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Tekcrete Fast®: Fiber-reinforced, rapid-setting sprayed concrete for rib and surface control

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ABSTRACT

Fiber-reinforced spayed concrete has been used for several years in civil and tunneling operations. Research conducted to reduce cure times and increase compressive and flexural strengths resulted in the development of Tekcrete Fast®, a cementitious product capable of obtaining 41 MPa compressive strength and 8 MPa flexural strength in only 3 h and reaching 7 d strengths of 62 and 11.7 MPa, respectively. A single bag product that uses conventional shotcrete and gunite application systems makes it a natural crossover product for mining applications. The discovery of incredible adhesion properties and high resistance to chloride permeability helps ensure long-term stability and increases the ease of application. Project results from Disaster City® in Texas and the application for rehabilitating a coal mine belt entry are presented. The case study illustrates the effectiveness of the product in stabilizing a coal mine beltway and adjacent cross-cuts that were subjected to progressive sloughage due to humidity and cyclical loading.

1. Introduction

Original research produced a shotcrete formulation that extends beyond stabilization and can be used to restore the structural integrity of damaged infrastructure. The primary challenge was to develop a shotcrete or gunite that had structural strength within a few minutes to prevent parasitic loading, allowing ingress into damaged structures minutes after applying the mix formulation. This also applies to mining conditions where rapid support of progressive failures can minimize failure. An additional benefit was discovering that the product had extremely high adhesion properties in addition to high flexural strengths. The approach to product design was the development of "single bag" dry mixes that are entirely self-contained, can be rapidly transported anywhere in the field or underground, and can be deployed using simple equipment. Dry mix eliminates issues relevant to high shear water mixing because water is added in the form of a mist at the point of delivery; thus a low water-to-cement ratio can be achieved. However, since there is no onsite powder mixing, the product must have a high degree of inherent homogeneity. Minova offers a commercial version of this material, Tekcrete Fast®, a product that has been successfully deployed in the mining industry and is currently being used in civil, construction, and tunneling operations. The material can rapidly stabilize lose ground in metal, nonmetal, and coal mines. This paper described the technology development, product testing results, and applications and describes a case study to stabilize a coal mine beltway.

2. Background

Tekcrete Fast was originally developed to complete rapid stabilization of shock damaged structures, possibly due to earthquakes, bombing, etc., which falls outside the purview of normal construction and mining practices because of 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 specially prepared and conditioned and could be highly fractured, dusty, wet, 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

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system and been used in underground mining applications routinely to serve as part of the primary and secondary support system when used in conjunction with traditional roof bolts. Numerous rapid setting cements are commercially available. They are used for the 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 the principle component. Other components are added that to 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]. Cementitious mortars prepared with some of these cements can achieve compressive strengths of 6.8–13.8 MPa within 1 h. 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. In addition, 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 d, which means less cement can be used in the mix to achieve comparable early strength. Additionally, 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 (i.e., synthetic gypsum), which potentially represents both a cost advantage, as well as an environmental advantage [3].

3. Development of shotcrete

A primary consideration of this project was the rate of strength development (compressive and tensile), short-term dimensional stability, and bonding strength to the damaged surfaces. Other considerations include heat generation, ease of use, stiffness of the set material, and cost. CSA cements were 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-to-cement ratio, lower viscosity, butstill achieve very high early strength. This is due to the nature of the principal cementitious hydration product—ettringite. These properties are difficult to achieve with Portland cement-based rapid-setting materials. In addition, the large water-to-cement ratio of CSA cement shotcrete, coupled with the low heat 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].

$$Ca_4Al_6O_{12}SO_4 + 2CaSO_4 \cdot 2H_2O + 34H_2O \rightarrow Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O + 4Al(OH)_3$$

$$\text{(Klein's compound)} + \text{(Gypsum)} \rightarrow \text{(Ettringite)} + \text{Aluminum hydroxide}$$

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 the reaction with the aluminum 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 would meet project requirements.

4. 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 one 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 that 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. Instead, standards that determine bond strength between different concretes were used, such as the following: 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; variations of heat production based on cement thickness; calorimetry measurements for reaction time of CSA cement phases; slant-shear testing; pull-off testing; and time-of-set.

These methods are all included in the ASTM International Specifications: C192, C109, C78, C293, and C666 [8–12].

After years of research, Tekcrete Fast was developed. Worldwide patents have been filed jointly by the University of Kentucky and Minova USA, Inc, and awarded [13]. Tekcrete Fast can be used in conventional, dry-process shotcrete equipment as a one-bag system. It also has the ability to adhere to any structural surface, whether it is fractured, wet, hot, or cold. Dust is no problem either because the dry-mix shotcrete nozzleman will spray water before spraying the Tekcrete Fast, quickly removing any dust accumulation. These features are ideal for use by first-responders because there is usually little time to prep the surface to be sprayed. It

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