rapid strength development, the placed shotcrete quality was good to excellent (CSA-Polymer B mixture) for the mixtures shot according to the suggested indicators.

The rapid chloride penetration test (RCPT) results presented in Fig. 7 with the chloride ion penetrability index mentioned in ASTM C1202 also confirm a low to almost negligible (CSA-Polymer B mixture) chloride ion penetrability obtained with the rapid strength-gain dry-mix shotcrete mixtures tested.

Even if the absorption (ASTM C642) and the RCPT (ASTM C1202) tests present some limits to characterize shotcrete durability exclusively (Bolduc 2009; Bolduc and Jolin 2010), the excellent results obtained with the three mixtures under consideration demonstrate the high quality of the shotcrete produced with this alternative cementitious material.

In addition to the outstanding results presented previously in terms of strength development, material quality, and chloride ion penetrability, Table 1 confirms that the mixtures tested also possess excellent freezing-and-thawing resistance.

The air void system characteristics measured for the CSA-AEA mixture are presented in Table 2 and explain the excellent freezing-and-thawing resistance obtained with this mixture.

Based on the results obtained during this testing program, it is possible to produce a CSA cement-based dry-mix shotcrete that provides ultra-rapid compressive strength development, a good-to-excellent in-place material quality, a low- to almost-negligible chloride ion penetrability, and an excellent freezing-and-thawing resistance. Based on these very promising test results, the next step will consist of selecting one candidate shotcrete mixture to determine additional mechanical and durability properties required for materials used in repair applications.

**Table 1: Freezing-and-thawing test (ASTM C666) results obtained after 300 cycles**

Mixture	Durability factor (ASTM C666)
CSA-AEA	100%
CSA-Polymer A	100%
CSA-Polymer B	97%

## References

- ACI Committee 506, 2005, "Guide to Shotcrete (ACI 506R-05)," American Concrete Institute, Farmington Hills, MI, 40 pp.
- ASTM C116-90, 1990, "Test Method for Compressive Strength of Concrete Using Portions of Beams Broken in Flexure (Withdrawn 1999)," ASTM International, West Conshohocken, PA.
- ASTM C457/C457M-12, 2012, "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete," ASTM International, West Conshohocken, PA, 15 pp.
- ASTM C642-13, 2013, "Standard Test Method for Density, Absorption and Voids in Hardened Concrete," ASTM International, West Conshohocken, PA, 3 pp.
- ASTM C666/C666M-03(2008), 2008, "Standard Test Method of Resistance of Concrete to Rapid Freezing and Thawing," ASTM International, West Conshohocken, PA, 6 pp.
- ASTM C1117-89(1994), 1994, "Standard Test Method for Time of Setting of Shotcrete Mixtures by Penetration Resistance (Withdrawn 2003)," ASTM International, West Conshohocken, PA, 3 pp.
- ASTM C1202-12, 2012, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration," ASTM International, West Conshohocken, PA, 7 pp.
- ASTM C1604/C1604M-05(2012), 2012, "Standard Test Method for Obtaining and Testing Drilled Cores of Shotcrete," ASTM International, West Conshohocken, PA, 5 pp.
- Austin, S., and Robins, P., 1995, *Sprayed Concrete: Properties, Design and Application*, Whittles Publishing, Dunbeath, UK, 382 pp.
- Barde, A.; Parameswaran, S.; Chariton, T.; Weiss, J.; Cohen, M. D.; and Newbolds, S., 2006, "Evaluation of Rapid Setting Cement-Based for Patching and Repairs," *FHWA/IN/JTRP-2006/11*, Purdue University/Indiana Department of Transportation, West Lafayette, IN, 154 pp.
- Bernardo, G.; Telesca, A.; and Valenti, G.L., 2006, "A Porosimetric Study of Calcium Sulfoaluminate Cement Pastes Cured at Early Ages," *Cement and Concrete Research*, V. 36, No. 6, pp. 1042-1047.
- Bolduc, L.-S., 2009, "Études des Propriétés de Transport du Béton Projeté," master's thesis, Université Laval, Québec City, QC, Canada, 168 pp.
- Bolduc, L.-S., and Jolin, M., 2010, "Shotcrete Boiled Water Absorption," *Shotcrete*, V. 12, No. 1, Winter, pp. 12-17.
- Garcia, A.M., 2014, "Durability Testing of Rapid, Cement-Based Repair Materials for Transportation Structures," master's thesis, the University of Texas at Austin, Austin, TX, 167 pp.
- Heere, R., and Morgan, D., 2002, "Determination of Early-Age Compressive Strength of Shotcrete," *Shotcrete*, V. 4, No. 2, Spring, pp. 28-31.
- Juenger, M.; Winnefeld, F.; Provis, F.; and Ideker, J., 2011, "Advances in Alternative Cementitious Binders," *Cement and Concrete Research*, V. 41, No. 12, pp. 1232-1243.
- Lemay, J.-D., 2013, "Développement de Béton Projeté à Ultra Haute Résistance Initiale," master's thesis, Université Laval, Québec City, QC, Canada, 127 pp.
- Lemay, J.-D.; Jolin, M.; and Gagné, R., 2014, "Ultra Rapid Strength Development in Dry-Mix Shotcrete for Ultra Rapid

**Table 2: Air void system characteristics measured on CSA-AEA shotcrete mixture**

Mixture	Air void system—ASTM C457, Procedure B	
	Hardened air content	Spacing factor
CSA-AEA	5.8%	214 µm

Support in Challenging Mining Conditions," *Deep Mining 2014: 7th International Conference on Deep and High Stress Mining*, M. Hudyma and Y. Potvin, eds., Australian Centre for Geomechanics, Nedlands, Australia, pp. 271-279.

Pelletier, L.; Winnefeld, F.; and Lothenbach, B., 2010, "The Ternary System Portland Cement-Calcium Sulphoaluminate Clinker-Anhydrite: Hydration Mechanism and Mortar Properties," *Cement and Concrete Composites*, V. 32, No. 7, pp. 497-507.

Reny, S., and Clements, W., 2013, "Reaching 20 MPa (2900 psi) in 2 Hours is Possible," *Shotcrete*, V. 15, No. 4, Fall, pp. 26-30.

Reny, S., and Ginouse, N., 2014, "Development of a Rapid Strength Gain Dry-Mix Shotcrete using Calcium Sulfoaluminate Cement for Mining and Tunnelling Applications," *Deep Mining 2014: 7th International Conference on Deep and High Stress Mining*, M. Hudyma and Y. Potvin, eds., Australian Centre for Geomechanics, Nedlands, Australia, pp. 281-290.



**Nicolas Ginouse** is Research and Development Leader for ASA Corporate Member King Packaged Materials Company and Associate Professor at Laval University, Québec, QC, Canada. His research interests include all the aspects involved in shotcrete technology whereas his expertise contributes to the development of new cementitious materials for mining, tunneling, and repair applications. Ginouse received his degree in mechanical and industrial engineering from Art et Métiers Paritech, Paris, France, in 2010 and his PhD in civil engineering from Laval University in 2014. He is a member of ACI Committees 506, Shotcreting, and ITG-10, Alternative Cementitious Materials.



**William Clements** is a Technical Services Engineer for King Packaged Materials Company. His areas of focus include cementitious material mixture design development, structural rehabilitation, and shotcrete technology. He received his bachelor's and master's degrees in civil engineering from the University of Windsor, Windsor, ON, Canada. He is currently a practicing civil engineer in Ontario, Canada, and a member of the American Concrete Institute (ACI) and Building and Concrete Restoration Association of Ontario (B&CRAO).