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RAPIDLY DEPLOYABLE SHOTCRETE SYSTEM FOR THE STRUCTURAL STABILIZATION OF SHOCK DAMAGED STRUCTURES

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ABSTRACT. The University of Kentucky Center for Applied Energy Research, along with Minova USA Inc., and the University of Dundee, developed a rapid strength, high bonding shotcrete system for infrastructure repair and stabilization, at the request of a mandate from the U.S. Department of Homeland Security. This mandate 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. 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 like airport runways, tunnels, bridges, and dams that have been shocked and damaged by explosives, or seismic activity, etc. before they fail, by reaching compressive strengths of 41.4 MPa in 3 hours, and 75.8 MPa in 28 days. Additionally, in November 2014, a civil engineering demonstration of Tekcrete Fast® took place in Disaster City, Texas to show that Tekcrete Fast® can help first responders to stabilize building structures.

Keywords: CSA cement, Shotcrete, Infrastructure repair.

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INTRODUCTION

Background

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 [1]. Shotcreting has played a major role in structures like the Washington D.C. 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 principle 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 (e.g. gypsum plaster) [2]. Mortars prepared with some of these cements can achieve compressive strengths of 6.8 – 13.8 MPa (1000-2000 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 accelerators. Also, high early strengths require the use of large proportions of Portland cement in the concrete mix, 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 75-80% of their strength within 1 day, which means less cement can be used in the mix to achieve comparable early strength [2]. CSA cement and calcium sulfate hemihydrates can also be fabricated, for the most part, from coal combustion by-products (CCB’s). These CCB’s include fluidized bed combustion spent bed materials and forced air oxidation flue gas desulfurization by-products, i.e. synthetic gypsum, which potentially represents both a cost advantage, as well as an environmental advantage [3].

Development of Shotcrete

The primary considerations of this project were the rate of strength development (compressive and tensile), short-term dimensional stability, and bonding strength to the damaged surfaces. 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 [2]. CSA-based shotcrete materials can be formulated so that they have lower cement content than Portland-based shotcrete, a higher water to cement ratio, lower 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.

In addition, the large water/cement ratio 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. Unlike Portland cement, which gains its strength primarily from the hydration of the calcium silicates “alite” (Ca_3SiO_5) and “belite” (Ca_2SiO_4), calcium sulfoaluminate (CSA) cements contain Klein’s compound which hydrates in the presence of calcium sulfate (e.g. gypsum) to form a cementitious phase called ettringite [4]:

$$\underset{\text{Klein's compound}}{Ca_4Al_6O_{12}SO_4} + \underset{\text{Gypsum}}{2CaSO_4\cdot 2H_2O} + 34H_2O \rightarrow \underset{\text{Ettringite}}{Ca_6Al_2(SO_4)_3(OH)_{12}\cdot 26H_2O} + \underset{\text{Aluminum hydroxide}}{4Al(OH)_3}$$

A compound similar to ettringite called “monosulfate” can also form under sulfate-deficient conditions. Belite is often present in CSA cement, but its hydration is slow and only contributes to long-term strength [5, 6]. Because of the rapid rate of formation of ettringite, CSA cements gain strength very quickly. If enough lime ($Ca(OH)_2$) and calcium sulfate is present in the system, additional ettringite can also be formed through reaction with the aluminium hydroxide, a product of the Klein’s compound. However, if the system contains excess lime, the cement can induce destructive expansion [4].

CSA cement actually represents a series with a broad range of compositions, from nearly pure Klein’s compound, to Klein’s compound with belite, calcium ferroaluminate or ($Ca_4(Al_2Fe_2)O_{10}$), free lime (CaO), calcium sulfate ($CaSO_4$) and other minor phases (e.g. $Ca_{12}Al_{14}O_{33}$). Three types of CSA cements were studied and tested during this project to determine which of the three types was the best fit.

Testing of CSA-Based Shotcrete

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 mixes were tested for strength and dimensional stability. When determining what tests to use to evaluate the chosen mixes, 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.

ASTM C1140 “Standard Practice for Preparing and Testing Specimens from Shotcrete Test Panels” is typically used for the field testing of the shotcrete compressive and flexural strength [7]. This standard requires the shotcrete be pneumatically projected onto a wooden form and then samples cored or cut from the sample to be tested. However, because the basis of this research was the study of the interaction of shotcrete and ordinary Portland cement, the aforementioned standard was not used, but instead standards that determine bond strength between different concretes. Therefore, in addition to the standard cement/concrete testing, i.e. 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, the variations of heat production based on cement thickness, calorimetry measurements for reaction time of CSA cement phases, slant-shear test, pull-off tests, and time-of-set were a few of the additional tests also used during the project [8, 9, 10, 11, 12].

After years of research, Tekcrete Fast® was developed. Worldwide patents have been filed jointly by the University of Kentucky and Minova USA Inc., and received. Tekcrete Fast® 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 to be used to repair bridges and roadways, overpasses and runways, etc. Tables 1 and 2 show the average compressive strength and flexural strength for Tekcrete Fast®.

Table 1 Average compressive strength for Tekcrete Fast® in MPa and psi

COMPRESSIVE STRENGTH, MPa (psi)						
15 min	30 min	1 h	3 h	1 d	7 d	28 d
17.2 (2,500)	24.1 (3,500)	31.0 (4,500)	41.4 (6,000)	55.2 (8,000)	62.1 (9,000)	75.8 (11,000)

Table 2 Average Flexural Strength for Tekcrete Fast® in MPa and psi

FLEXURAL STRENGTH, MPa (psi)		
3 h	1 d	7 d
17.2 (2,500)	24.1 (3,500)	31.0 (4,500)

Equipment and Delivery Vehicle Development

We have found that there are many issues to be addressed in determining which shotcrete delivery 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, as Table 3 shows.

Table 3 System Comparisons

COMPONENT	DRY MIX	WET MIX
Cost	Low to Moderate, i.e. $10,000's	High, i.e.$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 Mix	Yes	Yes
Required Clean-Out	Simple, Blast Nozzle with Compressed Air	Must Clean Mixer, Pump, Hose
Fibre Capable	Yes	Yes

Wet mix systems are, as implied, produced with cement and water. The mix 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, and is then given the high velocity it needs for impact consolidation. Several different dry-mix nozzles were investigated 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 utilize 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.

The mobile delivery system that has been used previously was deployed on a trailer. The hitch end of the trailer houses the static components, i.e. the air compressor, water tank, and generator (if needed). The working area of the trailer houses the dynamic components that will require operator access, i.e. the dry-mix gun, water booster pump, hose reels, and material supply.

This deployable delivery vehicle includes everything needed for first responders to stabilize shock-damaged structures, all on the back of a flat-bed trailer. In addition, this delivery system will also work in non-emergency situations, allowing for easy deployment of all equipment and material for repairs of any type.

TEKCRETE FAST® - POST COMMERCIALIZATION

Additional testing

Residual strength of sprayed concrete

The deformation behaviour of cementitious composites such as concrete, fibre reinforced concrete (FRC), and fibre-reinforced ultra-high performance concrete (FR UHPC) is typically distinguished according to their tensile stress-strain characteristics, in particular, the post-cracking response.

Friable materials tend to lose their tensile load-carrying capacity very quickly after the development of the first crack in the matrix. Adding fibres to conventional fibre reinforced concrete can increase the toughness of the material. It has been found, though, that the tensile strength of the material, is not enhanced [13].

Method

Specimens were sprayed in accordance with EN 14488-1, and were tested following BS EN 14488-5 for the determination of energy absorption capacity of fibre reinforced slab specimens under large deflections [14, 15]. The dimensions of the square test panels were 600 mm × 600 mm with a thickness of 100 mm. Specimens were moist cured until testing at 28 days. The panel was loaded with a displacement control at a rate of 1 mm/min at the centre of the slab. The test, Figure 1, was concluded after the central deflection exceeded 30 mm.

The load-displacement results may then be expressed as the energy absorption until a deflection of 25 mm is obtained, Figure 2. The first crack occurred at a maximum load of approximately 80 kN at 6 mm of displacement, followed by a second crack which occurred perpendicular to the first with a peak load of approximately 90 kN at 9 mm of displacement. Due to the shorter length of the 12 mm polyvinyl-alcohol fibre, most of the potential energy absorption was complete after approximately 10 mm of displacement; which provided a toughness of 311.90 J for the shotcrete panel.

Figure 1 Square panel test apparatus

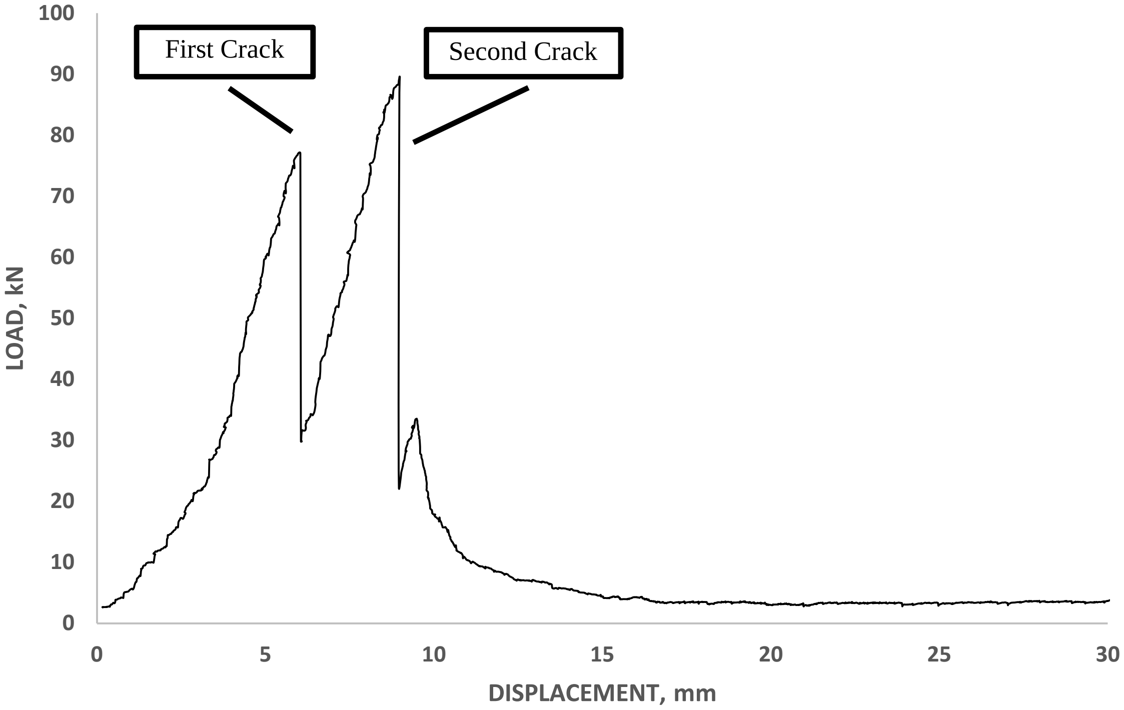

Figure 2 Load-displacement curve for residual strength of sprayed concrete

Disaster City Demonstration – College City, Texas

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 training facility located in College Station, Texas. 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, etc., which can be customized for the specific training of any group [16].

The UK CAER and Orica USA Inc., with the help of Mr. Carl Baur, ASA Certified Nozzleman and Examiner with the CCS Group of Millstadt, Illinois; 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 poured several months in advance 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” × 12” (300 mm × 300 mm), with the length of the damaged area on two of the four columns being approximately 18” (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 compressive strength 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 five hours. With less than five hours of curing time for the Tekcrete Fast® section, the beams tested were shown to fail outside of the repaired section, i.e. the original concrete failed while the section repaired with Tekcrete Fast® did not.

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 mix, 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.

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