Rapidly Deployable Shotcrete System

for the Structural Stabilization of Shock-Damaged Structures

By Anne Oberlink and Robert Jewell

The Department of Homeland Security was formed as a consequence of the terrorist attacks on September 11, 2001. The protection of the nation's critical infrastructure was made part of their mandate, and included in their mandate is the rapid repair and stabilization of shock-damaged structures. In response, the National Institute for Hometown Security, a subcontractor of the Department of Homeland Security, awarded a contract to the University of Kentucky Center for Applied Energy Research (UK CAER) and Minova USA Inc. This contract called for development of a material that gains structural strengths very rapidly, as well as the development of a corresponding deployment system to stabilize and repair shock-damaged structures to avoid catastrophic failure. A fast-setting material is imperative to an emergency situation because the faster first responders can stabilize a collapsed structure, the safer they make it for themselves, and for the people that are potentially inside the structure that may need help.

The system and material developed by the UK CAER and Minova USA Inc. consists of a delivery vehicle capable of shotcreting prepackaged, rapid-setting, fiber-reinforced dry-mix shotcrete material. Tekcrete Fast® is a material that was developed for this process, and is a specially designed, rapid-setting, and high-performance dry-mix shotcrete. This system will stabilize structures such as airport runways, tunnels, bridges, and dams that have been shocked and damaged by explosives, or seismic activity, before they fail. Tekcrete Fast M®, a low-dust version for underground mining, has also been developed by Minova USA Inc. Both Tekcrete Fast and Tekcrete Fast M are available at Minova USA Inc.

Introduction

The rapid stabilization of shock-damaged structures falls outside the purview of normal construction practices due to the critical time issue and the nature of the damaged structure. The stabilization of damaged structures requires materials and equipment that can be rapidly deployed to place materials that have very rapid-strength development. These materials need to be placeable at a distance to provide some degree of safety to the responders. In addition, the materials must be able to adhere to structural surfaces that have not been properly prepared and conditioned, and may also be highly fractured, dusty, wet, and very possibly hot or extremely cold.

The technology for the rapid delivery of large volumes of cementitious materials to vertical or even overhead surfaces currently exists. Pneumatic delivery (shotcreting) has been used in construction for over 100 years. Shotcreting has played a major role in structures such as the Washington DC Metro subway system and the England to France undersea rail connector (the Chunnel).

Numerous rapid-setting cements are commercially available. They are used for rapid repair of surfaces such as bridge decks, pavements, and commercial floors, as well as structural repairs of vertical and overhead surfaces. Few of these products are specifically marketed for use in shotcrete applications.

The majority of rapid-setting cements are based on, or at least contain, portland cement as a principal component. Other components are added that help provide early strength, such as high-alumina cement (HAC), organic polymers, chemical accelerators (which can also be added during concrete batching), and calcium sulfate hemihydrate (for example, gypsum plaster). Mortars prepared with some of these cements can achieve compressive strengths of 6.8 to 13.8 MPa (1000 to 2000 psi) within 1 hour. However, portland cement mortar and concrete typically require many weeks of proper curing to reach significant levels of their ultimate strengths, even when used with set accel-

Fig. 1: (a) Compressive strength of mortar cubes; (b) cylinder coring; and (c) flexural strength testing of shotcrete beam with fibers

erators. Also, high early strengths require the use of large proportions of portland cement in the concrete mixture, which can lead to high heat evolution, excessive shrinkage of the material, and cracking. The cost also increases substantially with increasing cement content.

Alternatives to portland cement are also capable of rapid strength development. These include calcium sulfate hemihydrate, and calcium sulfoaluminate (CSA) cements. Unlike portland cement, these rapid-setting cements can gain 75 to 80% of their strength within 1 day, which means less cement can be used in the mixture to achieve comparable early strength. CSA cement and calcium sulfate hemihydrates can also be fabricated, for the most part, from coal combustion by-products (CCBs). These CCBs include fluidized bed combustion spent bed materials and forced air oxidation flue gas desulfurization by-products—that is, synthetic gypsum, which potentially represents both a cost advantage, as well as an environmental advantage.

Development and Testing of CSA-Based Shotcrete

A primary consideration of this project was the rate of strength development (compressive and tensile), bonding strength to the damaged surfaces, and short-term dimensional stability. Other considerations include heat generation, pumpability, ease of use, stiffness of the set material, and cost.

CSA cements are of interest mainly because they gain strength very rapidly. They also require lower energy to produce, with significantly lower CO_2 emissions than portland cement. CSA-based shotcrete materials can be formulated so that they have lower cement content than portland-based shotcrete, a higher water-cement ratio (*w/c*), low viscosity, and yet still achieve very high early strength. This is due to the nature of its principal cementitious hydration product: ettringite. These properties are difficult to achieve with portland-cement-based rapid-setting materials.

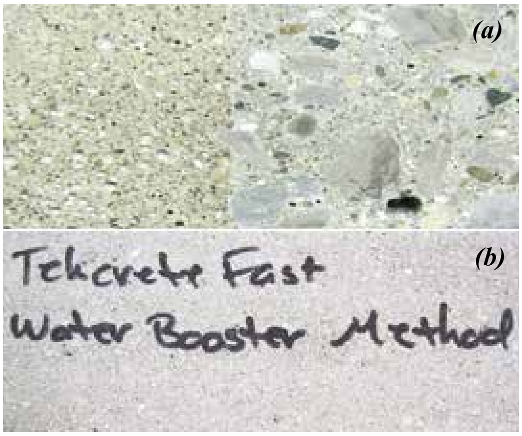

Fig. 2: (a) Tekcrete Fast bonding to OPC; and (b) showing no visible laminations after curing

In addition, the high *w/c* of CSA cement shotcrete, coupled with the low heat of hydration of plaster cement, offers a capacity to manipulate the heat of reaction of these materials within a wide band of strength and set parameters. Heat generation is critical in the rapid placement of masses of highly reactive cementitious materials. These cements also offer the potential of lower overall costs.

Once the CSA-based materials to be used in the shotcrete were developed and tested, they were used to fabricate shotcrete mortars and concretes. After an initial round of screening, specimens prepared from selected mixtures were tested for strength and dimensional stability. When determining what tests to use to evaluate the chosen mixtures, it was important to keep in mind that the sprayed-concrete material must provide structural strength within an hour, and bond sufficiently to any substrate or surface under any conditions long enough to provide the necessary assistance to first responders. Therefore, in addition to the standard cement/concrete testing—that is, compression and stability testing of ASTM standard cubes, cylinders, bars, and cores; flexural strength beam testing; tensile testing; rapid freezing and thawing testing; resistance to carbonation testing, and so on, as seen in Fig. 1 and 2—the variations of heat production based on cement thickness, calorimetry measurements for reaction time of CSA cement phases, slant-shear test, pulloff tests, and time-of-set were a few of the additional tests also used during the project.

After years of research, Tekcrete Fast was developed. Worldwide patents have been filed jointly by the University of Kentucky and Minova USA Inc. Tekcrete Fast is a CSA-based, fiber-reinforced material that achieves structural strengths in minutes—that is, a beam in a bag. It can be used in conventional, dry-process shotcrete equipment as a one-bag system. As mentioned previously, it also has the ability to adhere to any structural surface, whether it is fractured; dusty, as the dry-mix shotcrete nozzleman will spray water before the Tekcrete Fast and will thereby quickly remove any dust accumulation; or wet, regardless of temperature. These features are ideal for use by first-responders, as there is usually little time to prep the surface to be sprayed. It can also be used to repair bridges and roadways, overpasses and runways, and more. Tables 1 and 2 show the average compressive strength and flexural strength for Tekcrete Fast.

Equipment and Delivery Vehicle Development

We have found that there are many issues to be addressed in determining which shotcrete delivery

Table 1: Average compressive strength for Tekcrete Fast in MPa (psi)

Specimen type	Compressive strength, MPa (psi)						
Cores	15 minutes	30 minutes	1 hour	3 hour	1 day	7 days	28 days
	17.2 (2500)	24.1 (3500)	31.0 (4500)	41.4 (6000)	55.2 (8000)	62.1 (9000)	75.8 (11,000)

Table 2: Average flexural strength for Tekcrete Fast in MPa (psi)

Specimen type	Flexural strength, MPa (psi)		
Cores	3 hours	1 day	7 days
	17.2 (2500)	24.1 (3500)	31.0 (4500)

Table 3: System Comparisons

Component	Dry Mix	Wet Mix
Cost	Low to moderate; for example, $10,000	High; for example, $50,000 to >$100,000
Production rate (via Nozzle Person)	Moderate; 5 yd^3/h (3.8 m^3/h)	High; up to 16 yd^3/h (12.2 m^3/h)
Complexity	Air compressor, water	Pump, compressor, water, plus
Material control	Good	Good
Single bag mixture	Yes	Yes
Required clean-out	Simple, blast nozzle with compressed air	Must clean mixer, pump, hose
Fiber capable	Yes	Yes

system to use with the material. Wet-mix systems deliver the material as a paste, and compressed air is used to accelerate the concrete. Strong advantages include the ability to precondition the materials with a better control of heat and high delivery rates. However, highly reactive slurries can be difficult to manage and, based on our own experience, flash set can cause catastrophic equipment failure.

Shotcrete can be reasonably divided into two types or systems—"dry mix" and "wet mix"—and each system has advantages and disadvantages (Table 3).

Wet-mix systems are, as implied, produced with cement and water. The mixture is prepared in a mechanical mixer and then the wet concrete is pumped through a hose—the end of which is equipped with a high-pressure pneumatic nozzle. The water and cement mixture passes through the hose and into a mixing nozzle chamber, where the nozzle accelerates the mixture to give the high velocity needed for impact consolidation. In dry-mix systems, the dry material is exposed to a water stream at the nozzle where mixing occurs, while also providing the high velocity needed for impact consolidation. Several different dry-mix nozzles were investigated (refer to Fig. 4) and tested throughout the project, and all commercially available nozzles performed very well.

A dry-mix delivery system was determined to be best for the delivery of Tekcrete Fast due to the simplicity, the use of single-bag product formulations, and the ability to use very rapid-setting materials. A variety of dry-mix systems were tested throughout the project, including the Reed SOVA and the Meyco Piccola, and they all worked very well for this process.

Additionally, the delivery system was designed to be a rapidly deployable, low-cost, integrated structure that can be engineered into a facility, or a vehicle deployed by first responders to stabilize damaged structures. Ideally, the system would be maintained in a state of readiness in areas that are considered to be high-risk targets, which could include major subway systems, roadways, airports, or other critical infrastructure. The delivery vehicle is comprised of five essential components: water supply, air supply, cementitious material, a dry-mix shotcrete system, and the inline water heater for use in cold conditions. It has been determined that Tekcrete Fast will cure much quicker when the water is warm.


Fig. 4: Test nozzles

The mobile delivery system that has been used previously was deployed on a trailer. The hitch end of the trailer houses the static components—that is, the air compressor, water tank, and generator (if needed). The working area of the trailer houses the dynamic components that will require operator access—that is, the dry-mix gun, water booster pump, hose reels, and material supply (refer to Fig. 5 and 6). This deployable delivery vehicle includes everything needed for first responders to stabilize shock-damaged structures, all on the back of a flatbed trailer. In addition, this delivery system will also work in nonemergency situations, allowing for easy deployment of all equipment and material for repairs of any type.

Disaster City Demonstration—College City, TX

In November 2014, a civil engineering demonstration of Tekcrete Fast and its dry-mix shotcrete delivery deployment system took place in Disaster City, TX. Disaster City is a 52-acre

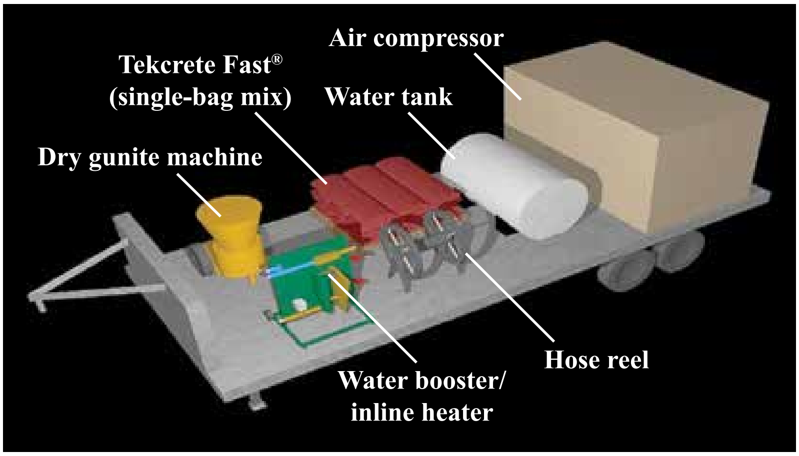

Fig. 5: Schematic of vehicle layout

Fig. 6: Actual delivery vehicle

training facility located in College Station, TX. It includes an extensive array of disaster scenario simulations for training emergency response professionals. Disaster City includes full-scale, collapsible structures designed to simulate various levels of disaster and wreckage, ranging from shock-damaged structures to chemical plant fires and overturned passenger trains, which can be customized for the specific training of any group.[1] The UK CAER and Minova USA Inc., with the help of Carl Baur, CCS Group LLC of Millstadt, IL; Jeff Saunders, the Director of the Texas Task Force 1 of the Texas A&M Engineering Extension Service (TEEX); and Dr. Peter Keating from the Texas A&M Civil Engineering High-Bay Structural & Materials Testing Laboratory, demonstrated the repairing and testing of damaged or wrecked reinforced concrete vertical beams, simulating catastrophic shocks from an explosion or earthquake to a building or parking-garage-type structure. The demonstration was to show that Tekcrete Fast and its dry-mix shotcrete delivery deployment system can help first responders to stabilize such a structure, so they can get in and out quickly and safely, and to bring any victims of said catastrophic wreckage the help they need.

The reinforced concrete vertical beams that were intentionally formed with a missing section and a purposefully damaged beam were placed into the ground and were repaired with Tekcrete Fast. All concrete beams used in the demonstration had been placed several months in advance

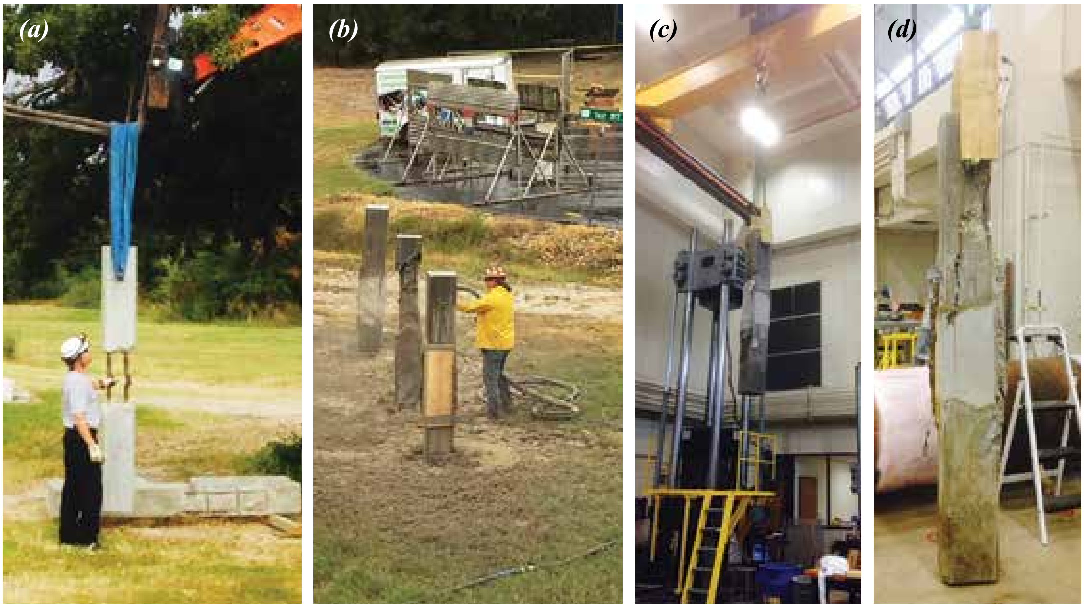

Fig. 7: Disaster City demonstration: (a) placement of damaged vertical beams into ground; (b) shotcrete repair of damaged beams; (c) compression testing of repaired beams; and (d) repaired beam after compression testing, showing that beam failed outside of repaired section

of the demonstration to make sure that they were fully cured and at full strength. The beams had a column cross section that was 12 x 12 in. (300 x 300 mm), with the length of the damaged area on two of the four columns being approximately 18 in. (450 mm) long. The third column was damaged a day or two before the demonstration by bending it until it cracked. The fourth column was left whole and used as a control beam during testing. Once spraying was finished, the repaired beams were immediately removed from the ground and taken directly to the Texas A&M Civil Engineering lab for testing. The entire process for this demonstration, including shotcreting the beams, getting the beams out of the ground, and transferring them over to the high bay lab for testing, took less than 5 hours. With less than 5 hours of curing time for the Tekcrete Fast section, the beams tested were shown to fail outside of the repaired section—that is, the original concrete failed while the section repaired with Tekcrete Fast did not. This is shown in the far right picture in Fig. 7, and Fig. 8 shows the bonding of Tekcrete Fast with the concrete beams.

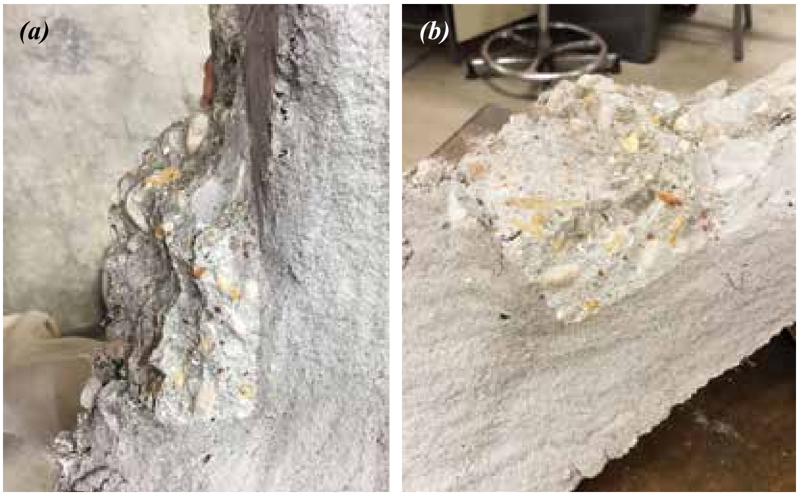

Fig. 8: Bonding abilities of Tekcrete Fast to portland cement

Conclusions

In conclusion, Tekcrete Fast and its dry-mix shotcrete delivery system has repeatedly demonstrated that it has an overwhelmingly superior rate of strength development to conventional portland-cement-based shotcrete. It has excellent bonding capabilities, and its potential for disaster recovery has been demonstrated. Tekcrete Fast is an easy, one-bag sand/cement mixture, or "beam in a bag," and has been proven to be nozzleman-friendly, with a very wide water range. The set times are very predictable, with no flash set, but with the ability to cure very quickly, within 15 minutes of shotcreting. Tekcrete Fast can be cut back and trimmed in small areas, if needed, and according to Carl Baur, "bonds like nothing I have seen in my 20 years of gunite."

Acknowledgments

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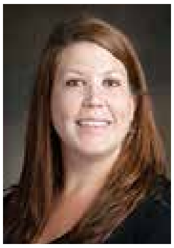

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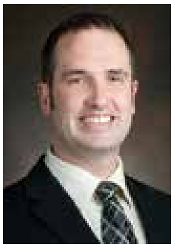

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