# PROCESS FOR CONVERTING WASTE GLASS FIBER INTO VALUE-ADDED PRODUCTS

**Project Title:** Process for Converting Waste Glass Fiber into Value Added Products

**DOE Award Number:** DE-FG36-03GO13015

**Date of Report:** December 31, 2005

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# Executive Summary

**Nature of the Event:** Technology demonstration. The project successfully met all of its technical objectives. Albacem has signed an exclusive licensing agreement with Vitro Minerals Inc., a specialty minerals company, to commercialize the Albacem technology (website: www.vitrominerals.com).

**Location:** The basic research for the project was conducted in Peoria, Illinois, and Atlanta, Georgia, with third-party laboratory verification carried out in Ontario, Canada. Pilot-scale trials (multi-ton) were conducted at a facility in South Carolina. Full-scale manufacturing facilities have been designed and are scheduled for construction by Vitro Minerals during 2006 at a location in the Georgia, North Carolina, and South Carolina tri-state area.

**The Technology:** This technology consists of a process to eliminate solid wastes generated at glass fiber manufacturing facilities by converting them to value-added materials (VCAS Pozzolans) suitable for use in cement and concrete applications. This technology will help divert up to 250,000 tpy of discarded glass fiber manufacturing wastes into beneficial use applications in the concrete construction industry. This technology can also be used for processing glass fiber waste materials reclaimed from monofills at manufacturing facilities. The addition of take-back materials and reclamation from landfills can help supply over 500,000 tpy of glass fiber waste for processing into value added products.

In the Albacem process, waste glass fiber is ground to a fine powder that effectively functions as a reactive pozzolanic admixture for use in portland cement-based building materials and products, such as concrete, mortars, terrazzo, tile, and grouts. Because the waste fiber from the glass manufacturing industry is vitreous, clean, and low in iron and alkalis, the resulting pozzolan is white in color and highly consistent in chemical composition. This white pozzolan, termed VCAS Pozzolan (for <u>V</u>itreous <u>C</u>alcium-<u>A</u>lumino-<u>S</u>ilicate). is especially suited for white concrete applications where it imparts desirable benefits such as increased long-term strength and improved long-term durability of concrete products. Two U.S. patents entitled have been issued to Albacem covering the technology. Third-party validation testing has confirmed that the pozzolanic product is an excellent, high performance material that conforms to a ASTM standards and improves the strength and durability of concrete.

Currently, there are no known significant competing technologies to process glass fiber manufacturing by-products and convert them into value-added products. Most glass fiber-forming and fabrication wastes continue to be disposed in landfills at significant costs and with associated negative environmental impact. It is estimated that in a typical glass fiber manufacturing facility, 10-20% by weight of the processed glass material is sent for disposal to a landfill. Today, supplementary cementing materials or mineral admixtures are key to achieving strong and durable concrete. Recovered materials such as coal fly ash, ground granulated blast furnace slag and silica fume are widely accepted and used in concrete all over the world, especially in the construction of “high performance” structures such as massive dams, bridges, subway tunnels, etc. These mineral admixtures are not suitable for white concrete and light-colored architectural concrete applications. Converting waste glass fibers into a high performance white pozzolan would allow white concrete producers to gain from the same durability benefits currently realized by gray concrete producers.

**Description of the Benefit:** Albacem's technology will enable the glass fiber industry to eliminate nearly 100% of its glass fiber production waste streams by converting them into viable value-added products. With this technology, the glass industry can prevent the landfilling of about 250,000 tons of waste glass fiber annually. Glass manufacturers will realize improved production efficiency by reducing process costs through the elimination of solid waste disposal costs and participation in revenue sharing for the creation of value-added market-ready products. Implementation of the technology will save a net amount of energy (estimated at 1.75-trillion BTU) consumed by eliminating the manufacture of material replaced by the processed waste glass. The technology also reduces the amount of $CO_2$, NOx, and other air pollutants emitted from the manufacturer of the replaced product (Portland cement). In addition, jobs will be created, and the cement industry will benefit from the introduction of a new product that will increase the service life of concrete and improve sustainability.

**Commercialization of the Technology:** A Commercialization Plan for the technology has been filed with the DOE as a restricted access report as one of the deliverables for the project. Commercialization of the technology has been initiated.

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# 1. Project Description

## 1.1 Project Goals and Objectives

The overall goal of the project was to develop technology to enable the glass fiber industry to eliminate nearly 100% of its glass fiber production waste streams by converting them into viable value-added products. With this technology, the glass industry can prevent the landfilling of about 250,000 tons of waste glass fiber annually. Glass manufacturers will realize improved production efficiency by reducing process costs through the elimination of solid waste disposal costs and the creation of value-added market-ready products. The concept will save a net amount of energy (estimated at 1.75-trillion BTU) consumed by eliminating the manufacture of material replaced by the processed waste glass. The technology also reduces the amount of $CO_2$, $NO_x$, and other air pollutants emitted from the manufacturer of the replaced product.

## 1.2 Variance from Original Goals and Objectives

There have been no substantive changes made to the original goals and objectives for the project.

## 1.3 Background

This technology consists of a process to eliminate solid wastes generated at glass fiber manufacturing facilities by converting them to value-added materials suitable for use in cement and concrete applications. This technology would help divert up to 250,000 tpy of discarded glass fiber manufacturing wastes into beneficial use applications in the concrete construction industry. With many companies implementing “take-back” programs as part of their product stewardship initiative, this technology allows for a revenue-producing outlet for recycling the unused and/or out of spec, take-back, glass fiber products. This technology can also be used for processing glass fiber waste materials reclaimed from monofills at manufacturing facilities. The addition of take-back materials and reclamation from landfills can help supply over 500,000 tpy of glass fiber waste for processing into value added products.

This technology has been under development for over 3 years. The concept has been scientifically proven at the bench-scale level. Glass fiber-forming waste from a major glass fiber manufacturer was processed into a fine-ground value-added product and tested as pozzolan in white and gray concrete mix formulations. It was found that once the waste glass fiber was ground to a powder of suitable fineness, the material could effectively function as a reactive pozzolanic admixture for use in portland cement-based building materials and products, such as concrete, mortars and grouts. This white pozzolan — termed VCAS Pozzolan (for <u>V</u>itreous <u>C</u>alcium-<u>A</u>lumino-<u>S</u>ilicate) — was found to be especially suited for white concrete applications where it imparts desirable benefits such as increased long-term strength and improved long-term durability of concrete products. Two U.S. patents entitled have been issued. The intellectual property ownership associated with the method and process of this technology resides with Albacem LLC.

Performance test results have shown that cement mortars with 20% of the portland cement replaced with the processed pozzolan have outperformed the control mix (containing no pozzolan) after 7 and 28 days. The tests were conducted in accordance with ASTM C-618. The strength activity index for the pozzolan containing mortar mix was 123% and 149% of control after 7 and 28 days, respectively. The effectiveness by which the produced pozzolan reduces the expansion caused by attack by sulfate solution was tested according to ASTM C-1012. The sulfate-induced expansion results showed significant expansion in the control mix (100% white portland cement) beginning at around 100 days and continued until the sample completely disintegrated before 290 days. By comparison, in the mortar with 20% white pozzolan substituting for the white cement, very little expansion occurred out to well over a year (405 days), demonstrating the marked improvement in durability for the pozzolan-containing system.

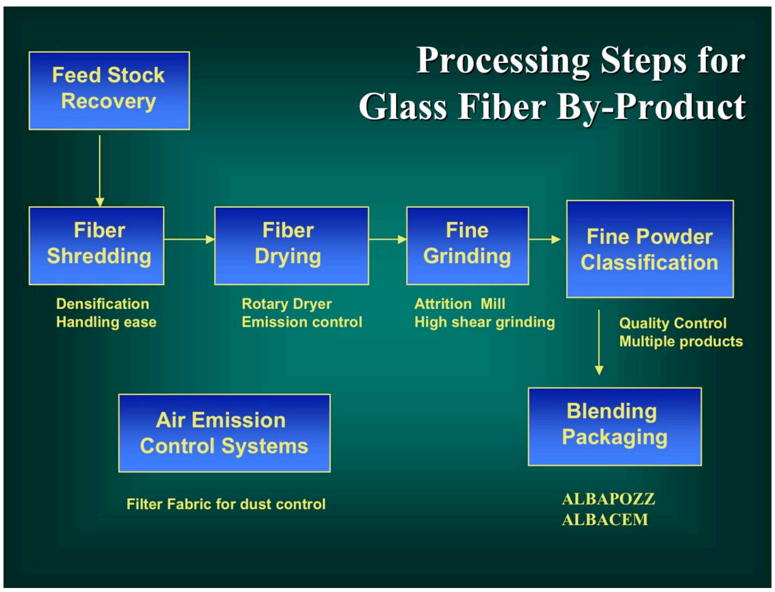
The technical feasibility of processing the waste glass fiber into value-added white pozzolan was validated. Existing shredding, grinding and fine powder classification technologies were tested and evaluated. Modifications and improvement needs to existing "off-the-shelf" unit processes were identified. For example, it was determined that a stirred ball attrition mill with high shear grinding would be required to process the glass fibers into fine, low-aspect ratio particles suitable for the proposed applications. The high-shear attrition mill must also be lined with abrasion-resistant ceramics to prevent product contamination and discoloration. For improved efficiency, the grinding mill will be coupled with a screening circuit and a high efficiency air classification system to produce the desired product gradations and recycle the oversize to the mill.

Currently, there are no known significant competing technologies to process glass fiber manufacturing by-products and convert them into value-added products. Most glass fiber-forming and fabrication wastes continue to be disposed in landfills at significant costs and with associated negative environmental impact. It is estimated that in a typical glass fiber manufacturing facility, 10-20% by weight of the processed glass material is sent for disposal to a landfill. Today, supplementary cementing materials or mineral admixtures are key to achieving strong and durable concrete. Recovered materials such as coal fly ash, ground granulated blast furnace slag and silica fume are widely accepted and used in concrete all over the world, especially in the construction of "high performance" structures such as massive dams, bridges, subway tunnels, etc. These mineral admixtures are not suitable for white concrete and light-colored architectural concrete applications. Converting waste glass fibers into a high performance white pozzolan would allow white concrete producers to gain from the same durability benefits currently realized by gray concrete producers.

# 2. Complete Equipment Assembly (Task 1)

## 2.1. Design and Procurement

The basic process design aspect of this technology is to convert intractable glass fiber wastes into high quality fine powder for pozzolan applications by shredding long strands of glass into short fibers, grinding the short fibers, and classifying the ground material to produce a uniform high quality product with precise control over the maximum particle size and particle size distribution. The overall design concept and process flow diagram in shown below.




In the first step of the process, the glass fiber wastes are collected and placed in a containment area for de-watering and removal of any trash. Water used to cool the waste fiber stream would be allowed to drain off the fibers, collected, and transferred to a wastewater treatment system. Incidental trash objects would be manually removed from the bulk waste materials to allow for further processing.

In the second step of the process, the long strands of waste glass fiber bundles are processed by a shredder to reduce the fiber length from infinitely long entangled strands to short fibers (typically less than 5 mm) for subsequent processing. The shredding stage consists of processing the entangled strands through a rapid rotating mandrel with protruding cutting knives. Stationary cutting edges are also located opposite the rotating mandrel. The fast cutting action of the knives snaps the entangled glass bundles and strands into the desired short individual fibers. A screen enclosure around the rotating mandrel is used to retain the large entangled strands and ensure shredding into short fibers.

In the third step of the process, the shredded short fibers are introduced into a grinding / classification circuit consisting of a horizontal ball mill and high efficiency classifier. A vertical attrition mill could also be used to supplement the ball mill and produce super fine pozzolan for high value applications. The short fibers can also be co-ground with clinkers at cement mills to produce blended cement products. The ground material exiting the grinding mill would be processed through a high-performance dry air classification system. The air classification is used to control the fineness and particle size distribution of the product from fine grind to low-micron range depending on the required specification. Particles larger than the maximum allowable are returned to the mill for further grinding. The use of an air classification system in this stage allows for precise control over the maximum particle size and ensures the production of a uniform product. The air used in classification is vented through a filter fabric dust collector.

### 2.2 Equipment Assembly and Evaluation

Full scale and pilot scale material processing equipment were assembled and evaluated for suitability to handle glass fibers and convert them into fine powders for value-added applications. Some of the pilot scale equipment was acquired and modified. Other equipment was tested at prospective vendors or third-party locations. The acquired pilot-scale equipment was customized for glass fiber processing and tested for optimization. All the equipment was used to produce samples for in-house testing, third-party validation, technology demonstration, and product promotion.

## 3. Prototype Start-up and Optimization (Task 2)

### 3.1 Start-up and Operation

The preliminary trials entirely validated the technical feasibility of the concept for processing the waste glass fiber into value-added white pozzolan. Existing shredding, grinding and fine powder classification technologies were procured, tested and evaluated. Modifications and improvement needs to "off-the-shelf" unit processes were identified. For example, it was determined that a stirred media attrition mill with high shear grinding would be required to process the glass fibers into super-fine pozzolan product with median particle size of 3 micron. However, a conventional horizontal ball mill would be sufficient to produce quality pozzolan with median particle size of 8 micron for white cement replacement.

Following is a description of the individual components of the process equipment:

**Shear / Fiber Chopper:** A fiber chopper device was acquired and modified to reduce the length of long strands of glass fibers (many feet in length) into smaller manageable size (4 to 6 inches in length) for further processing. In larger scale production, a shear or chopper would not be required. A heavy-duty shredder would be sufficient to handle the glass fiber strands and convert them into manageable short fibers for grinding.

**Shredders:** Three types of shredders were evaluated to produce short fibers required for grinder testing and material production. A pilot scale shredder and two full-scale vendors-provided were tested. These types of shredder will be used at glass manufacturing facilities, or elsewhere, to provide short fibers for our proposed plant in the Carolinas.

**Dryer:** A small-scale static bed dryer was built to reduce the moisture of the shredded fibers. Although the moisture content of fibers is low, it created some material handling difficulties when using small-batch scale equipment. A separate unit for fiber drying would not be required at commercial scale. The damp fibers would easily be dried when introduced into a large ball mill grinding circuit.

**Compression Mill:** A small compression roll mill was designed, fabricated and tested to increase the density (reduce the fluffiness) of the shredded fibers and improve material handling and feeding into the pilot scale grinding circuit. Our test work has confirmed that a compression mill would not be required at commercial scale. A larger scale ball or stirred media mill would be able to digest the shredded fibers without densification.

**Fine Grinding Mills:** Two types of fine grinding mills were evaluated. A pilot-scale stirred media mill was assembled for testing and material production. Three types of waste glass fibers from two major glass fiber manufacturers were ground into fine powders. The high-shear stirred media mill was lined with abrasion-resistant ceramics to prevent product contamination and discoloration. The pilot-scale mill was used to produce powders that required further classification in a small-scale classifier. A third-party ball mill with an integrated classifier was also tested and evaluated. It was determined that the stirred media attrition mill with high shear grinding would be more appropriate to process the glass fibers into super-fine pozzolan product with a median particle size in the range of 3 microns. However, a conventional horizontal ball mill would be sufficient to produce good quality pozzolan with median particle size of 8 micron for typical white cement replacement applications.

**Classification System**: A small high efficiency classifier was acquired and modified for material processing and testing. The performance of the fine powder classification system was exceptional. The system was capable of producing the desired powder fineness as needed for material testing. In commercial scale systems, the grinding mill will be coupled with a screening circuit and a high efficiency air classification system to produce the desired product gradations and recycle the oversize to the mill.

## 3.2 Equipment Optimization

The equipment described in the previous task was optimized through a series of iterative steps over a period of several weeks to determine the best feed rate and equipment settings to achieve the target production rates for specific grades of the fine powder pozzolan products.

Pictures showing the process equipment are collected on the following page.


**Figure 1**. Prototype pilot scale process equipment.

# 4. Material Production and Testing (Task 3)

## 4.1 Material Production

Several tons of glass fiber waste were successfully processed into a variety of fine powder grades for testing and distribution to prospective customers, researchers, and interested third parties.

## 4.2 Materials Testing

### 4.2.1 Materials Characteristics of VCAS Pozzolans

VCAS (Vitreous Calcium-Alumino-Silicate) pozzolans are new custom-engineered, high performance supplementary cementing materials for use in white Portland cement, mortar, and concrete products.

After primary sizing and drying, the feedstock is finely ground and processed through high efficiency classifiers to produce a fine bright white powder with quality assured physical properties. The consistent chemical composition and tightly controlled particle size distribution result in highly reactive and superior quality pozzolans for concrete applications. Currently, the VCAS patented technology produces pozzolans in two grades, VCAS-8 and VCAS-micronHS, evaluated during this program.

Unlike silica fume, coal fly ash, ground granulated blast furnace slag, and other by-products, VCAS pozzolans are free of iron, manganese, and other undesirable color-inducing impurities, making them ideally suited for all applications using white cement and in pigmented concrete.

VCAS pozzolans are value-added supplementary cementing materials that exhibit pozzolanic activity comparable to silica fume and metakaolin when tested in accordance with ASTM C618 and ASTM C1240. VCAS pozzolans react with calcium hydroxide produced during the hydration of Portland cement to form additional cementitious compounds such as calcium silicate and alumino-silicate hydrates. Pozzolans are widely used in cement and concrete technology to increase concrete strength, density, and resistance to chemical attack as well as control efflorescence [see Supplemental Information].

**Table 1. Chemical Composition of VCAS Pozzolans**

| | | | |
|---|---|---|---|
| Silica, $SiO_2$ | 50–55% | Titania, $TiO_2$ | <1% |
| Alumina, $Al_2O_3$ | 15–20% | Phosphorus oxide, $P_2O_5$ | <0.1% |
| Iron oxide, $Fe_2O_3$ | <1% | Manganese oxide, MnO | <0.01% |
| Calcia, CaO | 20–25% | Boron oxide, $B_2O_3$ | 0–6% |
| Magnesia, MgO | <1% | Sulphur oxide, $SO_3$ | <0.1% |
| Sodium oxide, $Na_2O$ | <1% | Chloride, Cl | <0.01% |
| Potassium oxide, $K_2O$ | <0.2% | Loss on ignition, LOI | <0.5% |

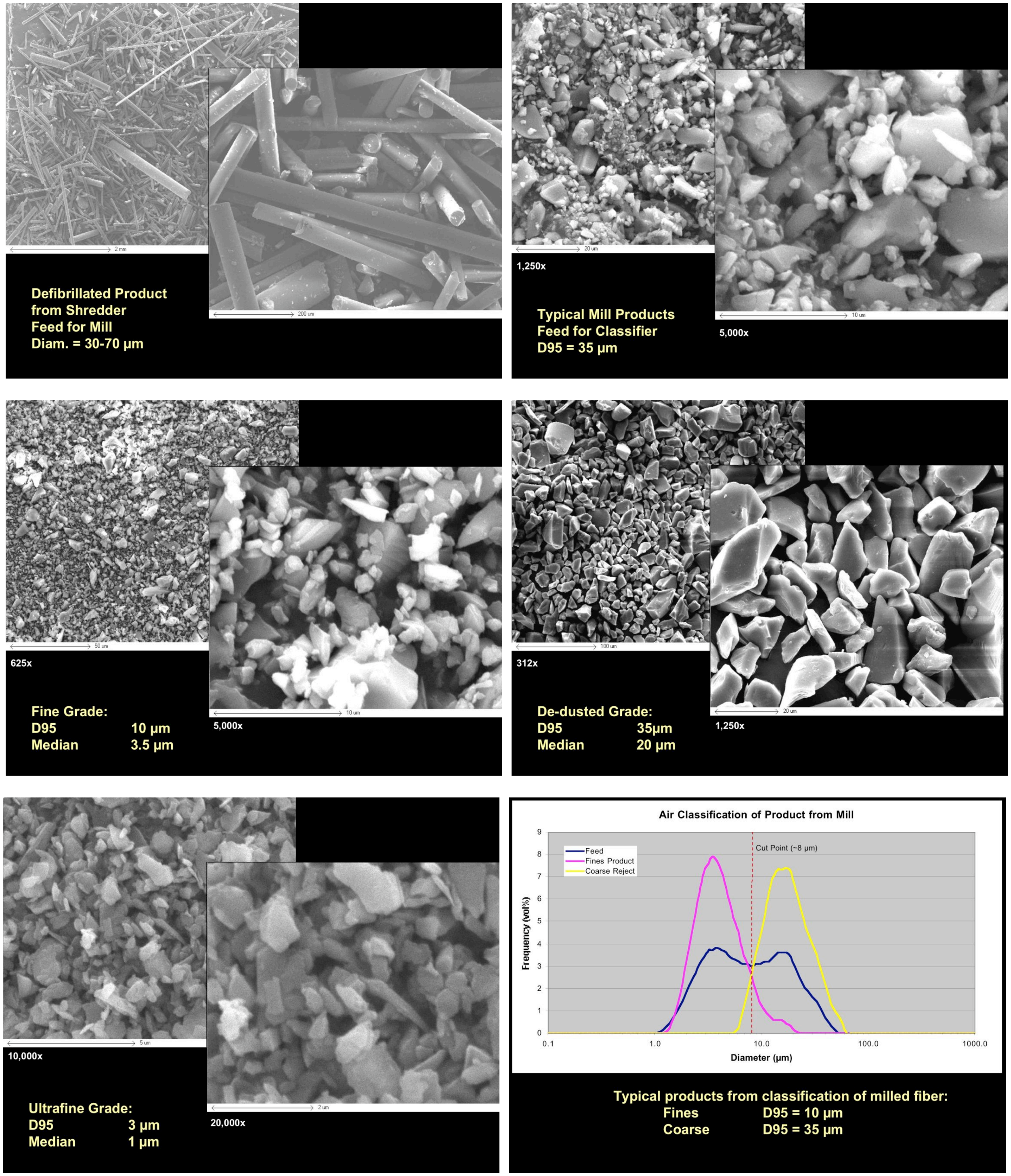



**Figure 2**. Electron microscope images of materials from various stages of the process. The particle size distribution (laser interferometer) for the products is shown in the bottom right hand corner.

Chemically, VCAS pozzolans are comprised largely of oxides of silicon, aluminum and calcium with no deleterious impurities (Table 1 & Fig. 3). The $CaO$-$SiO_2$-$Al_2O_3$ proportions (Fig. 4), the low alkali metal content, and the amorphous structure are ideal for a pozzolanic additive in hydraulic concrete. The low iron content makes them particularly well suited for applications using white cement, such as mortars, stuccos, terrazzo, artificial stone, and cast-in-place or precast concrete products.

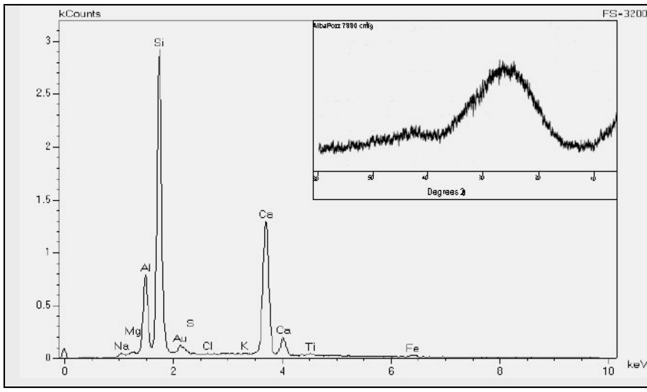



**Figure 3**.

Energy dispersive X-ray analysis (EDXA) pattern for VCAS pozzolan.

Inset: X-ray diffraction (XRD) powder trace showing amorphous nature of VCAS pozzolan.

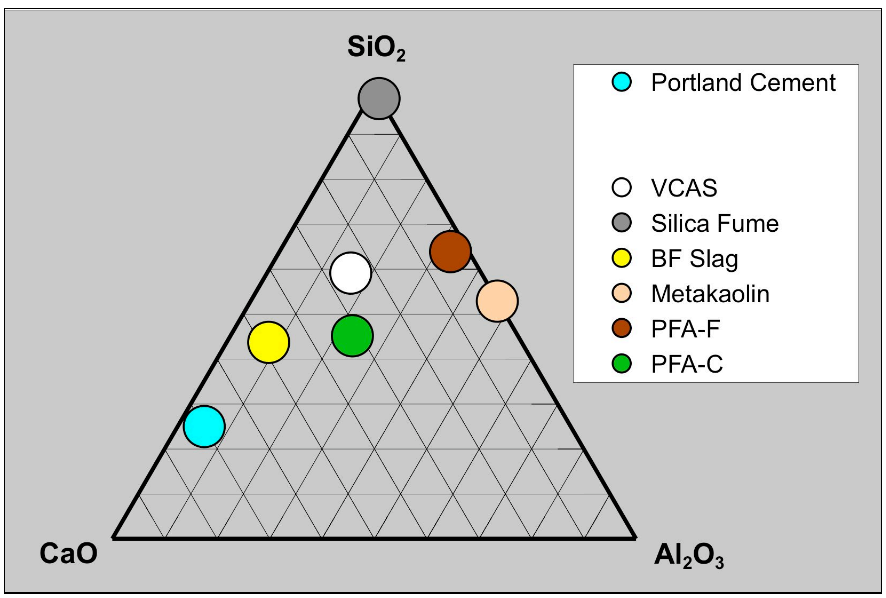



**Figure 4**. Ternary diagram ($CaO$-$SiO_2$-$Al_2O_3$) showing the composition of VCAS pozzolans relative to Portland cement and the common pozzolans.

VCAS pozzolans have superior powder handling compared with silica fume and metakaolin. Tight process control provides consistent product quality and physical properties (Table 2).

**Table 2. Physical Properties of VCAS Pozzolans**

| | ***VCAS-micronHS*** | ***VCAS-8*** |
|---|---|---|
| Specific Gravity | 2.6 | 2.6 |
| Bulk Density, Loose lb/ft$^3$ | 40-44 | 50-55 |
| Med Particle Size, µm | 3 | 8 |
| Passing No. 325 Mesh, % | 99.9 | 97 |
| Specific Surface Area, cm$^2$/g | 8,500 | 4,040 |
| Pozzolanic Strength Index, 28d, % control | 127 | 104 |
| Brightness, % | 92 | 89 |
| Melting Point, °C | 1200 | 1200 |
| Hardness, Mohs | 5.5 | 5.5 |

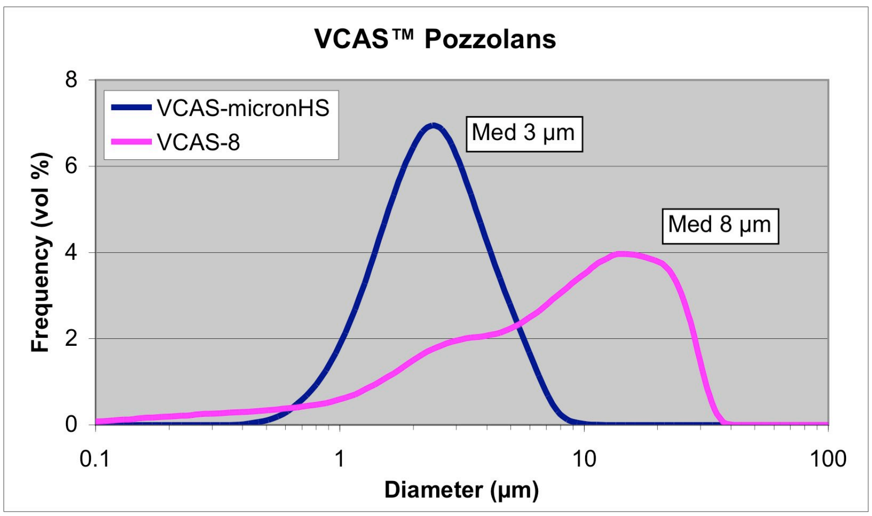



Figure 5. Particle size distribution curves (Coulter laser interferometer) for VCAS pozzolans

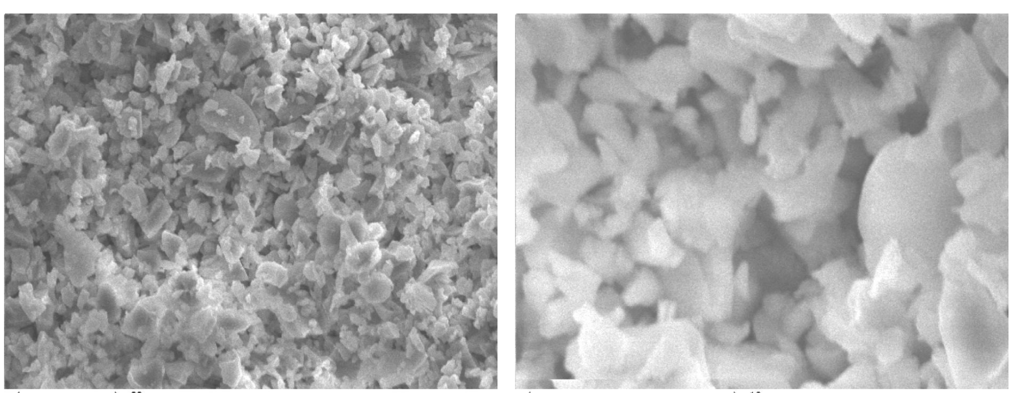



Figure 6. Scanning electron micrographs of VCAS-micronHS (scale bar = 20 µm)

## 4.2.2 Baseline Cementitious Properties of VCAS Pozzolans

**Table 3. Standardized Testing of Pozzolanic Properties**

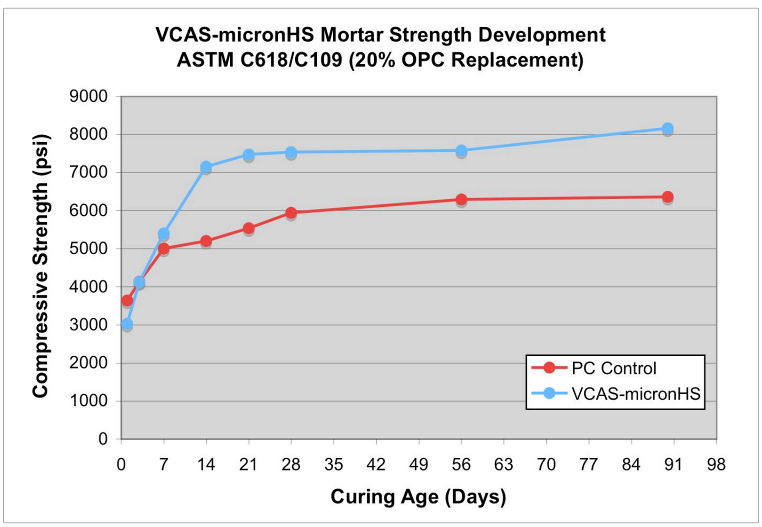
| | | | | SPECIFICATIONS | | |
|---|---|---|---|---|---|---|
| **Physical Properties** | **Test Method** | **VCAS-micronHS** | **VCAS-8** | **ASTM C618 FA & Nat Pozz** Requirement | **ASTM C1157 Blended Cement** Requirement | **ASTM C1240 Silica Fume** Requirement |
| Water Requirement, % control | ASTM C311 | 102 | 98 | 105 (FA), 115 (N) | .. | .. |
| Air content of mortar, vol % | ASTM C185 | | .. | | ns | |
| Set Time (Vicat): | ASTM C191 | | | | | |
| Initial, min (control = 123) | | 125 | | >45 | >45 | .. |
| Final, min (control = 220) | | 300 | | <420 | <420 | .. |
| Normal Consistency, % | ASTM C187 | | | | | |
| Control = 26% | | 26.8 | .. | .. | .. | .. |
| Drying Shrinkage, 28d, % control | ASTM C157 | 70% | | | | |
| Soundness: | ASTM C151 | | | | | |
| Autoclave expansion, max % | | 0.16 | .. | 0.8 | 0.8 | .. |
| Pozzolanic Activity Index (OPC): | ASTM C618 | | | | | |
| 7d, % control, min | | 108 | 86 | 75 | .. | .. |
| 28d, % control, min | | 127 | 104 | 75 | .. | .. |
| Strength Range, 20% VCAS (psi): | ASTM C109 | | | | *GU* *HE* | |
| 1d | | 3026 | 2346 | .. | .. 1450 | .. |
| 3d | | 4125 | 3223 | .. | 1450 2465 | .. |
| 7d | | 5399 | 4313 | .. | 2465 .. | .. |
| 28d | | 7532 | 6194 | .. | 4060 .. | .. |
| 56d | | 7585 | 7062 | | | |
| 90d | | 8161 | 7170 | | | |
| Accel Pozz Activity Index: | ASTM C1240 | | | | | |
| 7d, % control, min | | 123 | 100 | ns | ns | 105 |
| ASR Control: | ASTM C441 | | | | | |
| Expansion 14d (control = 0.337) | | 0.0045 | 0.0500 | | | 80 |
| Reduction of expansion, % | | -99 | -85 | 100* | | |
| Sulfate Resistance (Method A): | ASTM C1012 | | | | | |
| Expansion, 6 m, max % (mod) | | 0.04 | .. | 0.10 | 0.10 (MS) | 0.10 |
| Expansion, 6 m, max % (high) | | 0.04 | .. | 0.05 | 0.05 (HS) | 0.06 |
| Expansion, 1 y, max % (v high) | | 0.06 (4 y) | .. | .. | | 0.06 |
| Rapid Chloride Ion Penetration: | ASTM C1202 | | | .. | .. | .. |

**Notes:**

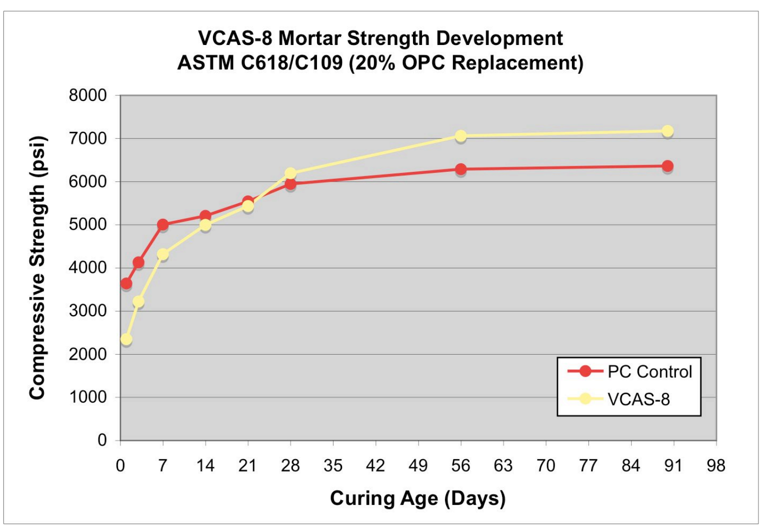
VCAS-micronHS™ and VCAS-8™ meet the technical requirements of ASTM C618 for use as supplementary cementing materials in concrete. Blended pozzolanic cements produced with VCAS-micronHS™ and VCAS-8™ also comfortably exceed the requirements of ASTM C1157: Standard Performance Specification for Hydraulic Cement. VCAS-micronHS™ meets the accelerated pozzolanic activity index, ASR control, and sulfate resistance requirements of ASTM C1240 for silica fume.

## 4.2.3 Strength Development of VCAS Pozzolans ASTM C618 Standard, 20% Pozzolan Replacement / OPC

| Age (Days) | OPC Control Strength (psi) w/c = 0.485 | VCAS-micronHS Strength (psi) | VCAS-micronHS % Control | VCAS-8 Strength (psi) | VCAS-8 % Control | ASTM C618 Spec % Control |
|---|---|---|---|---|---|---|
| 1 | 3639 | 3026 | 83 | 2346 | 64 | .. |
| 3 | 4131 | 4125 | 100 | 3223 | 78 | .. |
| 7 | 5002 | 5399 | 108 | 4313 | 86 | 75 |
| 14 | 5204 | 7155 | 137 | 4994 | 96 | .. |
| 21 | 5541 | 7475 | 135 | 5430 | 98 | .. |
| 28 | 5945 | 7532 | 127 | 6194 | 104 | 75 |
| 56 | 6289 | 7585 | 121 | 7062 | 112 | .. |
| 90 | 6360 | 8161 | 128 | 7170 | 113 | .. |




**Notes:**
The graph top left shows the strength development of mortar without pozzolan (control), and mortar with replacement of 20% cement with VCAS-micronHS™ pozzolan. Note that the use of VCAS-micronHS pozzolan not only well exceeds the 75% ASTM C618 strength index requirement, but also well exceeds the 28-day strength of the control. VCAS-micronHS also exceeds the control strength at 3 days, making it an excellent choice for high performance applications where high early strength is required.




VCAS-8™ pozzolan meets the strength requirements of ASTM C618 at 7 and 28 days and exhibits excellent long-term strength potential, reaching 113% of the control strength at 90 days.

Tests conducted with a medium alkali Type 1 Portland cement.

## 4.2.4 Strength Development of VCAS Pozzolan Mortars ASTM C1240 Standard, 10% Pozzolan Replacement / OPC

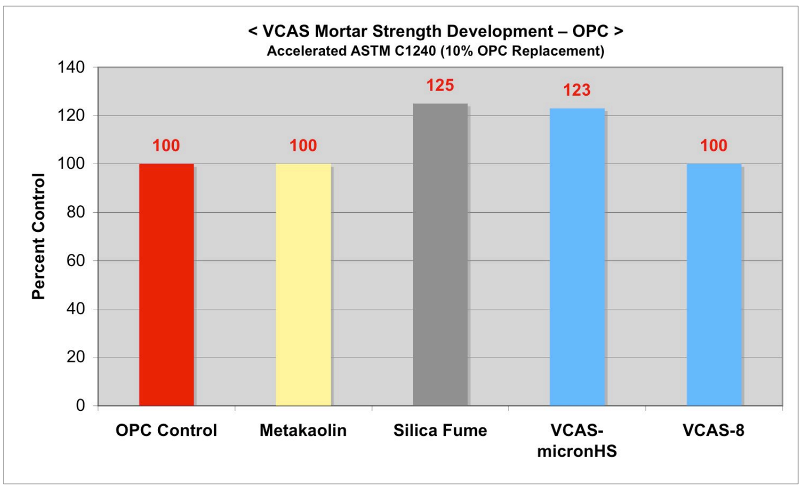
**ASTM C1240 Standard:
10% Pozzolan Replacement
Accelerated / OPC**

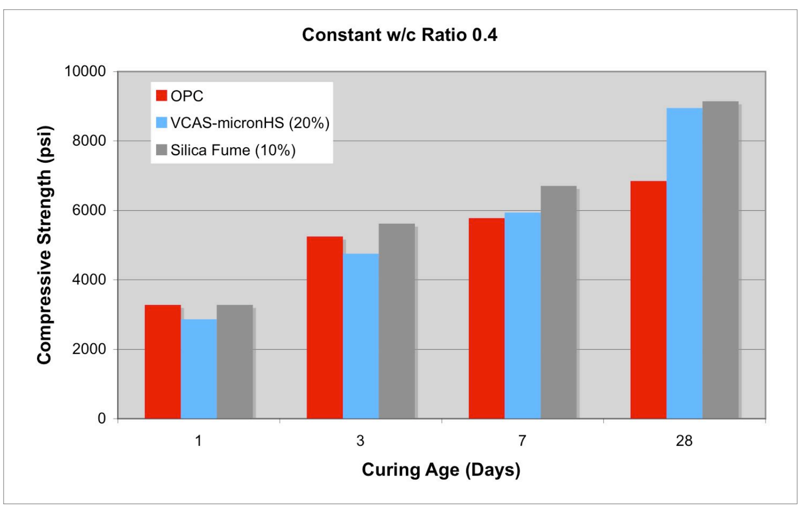
| Pozzolan | % Control |
|---|---|
| OPC Control | 100 |
| Metakaolin | 100 |
| Silica Fume | 125 |
| VCAS-micronHS | 123 |
| VCAS-8 | 100 |

**Pozzolanic Mortars at Constant w/c = 0.4 / OPC
Flow adjusted by Superplasticizer Dosage
Comparison of VCAS-micronHS™ and Silica Fume**

| Age (Days) | OPC Control Strength (psi) SP = 1.5* | VCAS-micronHS 20% Strength (psi) SP = 1.5* | VCAS-micronHS 20% % Control | Silica Fume 10% Strength (psi) SP = 2.5* | Silica Fume 10% % Control |
|---|---|---|---|---|---|
| 1 | 3277 | 2861 | 87 | 3280 | 100 |
| 3 | 5244 | 4749 | 91 | 5615 | 107 |
| 7 | 5781 | 5938 | 103 | 6705 | 116 |
| 28 | 6846 | 8951 | 131 | 9142 | 134 |
| 56 | | | | | |
| 90 | | | | | |

SP = Superplasticizer dosage (mL/500g) for standard flow at w/c = 0.4




**Notes:**

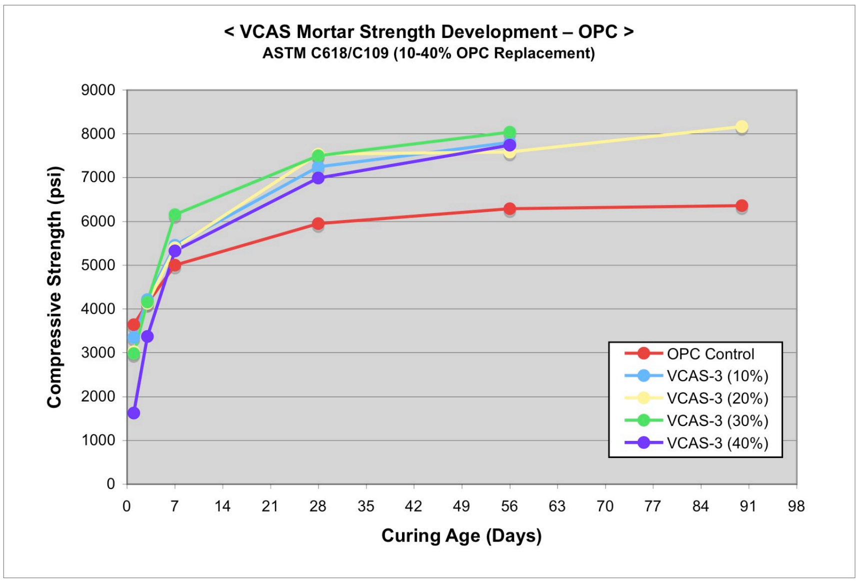
Under the accelerated conditions of ASTM C1240, at 10% Portland cement replacement, it can be seen in the upper graph that VCAS-micronHS has performance comparable with silica fume, and VCAS-8 has performance comparable with metakaolin.

Tests were also conducted in pozzolanic mortars prepared at constant w/c = 0.4, adjusted to standard flow by superplasticizer dosage (lower graph). Mortars with 20% VCAS-micronHS develop 131% of the control OPC at 28 days — performance comparable with 10% silica fume, and notably with 40% less plasticizer required for workability.

VCAS-micronHS provides an alternative to silica fume with considerably less requirement for costly superplasticizer dosage.

### 4.2.5 Strength Development of VCAS Pozzolan Mortars Effect of Pozzolan Replacement Level (10–40%) / OPC

| Age (Days) | OPC Control Strength (psi) w/c = 0.485 | VCAS-3 10% Strength (psi) w/c = 0.484 | % Control | VCAS-3 20% Strength (psi) w/c = 0.494 | % Control | VCAS-3 30% Strength (psi) w/c = 0.484 | % Control | VCAS-3 40% Strength (psi) w/c = 0.482 | % Control |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 3639 | 3348 | 92 | 3026 | 83 | 2980 | 82 | 1622 | 45 |
| 3 | 4131 | 4212 | 102 | 4125 | 100 | 4156 | 101 | 3369 | 82 |
| 7 | 5002 | 5449 | 109 | 5399 | 108 | 6152 | 123 | 5328 | 107 |
| 28 | 5945 | 7245 | 122 | 7532 | 127 | 7500 | 126 | 6992 | 118 |
| 56 | 6289 | 7801 | 124 | 7585 | 121 | 8037 | 128 | 7739 | 123 |
| 90 | 6360 | | | 8161 | 128 | | | | |




**Notes:**

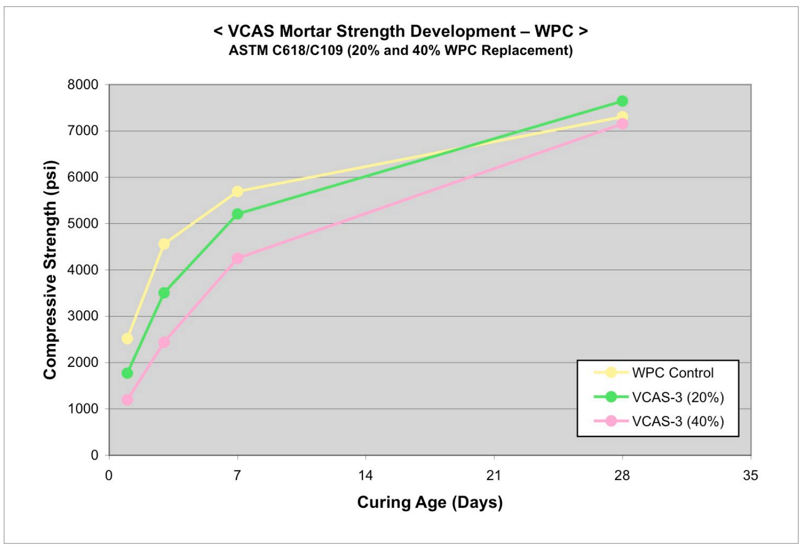
Using VCAS-micronHS (VCAS-3), strength development in the pozzolanic mortars is essentially independent of Portland cement replacement level in the range 10–30%. All VCAS mortars in this cement replacement range, meet or exceed the control strength at 3 days and exhibit strengths that are up to 128% of the control at 28 days.

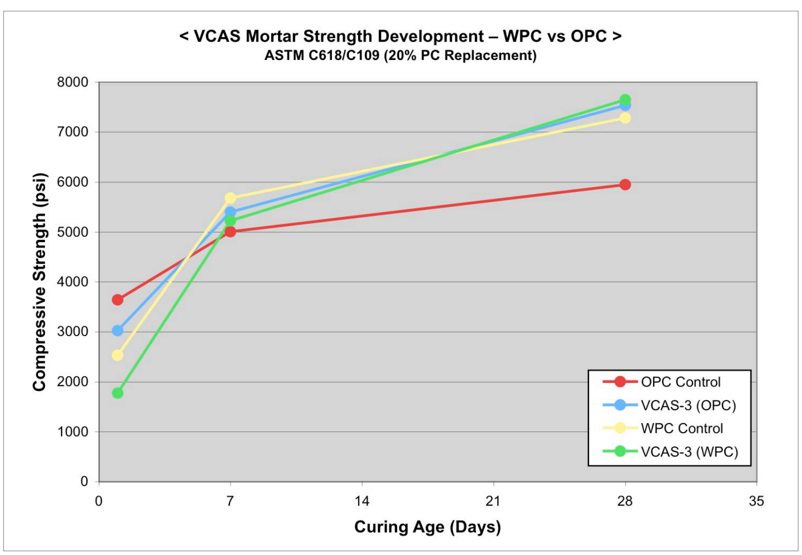
Performance in the pozzolanic mortars is still very good at 40% Portland cement replacement, with strengths that are 107% of the control at 7 days and 118% at 28 days.

This provides tremendous versatility in mix design with VCAS pozzolans that is not seen with high water demand pozzolans such as silica fume and metakaolin.

## 4.2.6 Strength Development of VCAS Pozzolan Mortars White Portland Cement with 20% and 40% VCAS Pozzolan Replacement

| Age (Days) | WPC Control Strength (psi) w/c = 0.484 | VCAS-3 (20%) Strength (psi) w/c = 0.472 | VCAS-3 (20%) % Control | VCAS-3 (40%) Strength (psi) w/c = 0.482 | VCAS-3 (40%) % Control | ASTM C1157 Blended Cement Req. *GU* | ASTM C1157 Blended Cement Req. *HE* |
|---|---|---|---|---|---|---|---|
| 1 | 2518 | 1770 | 70 | 1192 | 47 | .. | 1450 |
| 3 | 4558 | 3501 | 77 | 2436 | 53 | 1450 | 2465 |
| 7 | 5688 | 5207 | 92 | 4246 | 75 | 2465 | .. |
| 28 | 7304 | 7644 | 105 | 7150 | 98 | 4060 | .. |
| 56 | 8026 | | | 7568 | 94 | .. | .. |
| 90 | 8490 | | | | | .. | .. |




**Notes:**

Depending on the source, the strength development characteristics of white cements can be different from ordinary grey Portland cements.

Pozzolanic cement mortars with 20% VCAS-micronHS replacement achieve 92% and 105% of the control WPC strength at 7 and 28 days, respectively. Even with 40% VCAS-micronHS replacement, mortar strengths reach 98% of the control at 28 days.

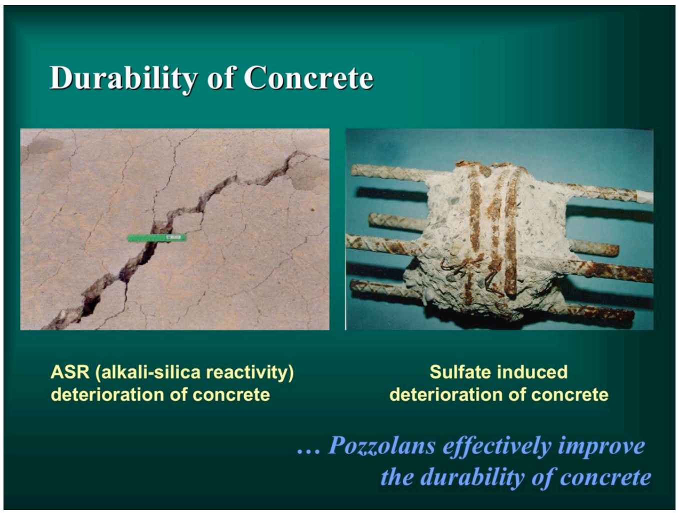
Note that the 28-day strength of the pozzolanic WPC mortar with VCAS is comparable with that produced by the pozzolanic OPC mortar — representing 128% of the OPC control strength. Strengths with WPC at 1 day are typically lower than OPC; but at 7 and 28 days, the strengths are higher.

At 20% VCAS replacement, the WPC blend meets the strength requirements for ASTM C1157 HE (high early) cement. At 40% VCAS replacement, the WPC blend meets the requirements for ASTM C1157 GU cement.

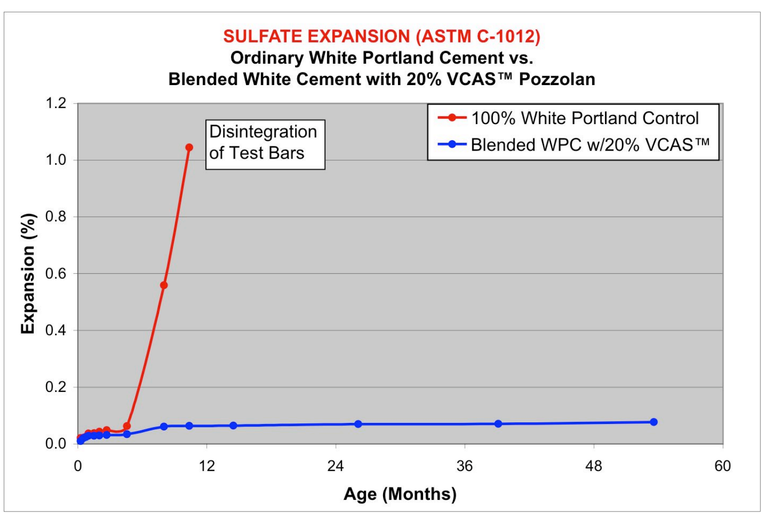
### 4.2.7 Durability Testing of VCAS Pozzolans

#### (a) Improved Sulfate Resistance of White Concrete

The production of white Portland cement (WPC) requires significant changes in the mineral feed to the kiln, largely to reduce the iron content responsible for color. As a consequence, the mineralization of the resulting WPC clinker is somewhat different from ordinary grey Portland cement (OPC). It is well known that WPC is inherently unstable when exposed to sulfate service environments, typically found in coastal regions of the southern United States and elsewhere, This has limited the broader use of WPC concrete to areas and applications not affected by sulfate. VCAS pozzolans provide WPC concretes with superior resistance to sulfate attack.




The graph below shows the excellent dimensional stability of a white cement mortar with 20% VCAS pozzolan replacement tested by ASTM C1012 after over 4 years of exposure. Under these harsh test conditions, the 100% WPC control mortar disintegrated in less than 200 days. The VCAS pozzolanic white cement has sulfate resistance comparable with or better than Type V cement.



### (b) Control of Alkali-Silica Reaction

VCAS pozzolans are also very effective at controlling the deleterious expansion caused by alkali-silica attack in concrete. This can be a particular problem in architectural concretes and precast products that must use light colored or decorative aggregates. Alkali silica attack in concrete involves a delayed reaction between the reactive silicates (e.g. chert, opaline silica) in the aggregate and the alkalis produced by Portland cement hydration. Pozzolans such as VCAS are effective at sequestering the aggressive cement alkalis, thereby reducing considerably the attack on the susceptible aggregates.

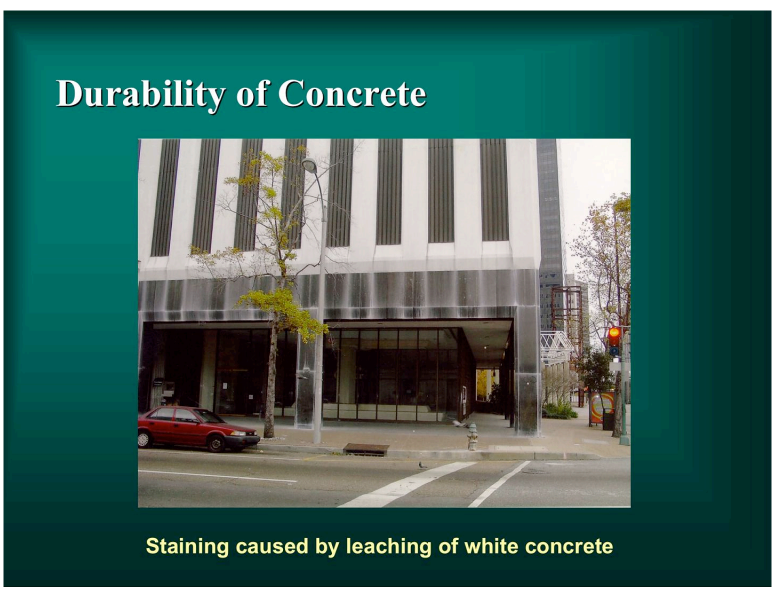
When tested by the ASTM C441 method, mortars prepared with 20% VCAS-micronHS™ pozzolan replacement typically showed 99% reduction of expansion at 14 days (0.0045 vs. 0.337 for the control). VCAS-8™ pozzolan typically exhibited 85% reduction of expansion at 14 days.

### (c) Reduced Permeability and Chloride Ion Penetration

The supplementary cementing reaction of VCAS pozzolans provides increased strength and densification of the cementitious matrix, which has the beneficial effect of significantly reducing the porosity and permeability of concrete. One consequence of this is that concretes incorporating VCAS pozzolans will have reduced chloride ion penetration (ASTM C1202) making them less susceptible to chloride-induced corrosion of embedded reinforcing steel.

### (d) Reduced Efflorescence and Staining

In much the same way that the sequestering of cement alkalis reduces alkali-silica attack, VCAS pozzolans are also very effective at reducing both short-term (lime-rich) and long-term (alkali-rich) efflorescence and staining in buildings and structures using white cement concrete. This property will also help the designer and architect achieve better color retention and matching in decorative and colored concretes and mortars used in applications such as cladding panels, roof tiles, swimming pools, terrazzo, and stucco.



### 4.2.8 Comparison of VCAS Pozzolans with Other Pozzolans

The following chart compares the properties of VCAS-8 and VCAS-micronHS pozzolans with other common pozzolans in the marketplace. The white color of VCAS pozzolans is unique among mineral admixtures used for concrete and is found in only a few select grades of metakaolin. The second distinguishing feature of the VCAS pozzolans is their low water demand that is in marked contrast with the 10% higher water demand of the other high reactivity pozzolans, silica fume and metakaolin. This low water demand enables the VCAS pozzolans to be used at significantly reduced dosages of chemical admixtures, and/or at much higher cement replacement levels, according to the design goals of the concrete.

| Pozzolan | % Replacement | Reactivity | Color (Powder) | Water Demand | Environmental |
|---|---|---|---|---|---|
| VCAS-8™ | 10-30 | Mod | White | Reduction | Positive |
| VCAS-micronHS™ | 10-30 | High | White | Reduction | Positive |
| Silica Fume | 5-8 | High | Dark grey | Large increase | Positive |
| Metakaolin | 5-8 | High | Cream/pink | Large increase | Negative |
| Blastfurnace Slag | 25-50 | Mod | Buff | Neutral | Positive |
| Fly ash | 10-30 | Low | Dark | Reduction | Positive |

The white color, high reactivity, and low water demand make VCAS pozzolans an excellent choice for use with white Portland cement to produce durable, high performance architectural concrete structures and reflective highway barriers.

## 5. Sustainability of Technology

VCAS pozzolans have an important role to play in sustainable "Green" construction by increasing service life and reducing the net greenhouse gas emissions (GHG) and energy consumption for a cubic yard of concrete. For every ton of cement replaced by pozzolan, there will be a net reduction of about 0.86 tons of carbon dioxide released to the atmosphere and about 4.3-million BTUs of energy consumed. To put this in perspective, every 7 tons of VCAS pozzolan used is the equivalent of taking one car off the road as far as carbon dioxide emissions; and every 49 tons pozzolan sold saves enough BTUs to heat one home for a year. In addition, when one ton of a pozzolan is used, it saves about 1.5 tons of virgin material required to make one ton of cement.

The LEED (Leadership in Energy and Environmental Design) Green Building Rating System® is a voluntary, consensus-based national standard for developing high-performance, sustainable buildings.

Many cities and government agencies require LEED certification for new public buildings. Improving the durability of concrete with recycled content reclaimed from local/regional sources and reducing heat island effects with the use of light-colored/high reflectivity materials help earning LEED points toward achieving a greater level of LEED certification.

## 6. Health & Safety

VCAS pozzolans are non-toxic, contain no crystalline silica, and are classed as nuisance dust, in common with other common fine particulate industrial minerals.

# 7. Patents

P1. "White Pozzolan Composition and Blended Cements Containing Same,"
US Patent No. 6,776,838, Aug. 17, 2004.
Copy included with project file.

| | |
|---|---|
| Patent Applic No. | US2003/0047119 |
| Date Filed: | March 1, 2002 |
| Date Published: | March 13, 2003 |
| Patent No | US 6,776,838 |
| Date Issued: | August 17, 2004 |
| Names of Inventors: | Raymond T. Hemmings, Robert D, Nelson, Philip L. Graves, Bruce J. Cornelius |

P2. "White Pozzolan Composition and Blended Cements Containing Same,"
PCT / International Application, No. WO 02/070424 A1, Sept. 12, 2002.

| | |
|---|---|
| Patent Applic No. | WO 02/070424 (PCT) |
| Date Filed: | March 4, 2002 |
| Date Published: | September 12, 2002 |
| Patent No. | Pending |
| Date Issued: | Pending |
| Names of Inventors: | Raymond T. Hemmings, Robert D, Nelson, Philip L. Graves, Bruce J. Cornelius |

P3. "White Pozzolan Composition and Blended Cements Containing Same,"
US Patent No. 7,070,031, July 4, 2006.
Copy included with project file.

| | |
|---|---|
| Patent Applic No. | US2003/0047119 |
| Date Filed: | June 21, 2004 |
| Date Published: | December 16, 2004 |
| Patent No. | US 7,070,031 |
| Date Issued: | July 4, 2006 |
| Names of Inventors: | Raymond T. Hemmings, Robert D, Nelson, Philip L. Graves, Bruce J. Cornelius |

# 8. Conclusions and Recommendations

The project successfully met all of its technical objectives and has demonstrated that it is feasible to process waste glass fiber into high quality white pozzolan products. This sustainable technology will eliminate solid wastes generated at glass fiber manufacturing facilities by converting them to value-added materials suitable for use in the construction industry in portland cement-based building materials and products, such as concrete, mortars, terrazzo, tile, and grouts. It will help divert up to 250,000 tpy of discarded glass fiber manufacturing wastes into beneficial use applications. This technology can also be used for processing glass fiber waste materials reclaimed from monofills at manufacturing facilities. The addition of take-back materials and reclamation from landfills can help supply over 500,000 tpy of glass fiber waste for processing into value added products.

Because the waste fiber from the glass manufacturing industry is entirely vitreous, clean, and low in iron and alkalis, the resulting pozzolan is white in color and highly consistent in chemical composition. This white pozzolan is especially suited for white concrete applications where it imparts desirable benefits such as increased long-term strength and improved long-term durability of concrete products. Two U.S. patents entitled have been issued to Albacem LLC. Third-party validation testing has confirmed that the pozzolanic product is an excellent, high performance material that conforms to a ASTM standards and improves the strength and durability of concrete.

Currently, there are no known significant competing technologies to process glass fiber manufacturing by-products and convert them into value-added products. Most glass fiber-forming and fabrication wastes continue to be disposed in landfills at significant costs and with associated negative environmental impact. It is estimated that in a typical glass fiber manufacturing facility, 10-20% by weight of the processed glass material is sent for disposal to a landfill. Today, supplementary cementing materials or mineral admixtures are key to achieving strong and durable concrete. Recovered materials such as coal fly ash, ground granulated blast furnace slag and silica fume are widely accepted and used in concrete all over the world, especially in the construction of "high performance" structures such as massive dams, bridges, subway tunnels, etc. These mineral admixtures are not suitable for white concrete and light-colored architectural concrete applications. Converting waste glass fibers into a high performance white pozzolan would allow white concrete producers to gain from the same durability benefits currently realized by gray concrete producers.

Implementation of the technology will save a net amount of energy (estimated at 1.75-trillion BTU) consumed by eliminating the manufacture of material replaced by the processed waste glass. The technology also reduces the amount of $CO_2$, NOx, and other air pollutants emitted from the manufacturer of the replaced product (Portland cement). In addition, jobs will be created, and the cement industry will benefit from the introduction of a new product that will increase the service life of concrete and improve sustainability.

A Commercialization Plan for the technology has been filed with the DOE as a restricted access report as one of the deliverables for the project. Albacem has signed an exclusive licensing agreement with Vitro Minerals Inc., a specialty minerals company, to commercialize the Albacem technology (website: www.vitrominerals.com).

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# Appendices

## Appendix A

# Final Task Schedule

| Task Number | Task Description | Task Completion Date | | | | Progress Notes |
|---|---|---|---|---|---|---|
| | | Original Planned | Revised Planned | Actual | Percent Complete | |
| **Task 1** | **Complete Equipment Assembly** | | | | | |
| 1.1 | Design and Procurement | 10/31/03 | 03/31/04 | 06/30/04 | 100% | Completed |
| 1.2 | Equipment Assembly | 12/31/03 | 06/30/04 | 06/30/04 | 100% | Completed |
| **Task 2** | **Prototype Start-up and Optimization** | | | | | |
| 2.1 | Start-up and Operation | 01/31/04 | 06/30/04 | 06/30/04 | 100% | Completed |
| 2.2 | Equipment Optimization | 02/28/04 | 08/31/04 | 08/31/04 | 100% | Completed |
| **Task 3** | **Material Production and Testing** | | | | | |
| 3.1 | Material Production | 06/30/04 | 03/31/05 | 03/31/05 | 100% | Completed |
| 3.2 | Material Testing | 09/31/04 | 09/31/05 | 09/31/05 | 100% | Completed |
| **Task 4** | **Project Management and Reporting** | | | | | |
| 4.1 | Submit quarterly reports | 1st report 10/31/03<br>2nd report 1/31/04<br>3rd report 3/31/04<br>4th report 6/30/04<br>5th report 9/30/04<br>6th report 12/31/04<br>7th report 3/31/05 | | 1st report 10/31/03<br>2nd report 1/31/04<br>3rd report 3/31/04<br>4th report 6/30/04<br>5th report 9/30/04<br>6th report 12/31/04<br>7th report 3/31/05 | 100%<br>100%<br>100%<br>100%<br>100%<br>100% | Completed |
| 4.2 | Submit Final Report | 12/31/04 | 12/31/05 | 12/31/05 | 100% | Completed |

## Appendix B

# Final Spending Schedule

**Project Period:** 07/01/03 to 12/31/05

| Task | Approved Budget | Final Project Expenditures |
|---|---|---|
| **Task 1** Design/Procurement/ and Equipment Assembly | $150,000 | $149.900 |
| **Task 2** Start-up/Operation and Equipment Optimization | $35,000 | $36,900 |
| **Task 3** Material Production and Testing | $50,000 | $49,100 |
| **Task 4** Project Management and Reporting | $15.000 | $14,100 |
| **Total** | $250,000 | $250,000 |
| | | |
| DOE Share | $200,000 | $200,000 |
| Cost Share | $50,000 | $50,000 |

## Appendix C

# Final Cost Share Contributions

| Funding Source | Approved Cost Share | | Final Contributions | |
|---|---|---|---|---|
| | Cash | In-Kind | Cash | In-Kind |
| Albacem LLC | .. | $50,000 | .. | $50,000 |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| **Total** | .. | $50.000 | .. | $50,000 |
| | | | | |
| **Cumulative Cost Share Contributions** | | | | $50,000 |

# Appendix D

# Energy Savings Metrics

## Introduction

This technology consists of a process to convert solid waste generated at glass fiber manufacturing facilities to a value-added product suitable for use in cement and concrete applications. This technology would help divert up to 250,000 tpy of glass fiber forming wastes into beneficial use applications in the concrete construction industry. With many companies implementing "take-back" programs as part of their product stewardship initiative, this technology allows for recycling the unused and out of spec (take-back) glass fiber products. This technology can also be used for processing glass fiber waste materials reclaimed from monofills at manufacturing facilities. The addition of take-back materials and reclamation from landfills to on-going generation of glass fiber forming waste can help supply over 500,000 tpy of materials for processing into value added products for the cement and concrete markets.

Glass fiber forming waste is processed into a fine-ground value-added product known as pozzolan for use in white and gray concrete mix formulations. Pozzolan use in concrete mixes and products can typically replace 20% to 40% of the Portland cement ingredient - the main binding agent in concrete structures and products. Portland cement consumption in the US is over 100 million tons per year.

## One Unit of Proposed Technology

The pozzolan proposed in this technology to replace portion of Portland cement can be pre-milled to powder form and sold to concrete producers for use in their mixes or co-milled with clinker at the cement mill. The nominal plant capacity to produce ground Pozzolan is 50,000 tpy. It the glass fiber is co-milled at the cement mill, the 50,000 tpy will constitute 20% cement replacement at a typical 250,000 tpy cement plant. For the purpose of energy comparison, the unit of proposed technology would consist of 50,000 tpy of new product, which is equivalent to the capacity of one plant using the proposed technology or one cement plant converting to blended cement using this technology.

## One Unit of Current Technology:

Pozzolan replacement for Portland cement is typically done on a one-for-one weight basis. For the purpose of energy comparison, the unit of current technology would consist of 50,000 tpy of replaced Portland cement.

## Discussion of Energy Savings:

The production of Portland cement is an energy-intensive process. On-site energy forms used for cement manufacturing include: coal, petroleum based (coke, oil, gasoline), natural gas, high

BTU waste materials, and electricity. The amounts of energy consumption shown in the Energy Savings Metrics Table are obtained from the DOE report entitled "*Energy and Emission Reduction Opportunities for the Cement Industry" Prepared for the Industrial Technologies Program - Energy Efficiency and Renewable Energy, December 2003***.** The energy data were based on the Cement Industry Fact Sheet 2002 Edition (the Portland Cement Association).

One of the largest opportunities for improving energy efficiency in the cement industry is to change cement product formulations by lowing the clinker content of the finished cement product (i.e., using pozzolans that do not require pyroprocessing). Pyro-processing energy consumption accounts for over 90% of cement's manufacturing energy requirement and operates at low thermal efficiency (about 30%). Clinker milling to form cement accounts for less than 5% of cement manufacturing energy consumption. It is estimated that inter-milling of glass fiber waste with clinker to make blended cements will consume 250,000 Btu per ton of product (5% of 5 million Btu needed for cement production). The electric energy consumption per 50,000 tpy unit is estimated at 12,500 million Btu. For the purpose of energy saving comparison, it is estimated that 200,000 tons per year of materials could be processed and marketed in the US by 2010.

**Energy Savings Metrics**
**(each Unit = 50,000 tpy)**

| Type of Energy Used | A | B | C=A-B | D | E=CxD |
|---|---|---|---|---|---|
| | Current Technology (million Btu / yr / unit) | Proposed Technology (million Btu / yr / unit) | Energy Savings (million Btu / yr / unit) | Estimated Number of Units in U.S. by 2010 (units) | Energy Savings by 2010 (million Btu / yr) |
| Petroleum (Coke, Oil/Gasoline, etc.) | 40,445 | 0 | 40,445 | 4 | 161,780 |
| Natural Gas | 13,080 | 0 | 13,080 | 4 | 52,320 |
| Coal | 149,200 | 0 | 149,200 | 4 | 596,800 |
| Electricity (@ 10,500 Btu / kWh) | 26,235 | 12,500 | 13,735 | 4 | 54,940 |
| Other Energy (Waste Fuel) | 20,125 | 0 | 20,125 | 4 | 80,500 |
| Total Per Unit | 249,090 | 12, 500 | 236,590 | 4 | 946,340 |

# Supplemental Information

## S1. Pozzolans — General Description

A pozzolan is broadly defined as an amorphous or glassy silicate or aluminosilicate material that reacts with calcium hydroxide formed during the hydration of Portland cement in concrete to create additional cementitious material in the form of calcium silicate and calcium silicoaluminate hydrates. The first pozzolans were used by the Romans to make cement from burned limestone and Santorum earth from volcanic eruptions. These ancient concrete mixes were extremely durable and many architectural elements survive today. They underline the fact that one of the compelling reasons for incorporating pozzolans in concrete today is to improve quality and to extend service life by enhancing the durability of this ubiquitous construction material.

To function properly, pozzolans must be amorphous or glassy and generally finer than 325 mesh (45 microns) in particle size. Finer particle sizes generally have greater reactivity, meaning they more quickly convert to supplementary cementitious material, helping in early strength development as measured by standardized tests such as ASTM C618/C109.

Pozzolans can continue to react in concrete for many years, further strengthening the concrete and making it harder and more durable during its service life. Pozzolans also serve to densify and reduce the permeability of concrete, which helps to make it more resistant to deterioration and swelling associated with various exposure conditions.

### Types of Pozzolan

Pozzolans commonly used in modern concrete construction include coal fly ash (aka pulverized fuel ash or PFA), ground granulated blast furnace slag, silica fume, and metakaolin (calcined clay). The common feature of all these pozzolans is that they are silicates or aluminosilicates that have been converted to amorphous or glass phases in a high temperature furnace or combustion chamber, followed by rapid cooling or quenching under various conditions. The amorphous or glassy form allows the silicates to react readily as the concrete cures. For use in modern cement and concrete applications, pozzolans must be low in alkalis ($Na_2O$ and $K_2O$), which cause long-term durability problems in concrete by expansion due to the alkali-silica reaction (ASR). Chemically, pozzolans are comprised principally of oxides of silicon, aluminum and calcium. The composition of the common pozzolans, including VCAS pozzolans, relative to Portland cement are compared in the ternary diagram ($CaO$-$SiO_2$-$Al_2O_3$) below.

### The Pozzolanic Reaction

There are several steps involved in the so-called pozzolanic reaction in concrete. As Portland cement reacts with the gauging water, the tricalcium silicate ($C_3S$) and dicalcium silicates ($C_2S$) react to form calcium silicate hydrates (C-S-H), largely responsible for strength development, together with a by-product of portlandite, or calcium hydroxide. At the same time, the alkalinity of the water (now referred to as pore fluid) increases to pH 13 or higher. This combination of events provides ideal conditions under which the pozzolan can react. The high pH first causes the silicate network structure of the pozzolan to break down to smaller units, which then react with the calcium hydroxide to form more calcium silicate hydrate binder. The net effect is that the calcium hydroxide in the concrete — which itself has no strength-forming properties and is also a potential site of weakness for certain forms of chemical degradation — is converted by the pozzolan to additional C-S-H binder which is deposited in pore spaces. This leads to a general densification of the cement matrix, which contributes to increased strength, reduced permeability, and increased long-term durability.

Portland cement requires only about 25% water to completely react to form concrete. However, most concrete mixes employ considerably larger percentages of water content to allow the mix to flow properly into the formwork or to achieve proper workability. This excess water inevitably introduces void spaces in the concrete that make the concrete porous and provide conduits for the passage of water and aggressive solutions. It is therefore easy to understand that the water-to-cement (w/c) ratio is a major controlling factor in the strength potential of a given concrete mix design: low w/c ratios are associated with higher strengths; whereas high w/c ratios are associated with lower strengths. The conversion of the calcium hydroxide to C-S-H by the pozzolanic reaction and the filling of the void spaces both contribute to improved concrete quality, compressive and flexural strength, and long-term durability.

### Mix Design with Pozzolans

Over the last 50 or more years, engineers and scientists have developed a number of strategies for effectively designing concrete with pozzolans. Depending on the type of pozzolan used and the design goals for the concrete, adjustments will be made to at least the cement replacement factor and the w/c ratio. Pozzolans such as blast furnace slag and fly ash have relatively low water demands and can be used to replace up to 40% of cement in some concrete mixes. In contrast, silica fume has much finer particles with very high water demand, necessitating the use of high range water reducers or superplasticizers to even achieve a 10% cement replacement. At the same time, the fine particle size renders this pozzolan more reactive, allowing concretes to achieve higher strengths more quickly. Metakaolin requires somewhat less water than silica fume and can be used at replacement levels of 10-15%.

Depending on the reactivity of the pozzolan, the cement replacement factor, and the w/c ratio, the initial strength (up to 3 days) of concrete with pozzolans may be reduced by up to 20% compared to the strength of a control concrete without pozzolan. Between 14 and 28 days, however, the pozzolanic concretes typically have similar or higher strengths than the control concrete, with great benefit to the long-term durability, hardness, and strength of the concrete structure or component. High performance pozzolans, such as silica fume and metakaolin, typically have the least impact on the early strength. VCAS pozzolans fall into this high performance category and can reach or exceed the control strength by 3 days. Specific strength development data on the performance of VCAS pozzolans can be found in the VCAS technology sections, Data Sheets, and Technical Bulletins.

VCAS pozzolans are comparable in reactivity with silica fume and metakaolin, and are engineered to achieve their performance both by uniform materials chemistry and quenching and by fine particle size. As such, VCAS pozzolan have low surface area and smooth surfaces that have 10% less water demand than silica fume or metakaolin. This allows VCAS pozzolans to be used at cement replacement rates up to 30% or higher.

Low water demand, high reactivity, and white color after cure are the hallmarks of an excellent pozzolan for white Portland cement concrete.

## Benefits of Using Pozzolans

The following are benefits that are generally obtained from using pozzolans in concrete.

Workability: As they are replacing various percentages of cement, pozzolans can have a significant impact — both positive and negative — on the workability of a concrete mix. Low water demand pozzolans, such as blast furnace slag and fly ash, generally increase workability at a given w/c ratio. In contrast, high surface area pozzolans such as silica fume and metakaolin cause a large reduction in the fluidity of the concrete, which necessitates the use of costly chemical admixtures (high range water reducers, superplasticizers) to make them workable. Even then, these types of concrete tend to be sticky and difficult to finish. VCAS pozzolans fall into the category of low water demand pozzolans.

Reduced Heat of Hydration: Historically, one of the most important reasons for including pozzolans in concrete was to lower the heat of hydration of the Portland cement in order to reduce thermally induced stress cracking. This is an especially important factor in massive concrete structures such as dams, tunnels, bridges, and large precast elements.

Increased Durability: Properly designed concretes made with pozzolans are generally stronger, harder and more durable. The physical densification of the cement matrix, coupled with the consumption of calcium hydroxide and cement alkalis brings about the following improvements in durability in pozzolanic concretes: greater resistance to sulfate attack; reduced alkali aggregate reactivity; less susceptibility to corrosion of embedded steel by chloride ion intrusion; and reduced efflorescence.

Reduced Efflorescence: Pozzolans react with excess calcium hydroxide and cement alkalis, helping to prevent primary efflorescence. Once the concrete cures, the pozzolanic reaction described earlier causes the concrete to become denser and less permeable. This limits egress of moisture, and reduces the lime and alkalis available to migrate to the surface causing primary and secondary efflorescence. VCAS pozzolans are similarly very effective at controlling efflorescence, particularly in white or colored concretes where this phenomenon can be a serious problem.

Improved Form Detail: A high fineness, high performance pozzolan such as silica fume is effective at reducing bug holes and better reproducing form detail in precast gray concrete. Similarly, VCAS pozzolans are very effective at improving the surface quality and detailing of precast and molded white cement concrete products such as artificial stone, stucco, cladding panels, pool mixes, and terrazzo.

Pozzolan Color: The vast majority of pozzolans, such as coal fly ash, iron ore blast furnace slag, and silica fume, are dark colored and will usually strongly discolor white cement. Over 14-million tons of these pozzolans are used in gray Portland cement. VCAS and metakaolin pozzolans can be used with white cement. Upon the initial mixing of the white concrete paste, VCAS pozzolan will be slightly blue tint, and metakaolin will be slightly buff tint. During the first seven days of curing, the white concrete will brighten as the pozzolan reacts, such that both pozzolan will be about as white as the white cement control. The VCAS blue tint, measured as lower B value, will often make the VCAS pozzolan appear whiter to the human eye than metakaolin.

## Pozzolans and Sustainability

Pozzolans have an important role to play in sustainable "Green" construction by increasing service life and reducing the net greenhouse gas emissions (GHG) and energy consumption for a cubic yard of concrete. For every ton of cement replaced by VCAS pozzolans, there is a net reduction of 0.86 tons of $CO_2$ emissions, which means that every 21-ton truckload used is equivalent to taking three automobiles off the road. In addition, the heat saved is 4.29 million BTU's/ton, which would heat the average home for more than a week. In addition, every ton VCAS used saves 1.5 tons of virgin raw materials needed to make a ton of cement. VCAS pozzolans represent a high value recycling opportunity.